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**Extreme Worlds of the Outer Solar System:
Dynamic Processes on Uranus & Io**

by

Katherine Rebecca de Kleer

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Astrophysics

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Imke de Pater, Chair

Professor Geoffrey Marcy

Professor James Graham

Professor Michael Manga

Spring 2017

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Katherine Rebecca de Kleer

Abstract

Extreme Worlds of the Outer Solar System:
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Doctor of Philosophy in Astrophysics

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Professor Imke de Pater, Chair

A central goal of planetary science is the creation of a framework within which the properties of each solar system body can be understood as the product of initial conditions acted on by fundamental physical processes. The solar system's extreme worlds - those objects that lie at the far ends of the spectrum in terms of planetary environment - bring to light our misconceptions and present us with opportunities to expand and generalize this framework. Unraveling the processes at work in diverse planetary environments contextualizes our understanding of Earth, and provides a basis for interpreting specific signatures from planets beyond our own solar system. Uranus and Io, with their unusual planetary environments, present two examples of such worlds in the outer solar system.

Uranus, one of the outer solar system's ice giants, produces an anomalously low heat flow and orbits the sun on its side. Its relative lack of bright storm features and its bizarre multi-decadal seasons provide insight into the relative effects of internal heat flow and time-varying solar insolation on atmospheric dynamics, while its narrow rings composed of dark, macroscopic particles encode the history of bombardment and satellite disruption within the system.

Jupiter's moon Io hosts the most extreme volcanic activity anywhere in the solar system. Its tidally-powered geological activity provides a window into this satellite's interior, permitting rare and valuable investigations into the exchange of heat and materials between interiors and surfaces. In particular, Io provides a laboratory for studying the process of tidal heating, which shapes planets and satellites in our solar system and beyond. A comparison between Earth and Io contextualizes the volcanism at work on our home planet, revealing the effects of planetary size, atmospheric density, and plate tectonics on the style and mechanisms of geological activity.

This dissertation investigates the processes at work on these solar system outliers through studies of Uranus' atmosphere and rings and of Io's thermal activity. I show that Uranus' rings are spectrally flat in the near-infrared, setting them apart from all other ring systems in the solar system. I investigate the vertical profile of species in Uranus' atmosphere, and demonstrate evidence for seasonal trends in the upper atmosphere on decadal timescales.

Based on a large high-cadence dataset of Io’s volcanism obtained with adaptive optics over 100 nights, I show that the thermal timelines of Io’s volcanoes indicate at least two distinct classes of eruption. The asymmetric spatial distribution of Io’s volcanic heat flow suggests additional mechanisms at work modulating the effects of tidal heating. I present the detection of one of the most powerful eruptions ever seen on Io, which I use to derive a eruption temperature of >1300 K, consistent with a highly mafic magma composition. Geophysical modeling of the thermal timeline of Loki Patera, a distinctive volcanic feature on Io, indicates low lava thermal conductivities also consistent with a highly-mafic silicate composition. Ultra-high-resolution thermal mapping of this patera reveals a multi-phase volcanic resurfacing process that hints at the plumbing system underlying this massive volcanic feature.

The results presented here are founded on near-infrared observations of unprecedented resolution in the spatial, spectral, and temporal domains. The interpretation of the data utilizes rigorous statistical techniques to draw meaningful conclusions. In addition to the scientific impact of the findings, this work therefore also pioneers specific ground-based telescope capabilities and analysis tools, and demonstrates their utility to solar system science. Chapter 2 presents the first high-resolution spectra of Uranus’ rings. Chapter 3 introduces Markov Chain Monte Carlo simulations into ice giant atmospheric radiative transfer modeling, permitting a rigorous analysis of parameter uncertainties and correlations. Chapters 4-7 present results from the first multi-year, high-cadence ground-based observing campaign to study Io’s volcanism with sufficient spatial resolution to directly resolve individual volcanoes. The thermal timelines of these volcanoes provide unprecedented insight into the variability and distribution of Io’s volcanism over a wide range of timescales. Chapter 7 uses geometric arguments to deduce topography of a volcanic feature on Io based on observations at a range of viewing angles. Finally, Chapter 8 presents the first ground-based observations to map a thermal feature on Io at a spatial resolution of ~ 10 km on Io’s surface, derived from the first mutual satellite occultation event to be observed with adaptive optics on a dual-telescope interferometric system. These techniques can all be expanded and applied to these and other targets in future near-infrared studies.

For Johan de Kleer

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When I first arrived at UC Berkeley, I was not at all sure that an academic career was for me, nor even that I wanted to be in grad school. My years as a grad student involved not just the transition from a consumer of knowledge to an active contributor, but also the process of very slowly accepting the idea of myself as an academic and a scientist. This transition was catalyzed by supportive, enthusiastic mentors and role models who encouraged me to find the questions I cared about and take ownership of my ideas, and who taught me how to incorporate my personality into my choice of problems and my approach to problem-solving. I am therefore grateful to not only those individuals who supported my career and scientific development over the years, but also those who helped me overcome my resistance to academia and reconcile my identity with my research endeavors.

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Chapter 1

Introduction

1.1 The outer solar system

Our solar system is a diverse and dynamic place, consisting of rocky and gaseous planets that orbit the sun, many of which are themselves surrounded by complex systems of satellites, rings, and small particles. The factors that have led to the current state of these worlds are the same fundamental physical processes that are at work on our own planet Earth and throughout the galaxy. Each planetary body thus provides a unique laboratory for studying the processes that shape our universe.

Spacecraft missions during the past several decades have given us tremendous insight into the solar system planets and their satellites (Figure 1.1), but provide limited time coverage, sometimes as brief as a single fly-by. The ice giants Uranus and Neptune have not been visited by spacecraft since the *Voyager* mission in the late 1970's. Advancing our understanding of the outer solar system worlds, and their time-variable signatures in particular, relies on ground-based observing campaigns.

Advances in telescope technologies since the start of the 21st century have provided astronomers with powerful tools that yield unprecedented insight into the surfaces, atmospheres, and environments of planets and satellites. In particular, high-resolution imagers and spectrographs on 8-10 meter near-infrared telescopes, combined with adaptive optics (AO) and interferometric capabilities, can now achieve spatial resolutions on some targets that approach the best available spacecraft data.

The formation and evolution of planetary satellites and rings are tightly connected to the evolution of the host body. Some satellites, such as the galilean satellites of Jupiter, likely formed around their host planet in a disk analogous to the circumstellar disk in which the solar system formed. Irregular satellites are thought to be captured asteroids or Kuiper Belt objects, and tell the story of dynamical interactions between planets and small body populations throughout the solar system's history. Planetary rings, including their composition and dynamics, probe the evolution of the satellites and even the planet itself, identifying the sources and lifetimes of materials throughout the system.

Our framework for understanding geophysical and atmospheric processes is founded in

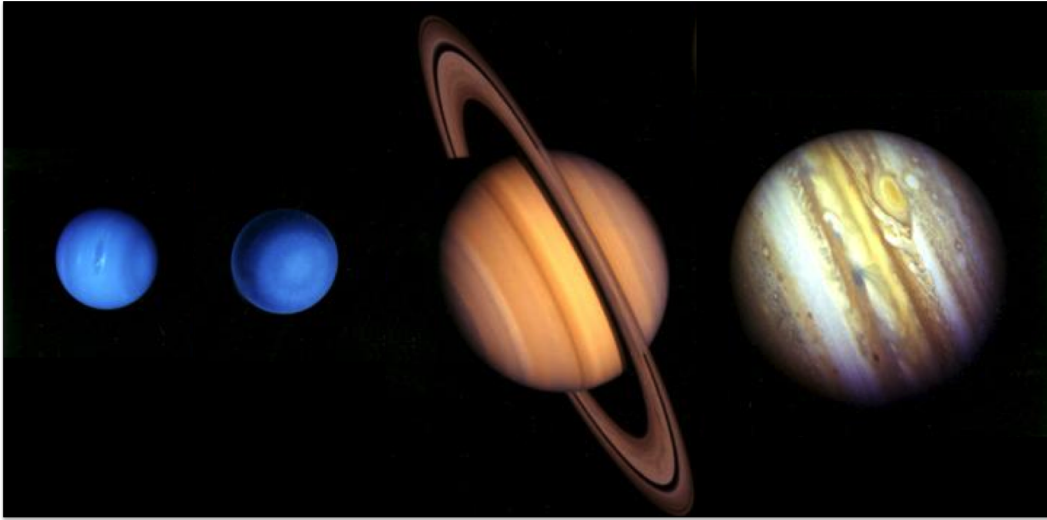


Figure 1.1: Montage of *Voyager 2* images of the outer solar system's gas giant planets. *Image credit: NASA/JPL.*

our understanding of Earth. While planets similar to Earth in size and solar distance may conform well to this framework, bodies dissimilar to Earth often challenge our understanding and reveal mistaken assumptions. Studies of these extreme worlds force us to take a larger perspective and develop a more generalized framework within which Earth is just one possible outcome of planetary evolution.

Uranus and Io are both outliers on the spectrum of planetary properties, and therefore present optimal laboratories for investigating the sources of diversity amongst planetary bodies. Uranus has the lowest intrinsic heat flow and the least cloud activity of all the giant planets, but its atmosphere exhibits detectable variability over timescales corresponding to its 21-year seasons. Its ring system is neither dusty like Jupiter's nor bright from water ice like Saturn's, and the processes confining the rings into narrow annuli are still not understood. At the opposite end of the spectrum, Io's tidally-heated interior generates a high heat flow and powers the eruption of hot magma onto its surface, producing thermal signatures that vary measurably in a matter of hours and sometimes even minutes.

These two bodies thus present opportunities for expanding our understanding of both gas giants (Uranus) and active rocky worlds (Io), including the effects of highly inclined and eccentric orbital configurations on the environments of such bodies. Understanding the mechanisms at work on these worlds is becoming more and more critical as exoplanet surveys discover planets beyond our solar system for which the ice giants and Io present the best analogs. A major finding from the *Kepler* mission was the discovery that the majority of planets around Sun-like stars fall between Earth and Uranus in size, and may have interior structures and evolutionary histories similar to our own ice giants (Figure 1.2; Petigura et al. 2013). Meanwhile, rocky exoplanets that are being discovered in close-in or eccentric orbits (e.g. Howard et al. 2013) may be undergoing extreme melting and outgassing due to

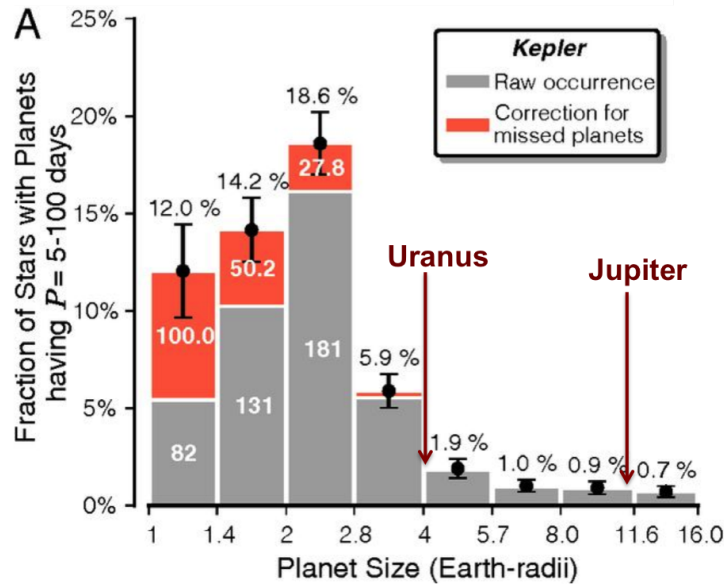


Figure 1.2: Occurrence rate of planets as a function of planet size. The majority of planets are between the size of Earth and Neptune/Uranus ($R_{Uranus} \sim 4R_{Earth}$). (Figure adapted from Petigura et al. 2013).

intense stellar radiation or tidal heating, for which Io presents our best local analog.

1.1.1 Uranus

Of all the solar system planets, the ice giants Neptune and Uranus are the least understood. Both planets are similar in temperature (50-60 K at the tropopause) and size (diameter of $\sim 50,000$ km), and their upper atmospheres are dominated by hydrogen, helium, and methane. However, Uranus' lack of detected intrinsic heat flow, its relative dearth of cloud activity, and its low abundance of stratospheric molecules relative to Neptune, point to a distinctive evolutionary history. In addition, Uranus orbits the sun on its side ($i = 98^\circ$), leading to 21-year-long seasons that produce long-term trends in its upper atmosphere.

The greatest leap in our understanding of Uranus resulted from the *Voyager 2* fly-by of the planet in 1986. Uranus' appearance is characterized by a nearly-complete absence of the bright, dynamic cloud features observed on the other giant planets, although the recent detection of a bright storm system on Uranus in 2014 (de Pater et al. 2015) has challenged long-standing assumptions about this planet's inactivity. Although Uranus also lacks the strong banding of Jupiter and Saturn, there is a transition near 45° in both hemispheres between the darker equatorial regions and the brighter polar regions, with the highest albedos occurring right at the transitional latitudes.

Uranus' 84-year-long "day" results in long-term seasonal trends. In 2007, Uranus passed through equinox, and the north polar latitudes that have been in shadow for decades are now emerging into sunlight. The effects of this transition are evident in the fading of the

bright southern collar and the emergence of a new northern mid-latitude collar (Figure 1.3); the brightening is attributed to the thickening of methane and aerosol cloud and haze layers at a depth of a few bars (e.g. Rages et al. 2014).

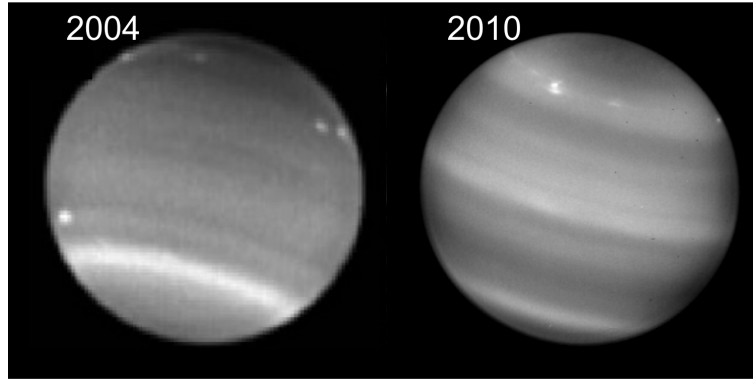


Figure 1.3: Images of Uranus at H-cont ($1.6 \mu\text{m}$) three years before and after equinox, demonstrating the brightening of the northern hemisphere. Uranus image from 2004 adapted from Sromovsky et al. (2007); Uranus image from 2010 adapted from de Kleer et al. (2015).

While Uranus' atmosphere reveals the planet's multi-decadal evolution, its ring system is the result of dynamical interactions and collisions over the past hundreds of millions of years. A planet's ring system, including the composition and size of the particles, provides information on the sources of material into the system and its collisional history. Uranus' main ring system consists of nine narrow annuli which vary longitudinally. Their narrow widths require a confining mechanism, without which the rings should disperse within 1 million years (Esposito 2002). Shepherd moons could provide this confinement, but have only been observed for the ϵ ring (Porco et al. 1987). Uranus' main ring particles are much larger in size (cm-m) than the dust grains that compose Jupiter's rings, but lack the reflective surfaces of Saturn's ring particles. The composition of the particles is likely water ice with an outer coating of dark material of unknown composition; spectroscopic signatures can be diagnostic of composition, but have not yet been detected for Uranus' rings.

1.1.2 Io

Jupiter's moon Io is a truly unique world within our solar system. It is the only body other than Earth where large-scale silicate volcanism can be observed (Figure 1.4). Despite the rarity of volcanic activity in our solar system today, volcanism is a fundamental planetary process that shaped the surfaces of all the terrestrial planets in our solar system during their early histories (Platz et al. 2015). In the first billion years after the solar system's formation, planetary heat flows were high due to residual heat of formation and decay of radioactive elements, while major impacts produced short-term yet extensive melting of surfaces and mantles. The planetary surfaces we see today still hold the record of this effusive volcanism, although later impacts and other exogenic processes have altered their signatures.

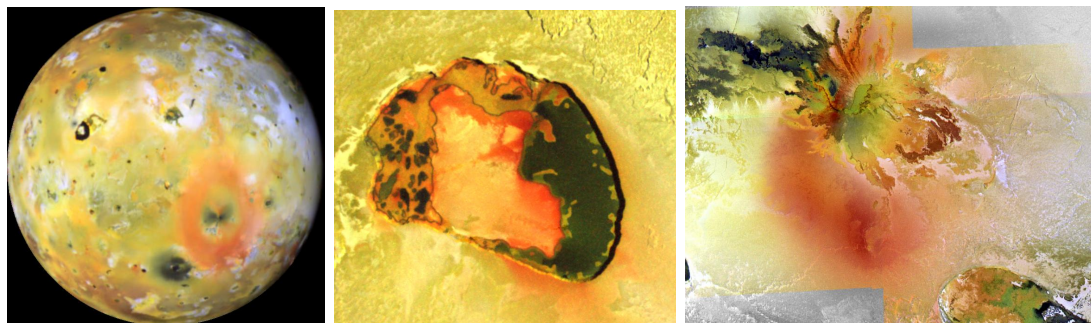


Figure 1.4: Images of Io from the *Galileo* spacecraft: (left) global image; (middle) Tupan Patera; (right) Culann Patera. *Image credit: NASA/JPL/University of Arizona.*

Today, surface volcanism (as far as we know) is restricted to Io, Earth, and Venus. On Venus, many lines of evidence point to ongoing volcanism, but it is difficult to observe through Venus' dense atmosphere. Cryovolcanism, or volcanism involving water melts rather than silicate melts, is ongoing on Enceladus, Triton, Titan, and perhaps Europa (Roth et al. 2014). Tidally-heated satellites such as Europa and Enceladus may also have ongoing silicate volcanism injecting gasses and magma into their sub-surface oceans. As the environment with the most easily-observed ongoing volcanism, Io presents an opportunity for understanding how planetary properties (size, composition, volatile inventory) and environment (atmosphere, radiation environment) affect the styles of volcanic activity, enabling us to generalize our understanding of this geophysical process and place Earth in a greater context.

Io hosts several hundred active volcanoes, which range in style from lava lakes and effusive lava fountains to massive lava flow fields (Figure 1.4; Lopes and Spencer, 2007). Many of these features emit massive plumes of dust and gas, dominated by SO_2 , SO , and S_2 , that extend hundreds of kilometers above Io's surface (Figure 1.5). The largest volcanic feature on Io, Loki Patera, covers a surface area of over $20,000 \text{ km}^2$ and produces over a tenth of Io's total thermal power (Veeder et al. 2011).

The dramatic volcanism of Io is powered by tidal heating. Io is in an orbital resonance with the satellites Europa and Ganymede: Europa's orbital period is twice that of Io, and Ganymede's period is twice Europa's. The resulting coherent gravitational forcing between the satellites locks them into eccentric orbits, so that they experience a time-varying gravitational field that distorts their shapes. The three satellites are all tidally-locked, facing the same hemisphere to Jupiter at all times; this results in a permanent distortion to their shapes. However, their eccentric orbits also cause subtle variations in the orientation of each satellite relative to Jupiter, causing a secondary diurnal bulge that moves across the body on the timescale of an orbital period (1.8 days in the case of Io).

The physics of tidal heating holds the key to understanding heating in the potentially-habitable worlds Europa and Enceladus, and numerous other solar system bodies are thought to have passed through orbital resonances that resulted in disruption of their surfaces (e.g. Tittlemore and Wisdom 1990). Even beyond the solar system, more and more planets are

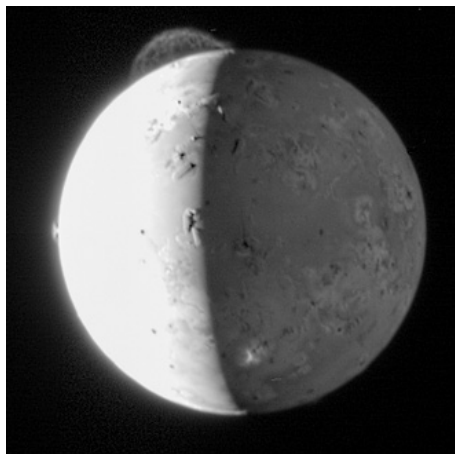


Figure 1.5: Volcanic plumes on Io observed by the *New Horizons* spacecraft during its Jupiter fly-by. *Image credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute.*

being discovered in orbital resonances; tidal heating may be an important factor influencing the surface environments of these bodies as well. However, tidal heating is a process that is still poorly understood; in every case where it has been postulated, the amount of predicted heat flow, as well as its predicted spatial distribution, do not match the observations. On Io, the effects of tidal heating are directly detectable in the form of its volcanic heat flow, making this active moon the ideal target for studying the fundamental process of tidal heating in planetary and satellite interiors.

1.2 Planetary astronomy in the near-infrared

The surfaces and atmospheres of solar system objects interact with radiation through absorption, emission, and scattering, providing a host of specific observable signatures that can be exploited to study properties such as composition and temperature. At optical and near-infrared ($1\text{--}5\ \mu\text{m}$) wavelengths, the appearance of these bodies is dominated by the effects of incident sunlight. Radiation from the sun is scattered by small particles and absorbed by molecular and atomic species. Spectroscopic studies reveal the relative effects of these two processes, and provide compositional information.

1.2.1 Seeing through Earth's atmosphere

Ground-based observations must overcome the obscuring effects of Earth's atmosphere, even at the high elevations of many of the world's large near-infrared telescopes. Carbon dioxide and water interact strongly with radiation at these wavelengths, restricting the accessible wavelength regimes to specific windows with high atmospheric transmission (see Figure 1.6).

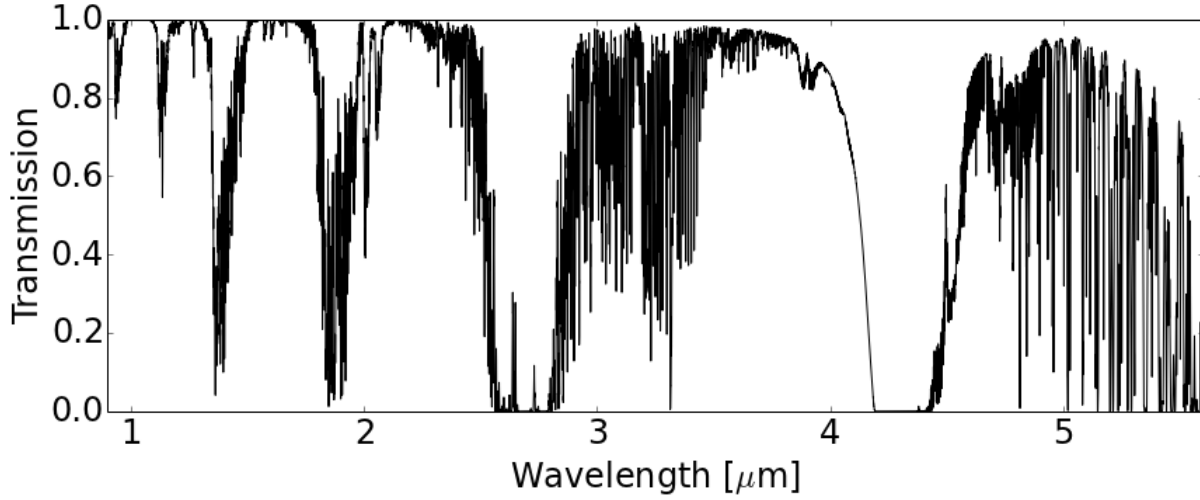


Figure 1.6: The near-infrared transmission spectrum of Earth’s atmosphere from Mauna Kea, Hawaii, at an airmass of 1.0 and 1.6 mm of precipitable water vapor (data from Lord 1992).

In addition, even at these dry, high-elevation locations, turbulence in Earth’s atmosphere blurs telescope images down to a resolution rarely better than 0.5-1.0 arcseconds, the diameter of Io as viewed from Earth. Adaptive optics (AO) technology allows astronomers to overcome these restrictions and approach the diffraction-limited resolution of

$$\theta = \frac{1.2\lambda}{D}. \quad (1.1)$$

For a telescope with a diameter of $D=10$ meters, such as the Keck telescope, the diffraction-limited resolution is ~ 0.025 arcseconds at a wavelength of $\lambda = 1 \mu\text{m}$, although the actual telescope resolution is always somewhat worse than the diffraction-limited resolution.

Adaptive optics technology utilizes a deformable mirror to correct for atmospheric turbulence in real time. The deformable mirror may be the secondary mirror, or may be a smaller mirror positioned farther down the light path. A wavefront sensor uses incoming light from a guide star - a bright, stable, point source that may be an astronomical object or an artificial laser-generated “star” - to determine the wavefront distortion at each point in time. The distortion is then corrected in real time with actuators that modify the shape of the deformable mirror. In this way, the incoming light is corrected for atmospheric turbulence effects before it is even recorded on the charge-coupled device (CCD) detector.

Figure 1.8 shows the effect of adaptive optics on $4\text{-}\mu\text{m}$ imaging of Io, demonstrating that adaptive optics enable the isolation of specific volcanoes that are unresolved without AO.

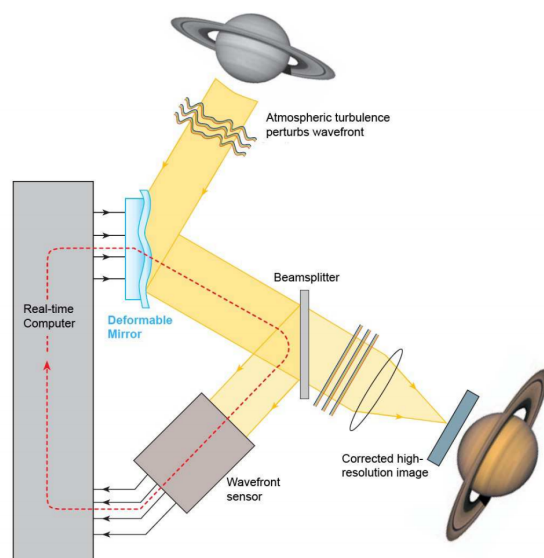


Figure 1.7: Schematic representation of a telescope adaptive optics system (Image from Davies & Kasper 2012).

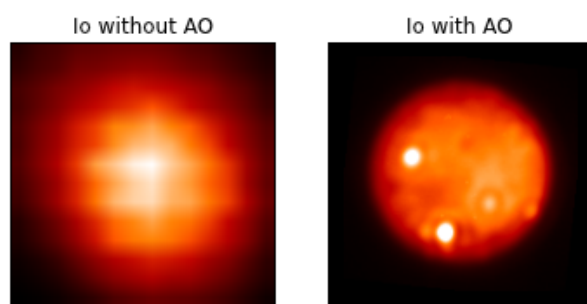


Figure 1.8: Images of Io at a wavelength of $\sim 4 \mu\text{m}$ from (left) a 3-meter telescope (the IRTF) without adaptive optics; and (right) a 10-meter telescope (Keck) with adaptive optics.

1.2.2 Uranus

1.2.2.1 Uranus' atmosphere

Near-infrared radiation from the sun penetrates down to a few bars in the atmospheres of the gas giants. Aerosols scatter the radiation, while molecules such as methane and ammonia absorb at characteristic wavelengths. In Uranus' atmosphere, absorption by methane is characterized by complex systems of lines produced by vibrational transitions. The strength of absorption depends on the wavelength of radiation. As a result, the amount of incident radiation that is scattered back to Earth provides information on the column of each absorbing molecule and the vertical distribution of aerosols. By measuring Uranus' intensity at many different wavelengths, we probe many different atmospheric depths, and can reconstruct the vertical profile of methane as well as constraining the depth of both global and localized cloud layers. While the composition of these clouds cannot be measured directly, their vertical location in the atmosphere constrains their potential compositions. An outline of this process is shown graphically in Figure 1.9.

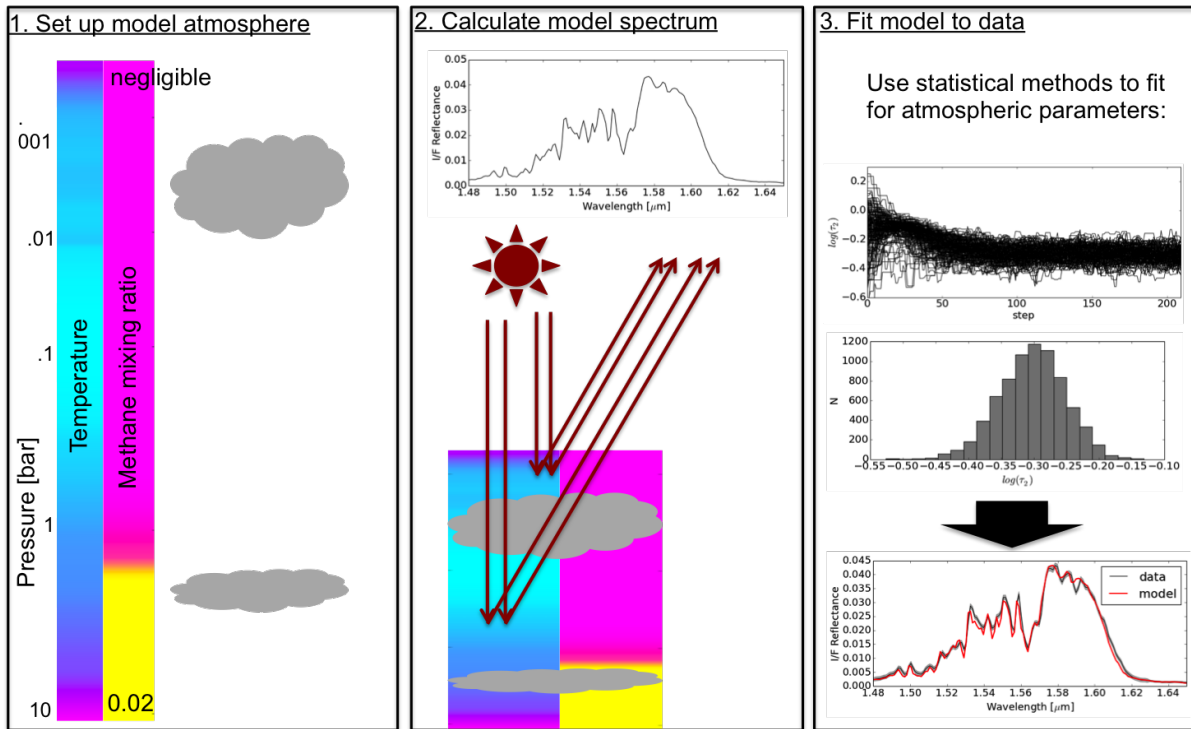


Figure 1.9: Schematic outlining the steps involved in fitting radiative transfer models to near-infrared spectra of planetary atmospheres to derive atmospheric properties. The data and models shown are described in Chapter 3.

1.2.2.2 Atmospheric modeling

Although the near-infrared spectra of planetary atmospheres encode extensive information on the atmospheric composition and particle properties as a function of depth, the function mapping the atmospheric parameters to the spectral signatures is complex and non-linear. Reconstructing atmospheric properties from spectral data requires a numerical integration of the radiative transfer equation. The transfer equation describing the absorption and isotropic scattering of the incident radiation field as well as emission originating in the material is:

$$\frac{dI_\nu}{ds} = -\alpha_\nu(I_\nu - B_\nu) - \sigma_\nu(I_\nu - J_\nu), \quad (1.2)$$

where the absorption and scattering coefficients are given by α_ν and σ_ν , and the source terms for each process are the thermal radiation B_ν and the mean intensity J_ν for absorption and scattering respectively. The calculation assumes conditions of local thermodynamic equilibrium, which is reasonable for densities in the upper troposphere primarily probed by near-infrared studies. In practice, this equation is integrated numerically through atmospheric layers defined to be small enough that the temperature, pressure, and composition are approximately constant across each layer.

The relative abundance of each scattering and absorbing species varies with atmospheric depth, and the atmosphere contains numerous sources of scattering and absorption that must be accounted for. In the case of the ice giant planets in the near-infrared, the dominant absorber is methane, and hydrogen and helium also produce collisionally-induced absorption. Cloud layers, which range from discrete storm systems to optically-thin global hazes, scatter incident radiation. Due to the unknown composition and properties of the particles themselves, simplifying assumptions must be made about the particle size distributions and scattering phase functions, which are typically based on atmospheres where we have more extensive data such as Earth and Titan.

1.2.3 Io

1.2.3.1 Io's volcanism

Io's spectrum at near-infrared wavelengths is dominated by sunlight reflected off of its bright, SO₂-coated surface. A series of broad SO₂ ice absorption features are prominent at the 3-5- μ m wavelengths (see Figure 1.10). However, at longer wavelengths the thermal emission from Io's high-temperature volcanic activity begins to dominate over reflected sunlight, and may constitute more than 50% of the total signal beyond $\sim 5 \mu\text{m}$ (see Figure 1.11). The thermal emission from erupting magma or cooling lava flows is produced by a range of emitting areas at different temperatures, each radiating according to Planck's law, with a characteristic emissivity ϵ . The area-integrated spectral intensity from a volcanic region, which can be expressed in units of GW/ $\mu\text{m}/\text{sr}$, is therefore given by

$$F_\lambda(\lambda, \mathbf{T}) = \sum_{i=1}^n A_i \epsilon \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T_i}} - 1}, \quad (1.3)$$

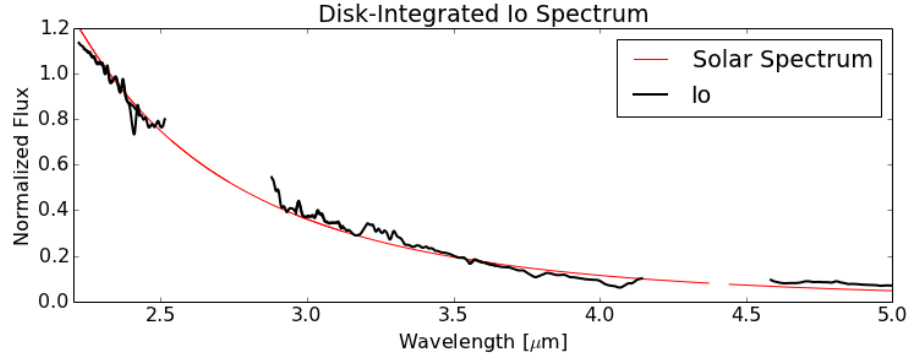


Figure 1.10: Spectrum of Io with the SpeX instrument on the NASA Infrared Telescope Facility, compared with the solar spectrum at Io. The dips in the spectrum around 3.55, 3.8, and 4.1 μm are broad absorption features from SO_2 ice on Io's surface, and the excess of emission beyond 4.5 μm is volcanic in origin.

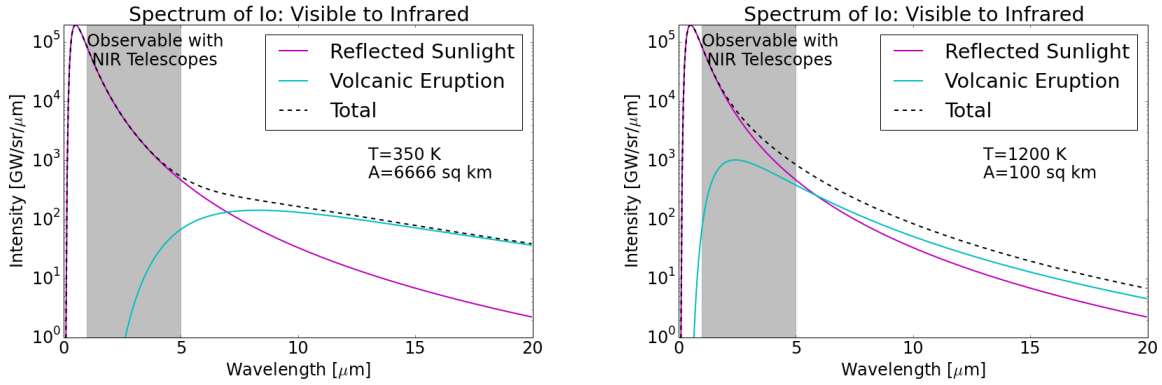


Figure 1.11: Model spectra demonstrating the relative contributions from reflected sunlight and volcanic emission to Io's disk-integrated spectrum for a single volcanic eruption of the temperature (T) and area (A) printed on each panel.

where h , c , and k_B are Planck's constant, the speed of light, and the Boltzmann constant, respectively, and A_i and T_i are the area and temperature of the i th component of the emitting region. Although a lava flow is a large surface with a continuous range of surface temperatures, the spectral information available on Io's volcanic hot spots is limited, and typically only two or even one temperature components are required to adequately fit the data.

1.2.3.2 Geophysical modeling

The specific ways that Io's volcanism differs from that of Earth shed light on the effects of a body's size, temperature, and tectonics on the mechanisms of volcanism. Io's magma composition reveals important information about its temperature, interior state, and extent

of differentiation and mantle recycling. The SO_2 ice coating Io's surface obscures spectroscopic signatures from the surface lava flows, but information can be inferred from properties that correlate with magma composition. Studies of Earth magmas, combined with our understanding of the chemical and thermal properties of rocks and melts, have taught us that properties such as temperature, viscosity, and thermal conductivity correlate with the ratio of heavy metals to silica in a silicate melt (Figure 1.12).



Figure 1.12: Correlation between composition of silicate melts and specific properties of the magma and eruption. These properties provide indirect means to constrain the composition of Io's magma.

High-silica magmas such as rhyolites have lower temperatures and higher viscosities, leading to more explosive eruptions. Low-silica magmas such as the basalts that dominate Earth's volcanism today, or even the komatiites prevalent in the early solar system, tend to produce high-temperature, low-viscosity, effusive volcanic events. Thermal conductivities are also lower for melts with lower silica content.

The correlations between these properties enable constraints on Io's magma composition despite the lack of detectable spectroscopic signatures. Temperature has been used extensively to diagnose Io's magma composition; measurements by the *Galileo* spacecraft of temperatures above 1475 K, the liquidus temperature of basalt, first suggested the presence of ultramafic magmas on Io (McEwen et al. 1998). However, the viscosity and effusion rate can also be estimated if the temperature and area of a lava flow are known as a function of time; this information can be derived from high-time-resolution observations of high-energy outburst eruptions. In addition, the thermal properties of the magma can be estimated by fitting model cooling curves to time-series observations of a volcano after the active eruption phase has ended.

Geophysical models of cooling lava assume a set of thermal properties including emissivity ϵ , density ρ , porosity ϕ , and thermal conductivity k . The temperature can be computed from the radiative intensity F_{rad} according to the Stefan-Boltzmann law:

$$F_{rad} = \sigma \epsilon (T_{surf}^4 - T_{env}^4). \quad (1.4)$$

where σ is the Stefan-Boltzmann constant and T_{surf}^4 and T_{env}^4 are the temperatures of the surface and the environment. The surface of a lava flow forms a crust and begins to cool almost instantaneously after eruption, but magma beneath the crust may stay molten for a year or more. The release of latent heat as this molten material solidifies slows the cooling process until the point when the entire crust has solidified. Taking into account the effects of latent heat release, the radiated intensity is given by (Turcotte and Schubert, 1982):

$$F_{rad} = k \frac{T_{z=C} - T_{z=0}}{\sqrt{\pi \kappa t} \times \text{erf}\left(\frac{C(t)}{2\sqrt{\kappa t}}\right)}, \quad (1.5)$$

where z is the vertical coordinate and C is the crust thickness, and k and κ are the thermal conductivity and diffusivity, respectively.

This equation yields the spectral intensity as a function of time, for a given set of thermal properties. Using such a formulation, the magma thermal properties can be derived from an observed cooling curve, or the lava crust age can be calculated from a temperature measurement if thermal properties are assumed.

1.3 Outline

This dissertation focuses on the composition and active processes of outer solar system bodies, targeting the unique worlds Uranus and Io in order to investigate what their unusual environments reveal about the processes governing the evolution of planets and their systems of satellites and rings. The results discussed here are based on data acquired with novel techniques at high spatial, spectral, and/or temporal resolution from the most powerful near-infrared facilities on Earth today.

Part I focuses on the planet Uranus. Chapter 2 investigates the composition and size of Uranus' ring particles as a probe of the source and age of the material as well as its subsequent processing. Chapter 3 focuses on the upper few bars of Uranus' atmosphere, and includes a detailed discussion of radiative transfer modeling and Markov Chain Monte Carlo simulations to retrieve atmospheric properties from spatially-resolved near-infrared spectra.

Part II focuses on Jupiter's moon Io. Chapter 4 introduces a time-domain observing campaign to track the evolution of Io's volcanic centers, and presents the detection of one of the most powerful volcanic eruptions ever detected on Io. Chapters 5, 6, and 7 present the results of this campaign, and Appendix A includes additional technical details. Chapter 5 discusses the observations and methods and gives an in-depth analysis of the time-variability of Io's volcanic centers over a 2.5-year period. Chapter 6 uses a statistical analysis of the spatial distribution of Io's volcanic heat flow to investigate the mechanisms of tidal heating in Io's interior. Chapter 7 focuses on Loki Patera, a distinctive volcanic feature central to understanding Io's heat flow and magma plumbing systems. The analysis includes a geophysical model that is fit to the cooling curve of three brightening events at Loki Patera to derive the thermal properties of the magma. Chapter 8 expands on the study of Loki Patera, pioneering a new technique to use mutual satellite occultations to gain the highest spatial resolution ever achieved from Earth on Io's hot spots. The results give insight into

the style of activity in this massive patera, and provide hints into its sub-surface plumbing system. The models presented in Chapters 7 and 8 are synthesized in Appendix B.

Part I

Uranus

Chapter 2

Near-infrared spectra of the uranian ring system

We present the first high-resolution near-infrared (1.18-2.38 μm) spectrum of the rings of Uranus, as observed with adaptive optics on the W.M. Keck II telescope in August 2010. We derive ring equivalent widths, as well as ring and particle reflectivities for the ϵ ring and ringlet groups based on H- and K-band data. We find the rings to be gray, indicating that they are dominated by large particles rather than dust, and we find no evidence for water ice. We present a reflectivity spectrum for the ϵ ring alone, which we also find to be consistent with a flat spectrum. We derive H-band ring particle reflectivities of 0.022 ± 0.010 , 0.051 ± 0.009 , 0.042 ± 0.012 , and 0.043 ± 0.001 and K-band ring particle reflectivities of 0.016 ± 0.010 , 0.034 ± 0.012 , 0.047 ± 0.008 and 0.041 ± 0.002 for the 456, $\alpha\beta$, $\eta\gamma\delta$, and ϵ ring groups. Previous observations have found ring particle reflectivities in the 0.033-0.044 range (de Pater et al. 2002, Gibbard et al. 2005), and are generally consistent with our results.

2.1 Introduction

Since the Voyager 2 encounter with Uranus in 1986, there has been interest in studying the Uranian ring system from space and from the ground to understand the structure and composition of this collection of faint, narrow rings.

The main Uranian ring system consists of ten thin annuli with wider, faint dust sheets interspersed (French et al. 1991, Esposito et al. 1991, de Pater et al. 2006). The ϵ ring is the outermost of the main rings, and is the dominant source of light from the ring system. Its width has significant longitudinal variability, ranging from 20 km at periapse to 96 km at apoapse, and its brightness may vary by almost a factor of 5 along the ring, depending on the ring opening and solar phase angles (de Pater et al. 2013, in press). The inner rings are clumped into three main groups: the $\eta\gamma\delta$ group, the $\alpha\beta$ group, and the 456 group; the widest of these rings is only 12 km. The η and δ rings are accompanied by broad, diffuse companion rings η_c and δ_c . Between the ϵ and δ rings lies the faint, narrow λ ring, which we

neglect in our analysis because it is too faint to be detected in our observations.

Uranus' rings are eccentric and non-uniform, causing their appearance to vary from year to year while the orientation of the system relative to Earth and to the sun is changing. At visible wavelengths, the scattered light from Uranus makes the ring system difficult to detect from the ground due to the apparent proximity of the faint rings to the bright planet. Observations in the near-infrared (near $2\ \mu\text{m}$) benefit from the fact that strong methane and hydrogen absorption in Uranus' atmosphere darken the planet at these wavelengths.

In 2001, Karkoschka (2001b) derived photometry of the Uranian rings and satellites from Hubble Space Telescope images. In 2000, de Pater et al. detected the rings interior to the ϵ ring from the ground for the first time using Keck adaptive optics (AO) images (de Pater et al. 2002). Using the Keck AO system newly optimized for imaging of extended objects, Gibbard et al. (2005) resolved individual rings within the ringlet groups, from which they derived satellite and ring particle reflectivities in J, H, and K' bands. By combining data from three separate observations over 2 years, de Pater et al. (2006) found evidence for dust sheets interior to the innermost ringlet group and between the main rings.

Observations of the Uranian ring system integrated over wide bands reveal the ring particles to be dark gray. The first spectroscopic studies of the Uranian rings were conducted by Nicholson & Jones (1980) and Nicholson et al. (1984) using broad and narrow band photometric data spanning the $1.5\text{--}4.0\ \mu\text{m}$ range, at a range of phase angles and a ring opening angle in the $57^\circ\text{--}75^\circ$ range. These studies indicate geometric ring albedos of 0.028 ± 0.007 (revised to 0.032 ± 0.005 by Matthews et al. 1982) and 0.023 ± 0.002 for the $2.0\text{--}2.5\ \mu\text{m}$ range respectively. Nicholson et al. (1984) additionally derive a $2.9\text{--}3.9\ \mu\text{m}$ geometric albedo of 0.026 ± 0.003 . Rather than geometric reflectivities of rings, several authors have also calculated the albedos of the ring particles, which relies on a model for particle filling factors and shadowing, but provides more information on the particles themselves. De Pater et al. (2002) determined an ϵ -ring particle reflectivity in H-band of 0.042, and similar particle reflectivities for the other rings. Gibbard et al. (2005) find averaged ring particle reflectivities of 0.043-0.045 in the J, H, and K band for a phase angle of 2.82° . They extrapolate the $0.55\ \mu\text{m}$ reflectivities from Karkoschka (2001a) to account for the different phase angle, and find a value consistent with this range.

We present high-resolution ($R\sim400$) near-infrared (J, H, and K) spectra of the Uranian ring system, obtained using the OSIRIS imaging spectrograph combined with adaptive optics on the Keck II telescope. In the H- and K-bands, we present separate ϵ ring spectra and derive ring particle reflectivities for the ϵ ring and the ringlet groups.

2.2 Observations and Data Reduction

We observed the western ansa of the Uranus ring system with the 10-meter W.M. Keck II telescope on Mauna Kea, Hawaii on UT 2010 August 22. Spectra were obtained using the OSIRIS imaging spectrometer with adaptive optics (Larkin et al. 2006), using the planet itself for wavefront sensing. The spectrograph uses a 2048×2048 pixel Rocket Hawaii-2 detector, from which data cubes were constructed with spatial dimensions of 16×64 pixels, and

spectral dimensions of (1564,1651,1665) pixels for the (J,H,K) filters. The 0.05" plate-scale in our observing mode corresponds to 695 km per pixel at Uranus disk center. Observations in the J-, H- and K- bands correspond to wavelengths of 1.180-1.416 μm , 1.473-1.803 μm , and 1.965-2.381 μm respectively. The field of view was 0.8" x 3.2", and covered the western ring ansa as well as a section of the planet's limb. Multiple 300-second exposures were taken in each band. We used the reference stars HD 220825 and HR 596 for flux calibration and to correct for wavelength dependencies in atmospheric transmission. See Table 2.1 for details on the observations.

Data were reduced using the standard OSIRIS pipeline, which includes flat-fielding, sky-subtraction, cosmic-ray rejection, wavelength calibration, and datacube assembly.

Reduced data cubes were further cleaned to remove bad pixels. The threshold for a bad pixel was defined as $\mu \pm 5\sigma$, where μ and σ were calculated for each wavelength individually. The value of a bad pixel was replaced by the median value of the four neighboring pixels. The percentage of pixels replaced varied with data cube between 0.03% and 0.06%.

The reduced data cubes were then combined to improve signal-to-noise. Data cubes within a given filter were aligned by eye to the nearest pixel, then averaged together. For the H- and K-band we had 4 data cubes each, and for the J-band we had 2 data cubes, yielding a factor of 2 improvement in signal-to-noise in the H- and K-bands, and a factor of $\sqrt{2}$ improvement for the J-band. Figure 2.1 shows the combined cubes in each filter, collapsed over wavelength.

2.2.1 Flux Calibration and Atmospheric Transmission Correction

A telluric correction spectrum was constructed by dividing the observed reference star spectra by model A-star spectra¹. Models of the stellar spectra were created via the method described in Laver et al. (2009). Observed spectra were extracted from the datacube by integrating a 2D Gaussian fit to the PSF of each reference star at each wavelength. The resulting "correction spectra" were divided into our ring data to produce corrected and flux-calibrated ring spectra. The stellar spectra were not adjusted for differing airmass between the science target and reference stars because we determined that such a correction would only change the computed fluxes by less than 3%, which is smaller than our errors from other sources.

Model stellar spectra were based on the J, H, and K magnitudes of the reference stars. In the case of our particular reference stars (HD220825 and HR0596), 2MASS J, H, and K magnitudes were not available. We thus inferred J, H, and K magnitudes from stars with similar B and V magnitudes and spectral types that did have documented JHK magnitudes. In each case, we used all stars with available 2MASS J, H, and K magnitudes that had B and V magnitudes within 0.1 mag of our observed stars, and were of spectral type A. In each case we found 4-6 stars matching these criteria, which we deemed sufficient because there was very little variation in the J, H, and K magnitudes of these stars (~ 0.3 magnitudes within a band). The JHK magnitudes of our observed stars were computed as the mean of the JHK

¹<http://kurucz.harvard.edu/stars.html>

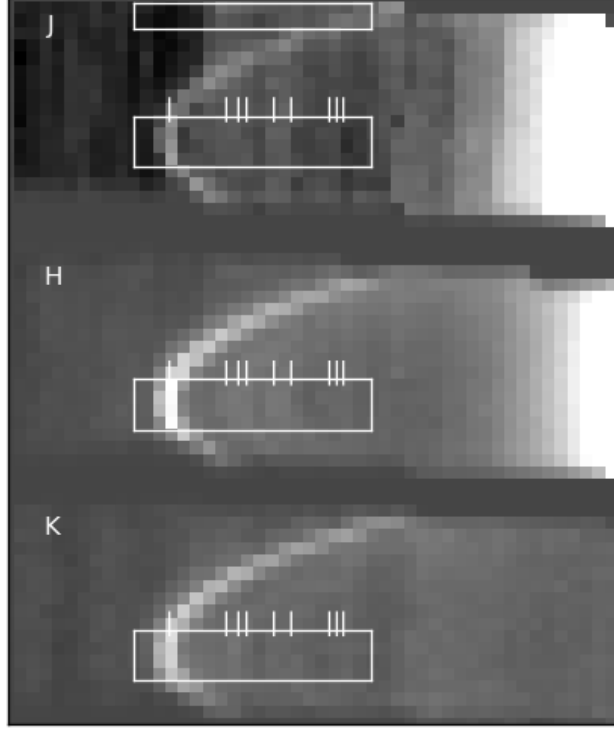


Figure 2.1: Ring data in J, H, and K bands (1.180-1.416 μm , 1.473-1.803 μm , and 1.965-2.381 μm respectively), integrated over wavelength. H and K images are an average of four 300-second integrations, while the J image is an average of two such integrations. Boxed regions show the area summed to produce ring spectra, and (for J-band) the region used in stripe subtraction. Vertical lines indicate the positions of the 9 main rings.

magnitudes of the chosen reference stars, weighted by how close their B and V magnitudes were to those of our observed calibration stars. That is,

$$M_J = \frac{1}{\sum_i w_i} \sum_i M_{J_i} w_i \quad (2.1)$$

where M_J is the computed magnitude of our observed star, M_{J_i} is the magnitude of the i th star used in the computation, and w_i is the weighting of the i th star, determined by

$$w_i = \frac{1}{\sqrt{(M_{B_i} - M_B)^2 + (M_{V_i} - M_V)^2}} \quad (2.2)$$

where the conventions are the same as above. Errors on these magnitudes were computed similarly, by quadrature mean. Table 2.2 lists the reference stars used. Based on a compari-

son of the individual observed stellar spectra with a spectrum median-averaged over multiple observations of both stars, we estimate that our absolute intensity calibration is accurate to $\sim 5\%$ in all three bands.

2.2.2 Background Light Subtraction

After flux calibration, H- and K-band data were binned down by a factor of 10 in wavelength, and J-band data were binned by a factor of 20. Binning thus reduces resolving power $R = \lambda / \Delta\lambda$ from $R \sim 3800$ to $R \sim 400$ for H- and K-bands, and to $R \sim 200$ for J-band. All further analysis was done on the resultant lower-resolution data sets.

In all bands, there was significant scattered light within and interior to the ring system. As discussed in Section 3.1, we attribute this background to a combination of scattered light from the planet and light reflected off the broad dust sheets interior to and within the ring system. Our spatial resolution was not sufficient to model these dust sheets, and this background did not drop off in a simple manner with distance from the planet.

At the distance of the ring ansa, the background light dropped off nearly linearly with distance from Uranus in the H and K bands, so we subtracted a linear fit to the out-of-ring flux within each wavelength bin. In the J-band images, the background light exhibited a north-south striping effect parallel to Uranus' rotation axis, with the ring system falling in a darker stripe. We removed this effect by averaging an east-west stripe north of the ring region, and subtracting this "stripe" background from each east-west scan through the data cube, prior to performing a linear fit to the out-of-ring flux as done in the H and K bands. Figure 2.1 shows the uncorrected data, and illustrates both this striping effect and the region used to remove it.

2.3 Analysis & Results

2.3.1 Ring Reflectivity Spectra

After removing the background light, we produced the ring spectra by summing over a slice through the ring system. This slice spanned $0.2''$ (2780 km) in the direction parallel to the planet's rotation axis and $1''$ ($\sim 23,000$ km) in the perpendicular direction. The region used to produce the spectra is shown in Figure 2.1. This region only covers a small fraction of the total light collected from the rings. However, regions farther from the ring ansa have a smaller apparent separation from the planet itself, increasing background light. In these regions, we were unable to cleanly remove the background light from the planet, and including a broader portion of the rings decreased our signal-to-noise ratio.

To convert our spectra into meaningful ring reflectivities, we modeled the ring system to determine what fraction of the area observed was occupied by ring. We modeled the inner and outer edge of each ring as ellipses, with a semi-major axis, e eccentricity, θ true anomaly, and δe , δa and $\delta \theta$ from French et al. (1986), who derived these values from stellar occultation data. Though we include the ring companions η_c and δ_c in modeling individual

rings, these were neglected in computing the reflectivity of the ring system as a whole. The values for ring-opening angle to the Earth and Sun, and the longitude of pericenter for each ring, were taken from ephemerides² for UT 2010 August 22 (Tables 2.3 and 2.4). The model was projected onto the plane of the sky via the ring-opening angle. We calculated the ring widths at the western ansa for the date and geometry of our observations, as well as the geometric visible ring area within our 0.2'' cut (Table 2.4).

We used these geometric ring areas to convert from flux densities to I/F reflectivity, defined as

$$\frac{I}{F} = \frac{R^2}{\Omega} \frac{f}{F_{\odot}} \quad (2.3)$$

where R is the Uranus-Sun distance in AU, f is the observed flux density, $\pi F_{\odot}$ is the solar flux density at Earth, and Ω is the solid angle subtended by the ring arc within the region of interest (Hammel et al. 1989). The resulting spectra are shown in Figure 2.2.

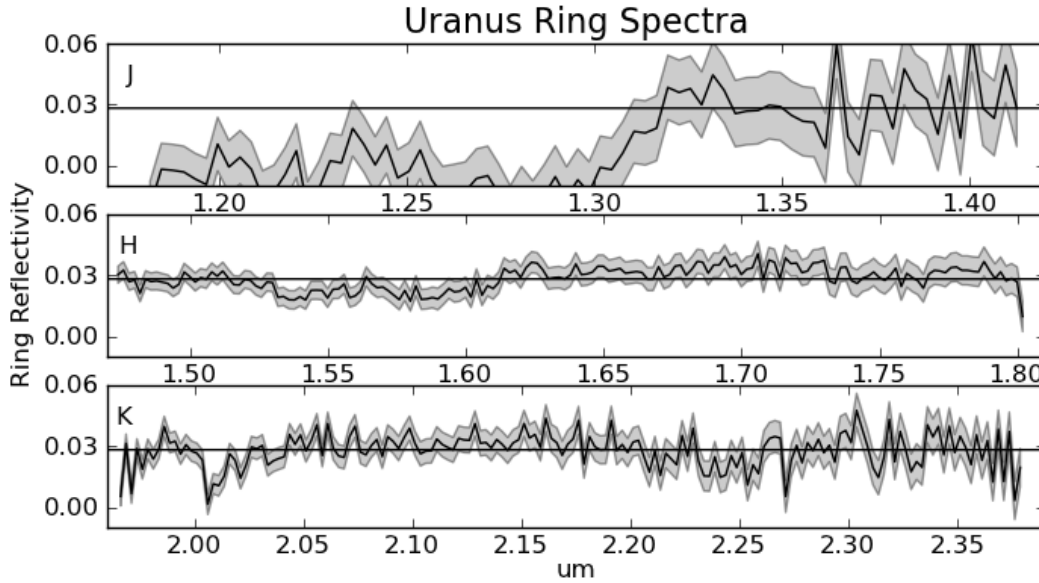


Figure 2.2: I/F spectra of the Uranian rings; shaded regions indicate 1σ confidence levels.

The H- and K-band data had sufficient signal-to-noise to separate the spectrum of the ϵ -ring from that of the other rings (in the J-band data, the rings were not sufficiently resolved to separate the spectra with confidence). The ϵ -ring spectrum was created by fitting a Gaussian to the ring profile in each wavelength bin. Within each wavelength bin a Gaussian amplitude A and width σ were calculated for the ϵ ring, where A was taken to be the maximum value achieved in the ring profile, and $\sigma = \text{FWHM} / (2\sqrt{2\ln 2})$ with the full width at half maximum (FWHM) determined directly from the ring profile. Given these parameters, the flux density of the ring within a wavelength bin was calculated as the area under the Gaussian, or $A\sqrt{2\pi\sigma}$.

²www.pds-rings.seti.org

These ϵ -ring spectra are shown in Figure 2.3, together with the spectra for all rings (from Figure 2.2), and a spectrum of Uranus itself for comparison.

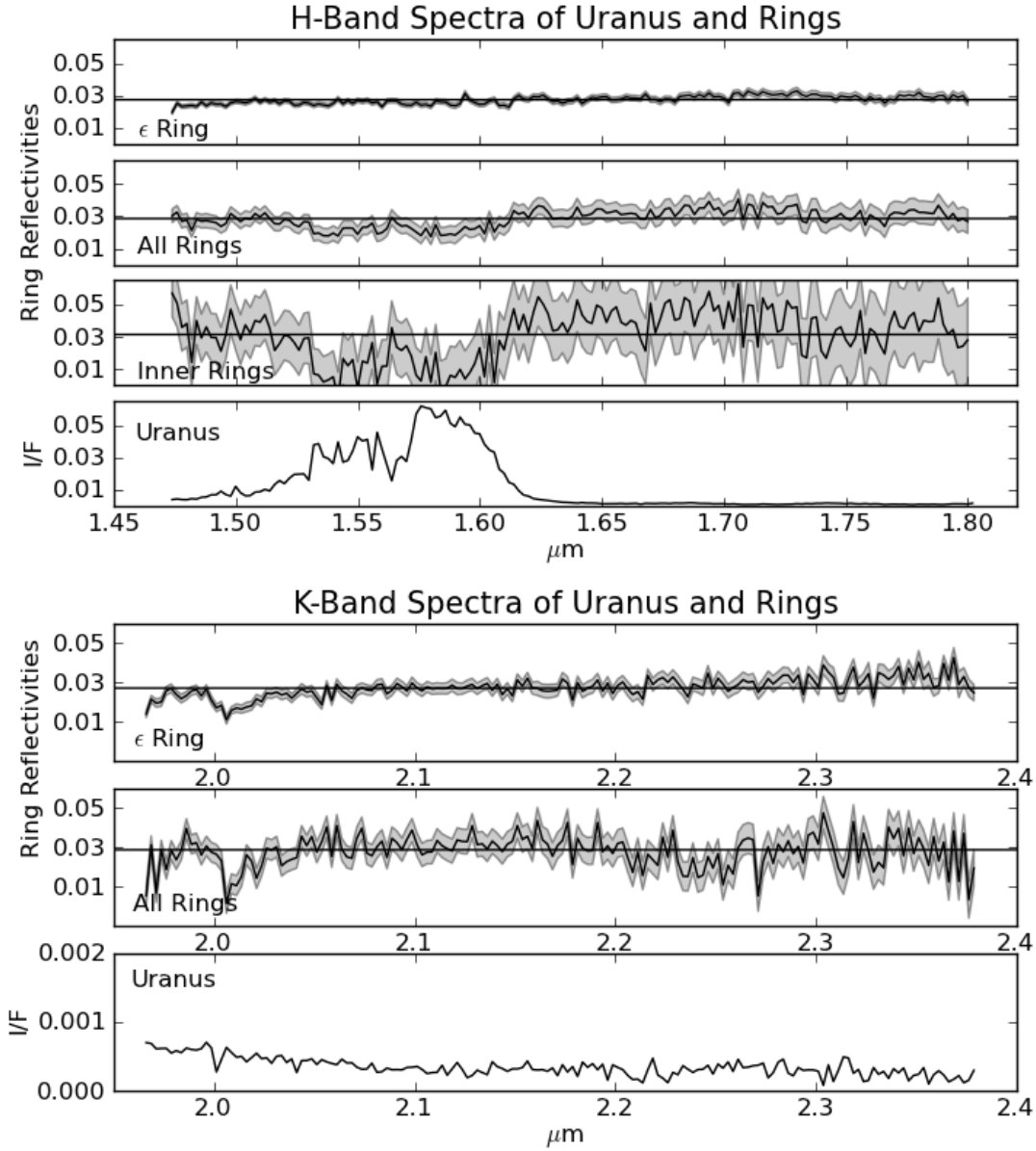


Figure 2.3: H- and K- band spectra of the Uranian rings: (a) ϵ ring only, and (b) all rings combined. Spectrum of Uranus is plotted in (c) for comparison. Shaded regions indicate 1σ confidence levels. Artifacts from the Uranian spectrum appear in the ring spectra, most likely due to imperfect removal of scattered light from the planet.

The dominant source of uncertainty in the spectra is the wavelength-dependent variability of the background. We attribute this background to a combination of scattered light from Uranus and reflected light from dust in the ring system. The background light drops off with distance from the planet initially, but reaches a minimum between the planet and ring system, and then increases again. This is not well-modeled by a convolution of the PSF with a bright disk, nor by a Gaussian or exponential drop-off. Because we lack the spatial resolution to model the dust in the system, we used a simplified model to remove this scattered light: our background subtraction is based on the assumption that background flux decreases linearly with distance from the planet, at the distance we are considering. As a result, this subtraction is imperfect and may introduce some error into our spectra. Our error bars primarily represent an estimation of this error, and are derived from the spectral scatter of the pixels used for background modeling; errors are shown by shaded regions in the spectra.

2.3.2 Ring Particle Reflectivities

To determine ringlet group and individual ring reflectivities, we fit a model to a wavelength-integrated, 1D scan through the ring system. The ring scan was produced by collapsing a 0.2''-wide slice (shown in Figure 2.1) through the ring system. The resulting ring scans in all three bands are shown in Figure 2.4, with the ephemeris-derived ring locations marked with vertical lines. The model was created as follows: each ring was modeled as a delta function at the position of the ring, whose magnitude was given by the ring's reflectivity multiplied by the solar flux incident on the solid angle subtended by that ring. This model was then convolved with a point spread function (PSF) derived from the outer half of the ϵ -ring profile, as was done by de Pater et al. (2006). PSFs based on Gaussian or reference star profiles did not provide a good fit to the ring profile data. As seen in Figure 2.3, the J-band ring profile is very noisy, and we did not fit models for ring reflectivities to this data. In addition, while we present individual ring reflectivities in the H-band, we present only ringlet group reflectivities in the K-band due to the higher noise level in the profiles.

This model was fit to the observed ring scan using a Markov Chain Monte Carlo technique based on the method described by Tegmark et al. (2004). In brief, this technique consists of calculating the χ^2 for a specific combination of parameter values, then varying one randomly chosen parameter at a time and accepting the new parameter based on specific criteria: if the change decreases the value of χ^2 it is always accepted; if it increases χ^2 it is accepted with probability

$$prob = e^{\frac{\chi_i^2 - \chi_{i-1}^2}{2}} \quad (2.4)$$

where χ_i^2 is the current χ^2 value and χ_{i-1}^2 is the value before the variation. The distribution of values each parameter takes over the run is treated as the probability distribution for that parameter. The median and confidence limits can then be read directly from this distribution.

In our fits, the spatial offset (distance from the ring system to Uranus center) was fixed based on the location of the peak flux of the ϵ ring. Within each of the three main ringlet

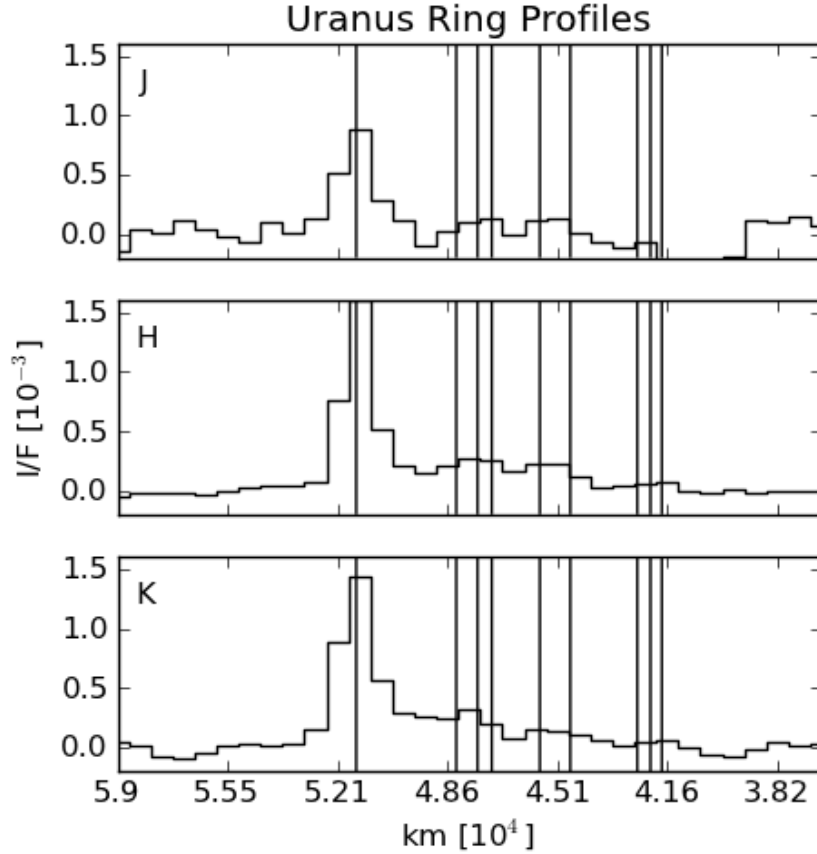


Figure 2.4: I/F ring profiles in J, H, and K bands. Vertical lines indicate the positions of the 9 main rings. x-axis is the distance in km from Uranus' center.

groups (456, $\alpha\beta$, and $\eta\gamma\delta$), the PSFs of the individual rings overlap significantly, leading to degeneracy in the ring reflectivities within a group. To account for this, two different models were used:

Model (1): all nine ring reflectivities were allowed as free parameters. Model (2): the ring particles within a given ringlet group were required to have the same reflectivity, resulting in only four free parameters: a particle reflectivity for each ringlet group, and one for the ϵ ring. In this model, the particle reflectivity determines the total intensity of the ringlet group, and we fixed the relative strengths of the rings within a group according to their geometric areas. It would be more physically correct to use the total visible particle surface area in each ring rather than the geometric area. However, such a model would require knowledge of the fractional visible area for each individual ring, which is unavailable. The use of geometric areas to compute the ringlet group profiles may erroneously affect the shape of the model profiles, but should not have a significant effect on the total computed intensity of each group. As we use Model (2) only to compute reflectivities for ringlet groups rather

than individual rings, the total fitted intensity for each group is indeed the only value of interest.

In both models, reflectivities converged quickly, and post-convergent parameter distributions were approximately Gaussian in shape. Error bars represent $1\text{-}\sigma$ uncertainties, and were assigned based on the peak and 68th percentile of the parameter distributions. These models are shown with the data in Figure 2.5; as discerned by eye, Model (1) gives a better fit to our data than Model (2). Note that while Model (1) allowed us to fit for geometric ring reflectivities, Model (2) required a conversion to particle reflectivities (discussed below), and our results for this model are thus sensitive to the model used for this conversion, in this case that of Karkoschka (2001a).

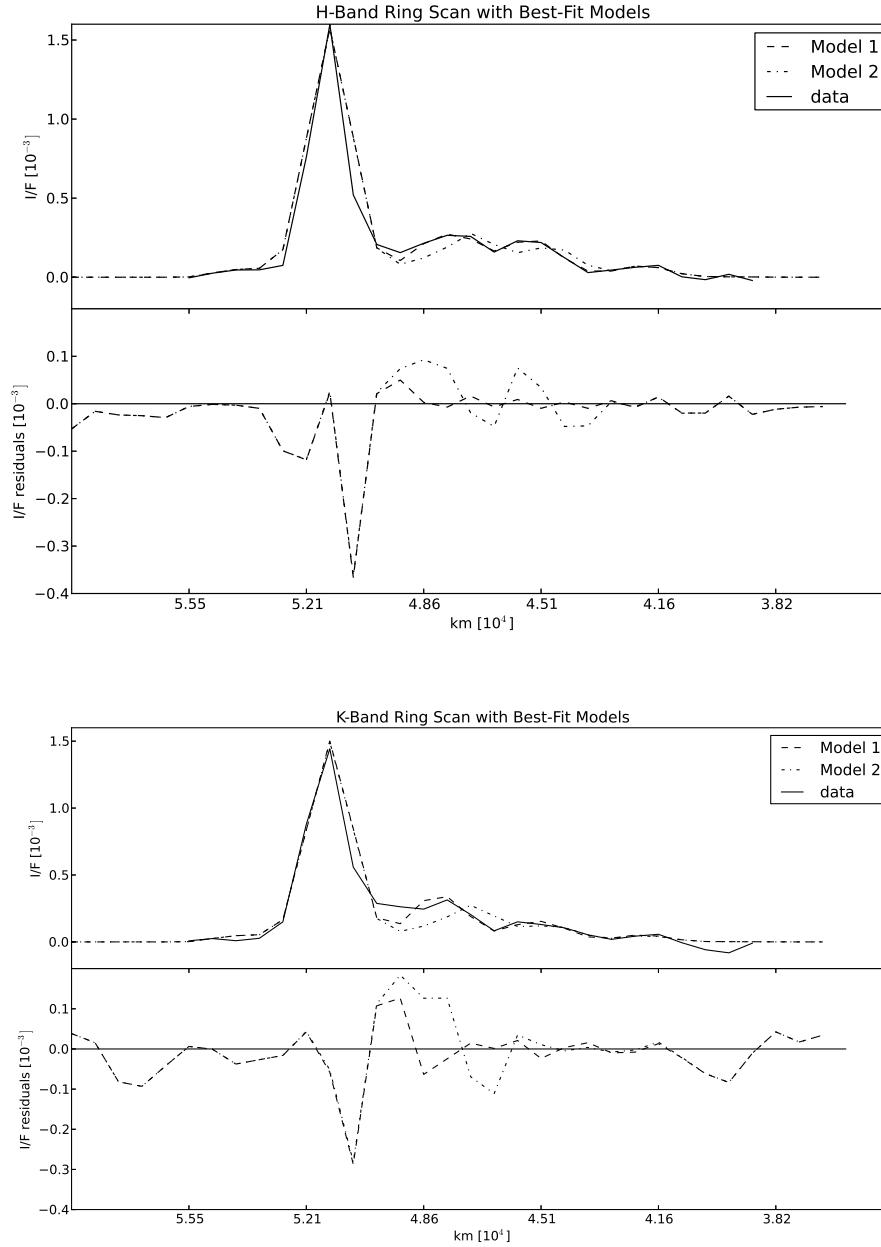


Figure 2.5: Ring system profiles for H- and K-bands with models. Model 1 is derived from a 9-parameter MCMC fit and Model 2 from a 4-parameter fit, requiring rings in the same ringlet group to have the same particle reflectivity.

These two methods give consistent results for particle reflectivities for ringlet groups in both H and K bands (see Tables 2.5 and 2.6). The geometric reflectivities of each ringlet group were calculated from the reflectivities of the individual rings, by averaging over the rings in the group with each ring weighted according to its geometric area. We calculate equivalent widths (EW) for each ring based on the H-band geometric ring reflectivities; EW is defined as the width a given ring would have if it were perfectly reflecting ($I/F=1$).

To convert our ring reflectivities to particle reflectivities, we use the model of Karkoschka (2001a), which provides an estimate of the visible ring particle area as a function of subsolar latitude. This estimate accounts for the difference between geometric ring area and reflecting surface area due to spaces between particles as well as shadowing at a specific geometry. We define a conversion factor, which is the ratio of Karkoschka’s visible ring areas to our modeled geometric ring areas, to derive particle reflectivities. We use visible ring fractions of 0.40 for the $\alpha\beta$ and $\eta\gamma\delta$ ring groups, 0.53 for the 456 ring group, and 0.18 for the ϵ ring, corresponding to a ring-opening angle to the Sun of 10.48° .

Karkoschka (2001a) presents conversion factors for ringlet groups rather than individual rings, and the conversion factor for a ringlet group cannot accurately be applied to its individual constituent rings because rings within a group can have quite different optical depths, which causes the fractional visible area and its dependence on ring opening angle to vary widely. Thus while we present geometric reflectivities for all individual rings, particle reflectivities are given only for ringlet groups (Tables 2.5 and 2.6).

2.4 Discussion and Conclusions

The spectra in Figure 2.2 confirm that the rings are dark gray, and show no evidence for absorption by water ice or other molecules. Averaging the spectra over each band, we find geometric albedos of 0.0285 ± 0.0005 , 0.027 ± 0.003 , and 0.028 ± 0.005 for the H, J (longward of $1.3\mu\text{m}$) and K bands respectively.

Equivalent widths and geometric ring reflectivities for each ring in the H-band are tabulated in Tables 2.4 and 2.5, and particle reflectivities for ringlet groups in the H- and K-bands are tabulated in Tables 2.5 and 2.6. We find particle reflectivities to be generally consistent between ringlet groups, as well as between the H- and K-band measurements. The main exception is the 456 ringlet group, which we find to be fainter than the others in both H- and K-bands. De Pater et al. (2002) and Gibbard et al. (2005) give ring particle reflectivities for the ϵ ring and three ringlet groups that are generally consistent with our results. We find the 456 ringlet group to be slightly fainter than the previous results. In addition, while de Pater et al. (2002) found the ϵ ring to be brighter in the K- than the H-band, we find this ring to be of comparable brightness across both bands.

Based on Voyager observations and stellar occultation data, French et al. (1991) determined that the Uranian ring particles are between 10 cm and 10 m in size. If the ring particles were comparable in size to the observing wavelength ($1\text{--}2\mu\text{m}$ in this case), we might expect to see a spectrum tipped toward the red or the blue depending on the particle size distribution. Pang et al. (1984) associate a blue spectrum with dusty, mono-size particles,

while typical dusty rings should appear red (Showalter et al. 1991). Our gray spectra confirm the Uranian rings to be dominated by large rather than dusty particles.

When the particle size is large compared to the wavelength of light, as we find to be the case here, near-infrared spectra can constrain the chemistry of the ring particles due the presence or absence of absorption features. Deep water ice absorption features have been identified in Saturn’s ring spectrum at 1.53, 1.65, and 2.02 μm (Clark et al. 1980, Pilcher et al. 1970). We find no evidence for absorption at these wavelengths, indicating that if water ice is present in the Uranian rings it is a minor constituent.

In the H-band ring spectra, we see a slight dip in flux coincident with the 1.5-1.6 μm methane window (see comparison to Uranus spectrum in Figure 2.3). This dip is most likely due to an over-estimation of the scattered light in the ring regime. This explanation is supported by the lack of such a feature in the ϵ ring spectrum, which was generated via a method less susceptible to contamination by background light (see Section 3.1).

The J-band spectrum is quite noisy compared to H and K, and exhibits step-like behavior around 1.3 μm . The additional noise arises in part from the fact that the total integration time was half that in the H or K bands, combined with the brighter sky background due to Uranus’ scattered light, and a poorer PSF. The longer-wavelength section of the J-band also lies at the start of the 1.3-1.5 μm H_2O band, making it particularly sensitive to any temporal atmospheric variation between the reference and science observations. Due to the poor quality of the data at shorter wavelengths, we do not attribute significance to the step-like behavior of the J-band spectrum. The relatively higher noise level in the K band is due in part to the lower flux density in this region of the solar spectrum, and thus lower reflected flux from the rings.

Future observations with more integration time would improve signal to noise in the J band in particular, which would perhaps allow one to separate out the spectrum of the ϵ ring alone, and fit for particle reflectivities for the ringlet groups in these bands, as was done here for the H- and K-band data.

Results could also be improved through a joint analysis of simultaneous high spatial and spectral resolution data, which would help distinguish between reflected light from the rings and from the inter-ring dust. As evidenced by the eccentricities and variable widths of the rings, the Uranian ring system varies greatly with longitude. An analysis of high spatial resolution data would allow for a model of the dust in the system at the exact time and geometry of the spectral data. Such a model could then be used to separate the spectrum of the dust from that of the rings themselves. Indeed, future observations and modeling of the dust in the Uranian ring system would also yield valuable information about the spatial and temporal variation in the dust distribution.

Table 2.1: Keck Observations on UT 2010 August 22

Target	Time (UTC)	T_{int} (sec)	filter ^a	platescale (")	airmass	N_{exp}
HD 220825	13:14	2	H	0.035	1.13	2
HD 220825	13:16	2	K	0.035	1.14	2
HD 220825	13:19	2	K	0.050	1.14	2
HD 220825	13:21	2	H	0.050	1.14	2
HD 220825	13:24	2	J	0.050	1.14	2
Uranus	14:03	300	H	0.050	1.18	2
Uranus	14:22	300	K	0.050	1.24	2
Uranus	14:41	300	J	0.050	1.31	2
Uranus	14:59	300	H	0.050	1.39	2
Uranus	15:16	300	K	0.050	1.50	2
HR 596	15:38	2	K	0.050	1.11	2
HR 596	15:39	2	H	0.050	1.11	2
HR 596	15:40	2	J	0.050	1.12	2
HR 596	15:47	2	H	0.035	1.12	2
HR 596	15:49	2	K	0.035	1.13	2

a. J, H, and K filters correspond to wavelength ranges of 1.180-1.416 μm , 1.473-1.803 μm , and 1.965-2.381 μm , respectively.

Table 2.2: Reference Stars

Star	B Mag	V Mag	J Mag	H Mag	K Mag
15 Dra ^a	4.917	4.959	4.859±0.017	4.962±0.015	4.961±0.018
V ET Uma ^a	4.903	4.935	4.962±0.037	5.003±0.020	4.998±0.018
HR 5489 ^a	4.939	4.923	4.813±0.037	4.852±0.044	4.778±0.020
iot CrB ^a	4.925	4.975	5.013±0.037	5.105±0.018	5.071±0.020
iot PsA ^b	4.303	4.335	4.289±0.236	4.596±0.020	4.424±0.018
rho Hya ^b	4.327	4.343	4.496±0.256	4.508±0.076	4.360±0.026
eta Phe ^b	4.362	4.365	4.160±0.290	5.354±0.076	4.308±0.027
bet PsA ^b	4.309	4.289	4.345±0.278	4.297±0.192	4.253±0.036
HR 2435 ^b	4.37	4.40	4.302±0.276	4.222±0.216	4.218±0.036
lam Per ^b	4.31	4.29	4.080±0.200	4.149±0.168	4.149±0.036
HR 596 ^c	4.36	4.33	4.288±0.112	4.376±0.049	4.299±0.012
HD 220825 ^c	4.974	4.927	4.892±0.018	4.956±0.018	4.918±0.010

- a. Star used in the computation of projected J, H, K magnitudes for HD 220825.
b. Star used in the computation of projected J, H, K magnitudes for HR 596.
c. B and V magnitudes from <http://simbad.u-strasbg.fr/simbad/>; J, H, and K magnitudes are inferred from the other data in this table.

Table 2.3: Ephemeris Parameters for UT 2010 Aug 22

Parameter	Value ^a
RA	24 h 59 m 43 s
Dec	-00° 53' 04.06"
Phase Angle	1.46°
Ring Opening Angle to Earth	11.93°
Ring Opening Angle to Sun	10.48°
Earth Distance	2.8743·10 ⁹ km

- a. www.pds-rings.seti.org

Table 2.4: Ring Ephemerides and Calculated Widths at Ansa

Ring	^a ω_o	^b Dist (km)	^b Width (km)	^b Area (10^6km^2)	EW (km)
6	142.03°	41809.1	2.1	0.10	31
5	49.35°	42168.1	4.5	0.19	54
4	190.16°	42583.8	3.5	0.19	49
α	37.36°	44701.6	8.0	0.43	70
β	196.38°	45664.4	5.9	0.52	389
η	0.0°	47182.9	2.4	0.15	179
η_c	0.0°	47182.9	54	3.34	
γ	281.7°	47633.0	3.6	0.26	101
δ	0.0°	48305.4	5.2	0.32	295
δ_c	0.0°	48305.4	10.5	0.65	
ϵ	310.27°	51467.1	88.4	3.85	2696

Columns: ω_o longitude of periapse, distance from planet center, width at ansa, total visible ring area in our model, and equivalent width (EW)

a: www.pds-rings.seti.org

b: Calculated from model, based on parameters from French et al. (1986).

Table 2.5: H-band Ring and Particle Reflectivities

Ring	Model 1 Geometric	Model 1 Particles	Model 2 Particles
6	0.015±0.013		
5	0.012±0.010		
4	0.014±0.011		
456	0.013±0.006	0.022±0.010	0.021±0.010
α	0.010±0.006		
β	0.066±0.011		
$\alpha\beta$	0.033±0.006	0.051±0.009	0.045±0.008
$\eta + \eta_c$	0.0027±0.0014		
γ	0.036±0.027		
$\delta + \delta_c$	0.018±0.006		
$\eta\gamma\delta$	0.0075±0.002	0.042±0.012	0.041±0.006
ϵ	0.0305±0.001	0.043±0.001	0.043±0.001

Table columns show geometric and particle reflectivities for Model 1 (using MCMC with all reflectivities as free parameters) and particle reflectivities for Model 2 (using MCMC with the particles of each ring group required to have identical reflectivity). Conversions between geometric and particle reflectivities are based on the model of Karkoschka (2001a).

Table 2.6: K-band Ring and Particle Reflectivities

Ring	Model 1 Geometric	Model 1 Particles	Model 2 Particles
456	0.010±0.006	0.016±0.010	0.014±0.010
$\alpha\beta$	0.023±0.008	0.034±0.013	0.028±0.008
$\eta\gamma\delta$	0.008±0.0014	0.047±0.008	0.040±0.006
ϵ	0.029±0.001	0.041±0.002	0.041±0.002

Table columns show geometric and particle reflectivities for Model 1 (using MCMC with all reflectivities as free parameters) and particle reflectivities for Model 2 (using MCMC with the particles of each ring group required to have identical reflectivity). Conversions between geometric and particle reflectivities are based on the model of Karkoschka (2001a).

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Chapter 3

Clouds and Aerosols on Uranus: Radiative Transfer Modeling of Spatially–Resolved Near–Infrared Keck Spectra

We observed Uranus in the near–infrared H and K' bands ($1.47\text{--}2.38\ \mu\text{m}$) in 2010 and 2011 with the OSIRIS imaging spectrograph on the Keck II telescope with adaptive optics. In 2010, three years past the equinox, we had a good view of the north polar region while still having access to southern latitudes down to 70°S . In 2011 our observations focused on a moderately bright discrete cloud feature in the middle of the bright circumpolar band at 45°N .

The spatial and spectral resolution of our data allow us to retrieve atmospheric parameters between $\sim 65^\circ\text{S}$ and 75°N via radiative transfer modeling. We test vertical aerosol profiles with combinations of diffuse and compact scattering layers, and find that we can reproduce our equatorial data for a range of cases, provided the deepest detectable aerosol layer is compact and located between 2 and 3 bars, with the higher cloud altitudes corresponding to models with higher methane deep volume mixing ratios. Using a parameterized atmosphere with a diffuse upper haze and a moderately compact lower cloud, we find that both the haze and the cloud reach their maximal optical depth just north of the equator and thin toward the poles. When we fix the abundance of methane with latitude, we find that the bottom cloud shifts to shallower depths at higher latitudes in both hemispheres; for a methane profile with a deep volume mixing ratio of 2.22%, the cloud rises from the 3–bar level equatorward of $\pm 20^\circ$ to above 2 bars by $\pm 60^\circ$. However, when we allow the tropospheric methane abundance to vary according to a parameterized vertical profile, we find that the lower cloud depth is stable in latitude while the methane becomes increasingly depleted toward both poles. In both cases, we find denser aerosol layers and higher methane abundances in the northern hemisphere than the southern, consistent with a seasonal post–equinox trend. In particular, the bright band near 45°N is relatively undepleted in methane, and represents a local peak in the opacity and altitude of the lower cloud. The

cloud feature we detected in 2011 falls in the middle of this band. This feature extends from a depth of ~ 1.3 bars up to the 0.5-bar level. Both CH_4 and H_2S are expected to condense below this level; if the cloud has formed as the result of a convective upwelling event, these are the most likely condensation species.

3.1 Introduction

Uranus is unique among the giant planets in that its rotational and orbital axes are nearly perpendicular, causing the distribution of solar insolation to differ significantly from the other planets. In addition, Uranus is the only giant planet that appears to have no internal heat source to drive convection and consequently displays far fewer discrete cloud features than the other gas planets in our Solar System. The effect of these differences on global circulation patterns is not well understood; improved models would help generalize our understanding of planetary atmospheric dynamics, which is becoming increasingly relevant to extrasolar planets via the modeling of near-infrared spectra.

The first flyby of Uranus by Voyager 2 in 1986 revealed a quiescent, nearly cloud-free atmosphere during the planet's southern summer. In the years surrounding the northern spring equinox in 2007, a multitude of discrete clouds at mid-latitudes were observed, indicating an increase in convective activity. In the years following the equinox, the activity level decreased (e.g. Irwin et al., 2011; 2012a; Sromovsky et al., 2009; 2012c), suggestive of seasonal trends. However, an unexpected surge of cloud activity was detected in August 2014 (de Pater et al., 2015), emphasizing our general lack of knowledge about the seasonal weather patterns and storms on Uranus.

Voyager 2 radio occultation observations were suggestive of a methane condensation cloud near 1.2 bar (Lindal et al., 1987), and West et al. (1991) combined ground-based measurements with Voyager data to identify an optically thin haze layer in the Uranian stratosphere, an optically thick methane haze at the 1.2-bar level, and an optically-thin condensation cloud near 3 bars. Since these first results, the existence of a compact methane cloud at the methane condensation level has been debated. Modeling of optical and near-infrared datasets has repeatedly failed to provide any evidence for this cloud (e.g. Sromovsky and Fry, 2007a; Karkoschka and Tomasko, 2009; Irwin et al., 2012). Sromovsky et al. (2011), however, do find evidence for it, and attribute the previous failure of detection to the difficulty of resolving it from the higher-opacity cloud layer at 1.4–1.7 bars. In addition, models with too low of a methane mixing ratio would require a longer column of methane to match the observed absorption and would thus position the cloud layer at deeper pressures inconsistent with methane condensation.

Recent disk-resolved observations have permitted an investigation of latitudinal trends in Uranus' atmospheric structure. It has been repeatedly found that the lower cloud deck shifts to higher altitudes toward the poles, and/or the methane abundance decreases (Irwin et al., 2007; Sromovsky, 2007a; Karkoschka and Tomasko, 2009), though these effects are difficult to distinguish from one another. In addition, Uranus sustains bright bands near 45°S and 45°N which have exhibited slow time variability over the past decade. The pre-equinox

brightness in the southern band is thought to be the result of a lower methane mixing ratio which results in lower absorption, and may have been accompanied by a lowering in the altitude of the tropospheric cloud (Sromovsky et al., 2008). Irwin et al. (2009; 2011; 2012a) and Sromovsky et al. (2009) observed Uranus frequently in the near-IR during and after Uranus’ northern spring equinox in 2007 and investigated changes in the distribution of aerosols over this time. Both groups found that the northern bright zone at 45°N has brightened significantly, while the southern zone at 45°S has steadily faded, suggesting that the appearance of these bands may be the result of solar forcing.

In this paper we present new near-infrared spectroscopic observations in the H band ($1.47\text{--}1.80\ \mu\text{m}$) from the Keck II telescope in 2010 and 2011. In 2010 we obtained spectra of Uranus at nearly all latitudes, which we use to compare atmospheric models and identify latitudinal trends in the atmospheric structure. From our 2011 observations, we present a high spectral-resolution near-infrared spectrum of an individual cloud feature on Uranus, which we use to model the vertical position and extent of the cloud.

We begin by describing our observations and data reduction and processing methods (Section 3.2), followed by a description of our radiative transfer code and parameter retrieval techniques (Section 3.3). We then give an overview of previous atmospheric models of Uranus and describe the models tested in this paper (Section 3.4). Our analysis and results are organized by three topics: model comparison, latitudinal trends, and discrete cloud feature. Section 3.5 describes our analysis methodology followed by a discussion of our results for each of these three topics. Our main conclusions are summarized in Section 3.6.

3.2 Observations and Data Processing

3.2.1 Observations: Keck II OSIRIS

We observed Uranus on UT 2010 July 28 and 2011 July 28 with the 10-meter W.M. Keck II telescope on Mauna Kea, Hawaii. In 2010 we observed a meridional stripe; as Uranus was nearly edge-on to Earth at this date, we were able to observe latitudes from 80°S up to the north pole. Prominent cloud activity on Uranus had been nearly absent in prior years, but in 2011 we observed a cloud feature at mid-northern latitudes.

Spectra were obtained using the OSIRIS imaging spectrometer with adaptive optics (Larkin et al. 2006), using the planet itself for wavefront sensing. The spectrograph uses a 2048×2048 pixel Rockwell Hawaii-2 detector, from which data cubes were constructed with spatial dimensions of 16×64 pixels, and spectral dimensions of 1651 and 1665 pixels for the H and K' broadband filters respectively. Observations in both years were made in these two filters, which correspond to wavelengths of $1.473\text{--}1.803\ \mu\text{m}$ and $1.965\text{--}2.381\ \mu\text{m}$ respectively, with a resolving power of $R \sim 3800$. The 2010 observations used a $0.05''$ platescale (field of view = $0.8'' \times 3.2''$), while the 2011 observations used a $0.02''$ platescale (field of view = $0.3'' \times 1.3''$) to achieve higher spatial resolution on the cloud feature; these platescales correspond to 710 and 284 km per pixel at disk center in 2010 and 2011 respectively. Images were also obtained on these nights with the NIRC2 instrument in H and K' filters. These images

are not used here in our analysis, but are shown in Figure 3.1 for context. Table 3.1 contains details on the observations.

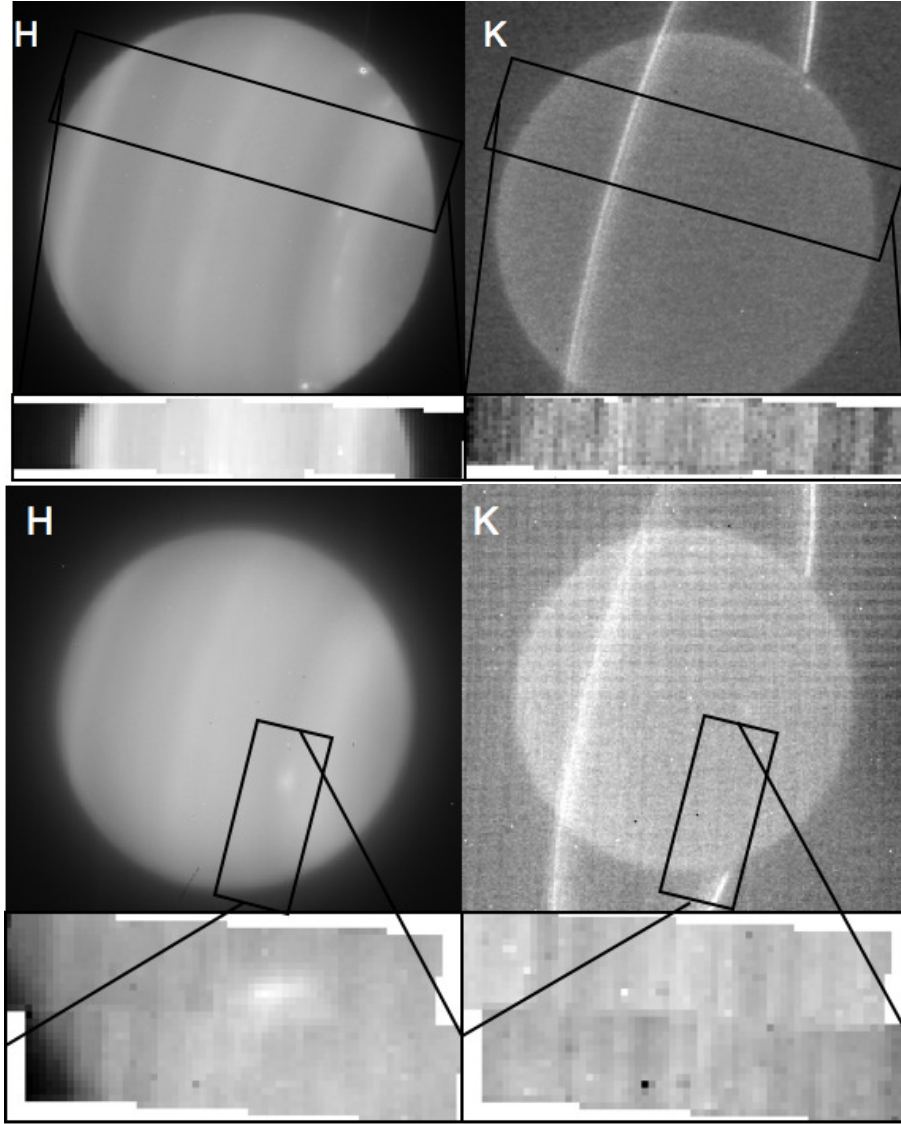


Figure 3.1: Observations of Uranus on 2010 July 28 (top) and 2011 July 28 (bottom) in H and K bands. Full-disk images were taken with the NIRC2 imager and demonstrate the rough location of the spectral data with respect to the planet. Insets were obtained with the OSIRIS imaging spectrograph, and are collapsed over the wavelength axis. Because the imaging and spectral data were obtained 1–2 hours apart, the location of specific cloud features is not identical between the observations.

Table 3.1: Keck OSIRIS Observations on UT 2010 Jul 28 & 2011 Jul 28

	Time	T_{int}	filter ^a	platescale	airmass
2010 Jul 28					
Uranus	13:58	300s	H	0.05''	1.07
	14:04	300s	H	0.05''	1.07
	14:16	300s	K'	0.05''	1.07
	14:22	300s	K'	0.05''	1.07
HD 220825	14:46	2x5s	K'	0.05''	1.12
	14:48	2x5s	H	0.05''	1.13
2011 Jul 28					
HIP 117774	12:13	10x2s	H	0.02''	1.15
	12:23	10x2s	H	0.02''	1.13
	12:31	10x2s	K'	0.02''	1.12
	12:39	10x2s	K'	0.02''	1.10
Uranus	13:17	360s	H	0.02''	1.09
	13:24	360s	H	0.02''	1.08
	13:47	360s	K'	0.02''	1.06
	13:54	360s	K'	0.02''	1.06

a. H, and K' filters correspond to wavelength ranges of 1.473–1.803 μm and 1.965–2.381 μm respectively.

Data were reduced using the standard OSIRIS pipeline, which includes flat-fielding, sky-subtraction, cosmic-ray rejection, wavelength calibration, and data cube assembly. Reduced data cubes were further cleaned to remove bad pixels not identified by the reduction pipeline. The threshold for a bad pixel was five standard deviations from the mean, where the mean and standard deviation were calculated for each wavelength individually. The value of a bad pixel was replaced by the median value of the four neighboring pixels. The percentage of pixels replaced varied with data cube between 0.027% and 0.066%. We also removed the rows of pixels at the edges of the field of view that exhibited anomalous brightness due to lenslet masking errors in the spatially-extended source. Prior to analysis, the data were binned to a spectral resolution of $R \sim 1200$ to match the resolution of our methane absorption coefficients, described in Section 3.4.2.2.

3.2.2 Flux Calibration and Photometry

We observed the standard stars HD 220825 and HIP 117774 in 2010 and 2011 respectively for flux calibration and to correct for wavelength dependencies in the atmospheric transmission. The stellar spectra were extracted via the OSIRIS pipeline and aperture photometry, using the largest aperture that fit in the detector area; this corresponded to a radius of 0.45'' in 2010 and 0.18'' in 2011. We assumed that the 0.45'' aperture captured all the light

from the star, and estimated the stellar flux lost off the edges of the detector in 2011 by extracting the 2010 stellar spectrum with both 0.18'' and 0.45'' aperture radii and assessing the difference in measured flux density. We determined that the fraction of flux lost off the edges was $\sim 30\%$ and varied linearly in wavelength due to wavelength dependencies in the point spread function (PSF), and we corrected the 2011 stellar spectrum accordingly.

Model spectra for each star were created using the Kurucz model¹ via the method described by Laver et al. (2009), which utilizes the 2MASS² H and K magnitudes of the reference stars. For each night, a telluric correction spectrum was constructed by dividing the observed stellar spectrum by the model spectrum for that star. Our spectra of Uranus were then divided by the relevant correction spectrum to minimize the effects of telluric absorption and to flux-calibrate the observations. We did not account for the difference in airmass between the calibration star and planet (<0.06 on both nights); the error contribution from this difference is much smaller than the errors from other sources, such as the uncertainty in the photometry ($\sim 10\%$).

The weather conditions during our 2011 observations were poorer than in 2010, and the data quality was less consistent over the time of observation. We therefore correct the 2011 data for atmospheric transmission via the 2011 stellar observations, but calibrate the absolute flux from our 2010 data via a wavelength-independent multiplicative factor of 1.3. This factor is calculated so that a feature-free region of Uranus' disk with matching latitude and emission angle gives the same H-band reflectivity between the two years, and its magnitude is consistent with the level of error introduced by non-photometric observing conditions. The shape of the spectrum in this region matches closely between dates after this scaling is applied, lending support to our choice of wavelength independence in the correction factor.

3.2.3 Navigation

We calculate the latitude, longitude, and incident and emission angles of our datasets at quarter-pixel resolution by a limb-fitting method based on that of Lii et al. (2010): a model grid of the planet with longitude and latitude lines³ is fit by eye to a wavelength-collapsed H-band image of the planet using the limb for reference. This procedure is repeated five times, and the average of the fits is taken as the final navigation. The accuracy of this method is limited by the accuracy with which the curvature of a small piece of limb can be matched to the model by eye. In the 2010 data, which covers a larger portion of the limb, we estimate the H-band navigation is accurate to ± 1 pixel, corresponding to 710 km or 1.6 degrees of latitude at the equator; in the 2011 data the fit is accurate to ± 2 pixels, corresponding to 570 km or 1.3 degrees of latitude.

Uranus is nearly invisible in our K'-band OSIRIS observations (see Figure 3.1), and we are unable to distinguish the location of the limb on either date. Though we do not include

¹<http://kurucz.harvard.edu/stars.html>

²<http://www.ipac.caltech.edu/2mass/>

³Ephemeris obtained from JPL's HORIZONS system: ssd.jpl.nasa.gov/horizons.cgi.

these observations in our analysis, the absence of light from the planet at these wavelengths, which probe Uranus' atmosphere above 1.0 bar, provides a check on our models.

3.2.4 Data Uncertainties

An accurate understanding of the uncertainties in our data is essential for getting the most accurate model fits. The size of the uncertainties entering the fits affects the uncertainties on the derived parameters as well as the degree to which one model is preferred over another, while the spectral variation in the uncertainties enters the fits as weights across the spectral axis and can therefore have a significant effect on the derived parameters themselves. In this section we briefly discuss the various types of uncertainty in our data and how we quantify and address them: Section 3.2.4.1 addresses the rms of the data and the effects of band shape, while Section 3.2.4.2 describes uncertainties in the photometric offset and slope.

3.2.4.1 Noise

The OSIRIS instrument records >1000 spectra on a single detector simultaneously by packing spectra very close together. Rectifying the resultant 2-d image into a 3-d data cube thus requires extracting each spectrum using the precise PSF of each individual lenslet at every wavelength (Larkin et al., 2006). There are numerous potential noise contributions, due to e.g. the filter shape, the effects of detector location, the contamination of faint spectra by neighboring bright spectra on the detector, and an imperfect spectral extraction due to instability in each individual PSF. We estimate the noise in the data empirically, and consider two types of noise contributions: pixel-to-pixel scatter within a spectrum, or spectral noise, and pixel-to-pixel scatter when considering a wavelength cut, or spatial noise.

We find a spectral noise of $\sim 2\%$ over most of the H band, rising to nearly 6% at the band edges, derived from the spectra of both Uranus and the standard star. We assess spatial noise at each wavelength by comparing neighboring pixels on a featureless region of Uranus' disk; however, we note that we don't expect any region of Uranus' disk to be perfectly uniform, due to physical differences across Uranus' atmosphere as well as the different viewing geometry at each pixel. We find that the spatial noise at a given wavelength is not a fixed fraction of the total brightness at that wavelength, and can be approximated by a step function with a value of 0.0005, in units of fractional reflected sunlight, at wavelengths $> 1.62 \mu\text{m}$ where Uranus is very faint, and 0.001 at shorter wavelengths where Uranus is brighter. This constitutes $> 2\%$ of the signal at all wavelengths, and is added in quadrature to the spectral noise term to produce our final uncertainty spectrum. Because the uncertainty spectrum has a signal-dependent term, it is calculated separately for each spatial location and varies slightly across Uranus' disk.

3.2.4.2 Photometry

We estimate the uncertainty in the photometry of our data and stellar calibration based on a comparison between successive integrations on the same target. In 2011 we obtained

two consecutive integrations on the reference star. Their difference is 5–10% in median flux density, with a linear trend in wavelength of $\sim 6\%$ over the 1.45–1.8 μm window. This level of consistency between stellar integrations is similar to what we have seen in past observations with the same instrument (e.g. de Kleer et al., 2013). We did not have multiple observations of the reference star in 2010, but note that weather conditions and data quality were both much better in 2010 than 2011.

Our observations of the planet itself give a more informative estimate of the quality of the photometry. On each date our observations of Uranus consist of two mosaicked integrations with a small overlapping region of 450 pixels in 2010 and 120 pixels in 2011. We extract the median spectrum from this region of overlap in each observation, and estimate the difference between the successive observations. We find that the difference is best modeled as a small offset whose magnitude is $<5\%$ of the signal from the planet in the 1.5–1.6 μm region. We add a wavelength-independent factor to each observation so that the overlapping regions on each date match the median of the two successive observations, and incorporate the value of this offset into our uncertainties.

The long-wavelength ($>1.62 \mu\text{m}$) region of the spectrum differs in slope between successive observations; this effect is most pronounced in the 2011 observations, and is mostly likely due to wavelength-dependent differences in atmospheric extinction and the PSF. Our atmospheric models predict a flat slope over this region, with variations due to methane absorption occurring only on smaller wavelength intervals; we therefore flatten this slope in our data before fitting the models.

3.3 Radiative Transfer Calculation and Parameter Retrieval

3.3.1 Radiative Transfer Calculation

We model the atmosphere of Uranus from the high stratosphere (0.1 mbar) down to 8 bars in the troposphere with a gaseous background atmosphere composed of molecular hydrogen, helium, and methane with additional layers of scattering particles. The models are parameterized by the vertical profiles of temperature and methane abundance, and by the locations and properties of the scattering layers; these parameters are discussed in detail in Section 3.4. We calculate near-infrared spectra for each model via our radiative transfer code, which is adapted from a code initially developed for Titan (Ádámkovics et al., 2007) and previously adapted for Neptune (Luszcz-Cook et al., 2010). We use the $\text{H}_2\text{--H}_2$, $\text{H}_2\text{--He}$ and $\text{H}_2\text{--CH}_4$ collision-induced absorption coefficients from Borysow et al. (1985; 1988) and Borysow (1991; 1992; 1993) assuming an equilibrium ortho/para hydrogen ratio. Our model uses the correlated- k approximation for methane absorption, and we use the k -coefficients of Sromovsky et al. (2012a) based on their new M5 line list compilation, which are tabulated at intervals of 5 cm^{-1} .

The radiative transfer equations are solved using the two-stream approximation (Toon et al., 1989). This method treats only the hemisphere-averaged scattering in the forward and

backward directions, sacrificing some degree of accuracy for computational efficiency. To assess the errors introduced by the use of this approximation, we compare model spectra calculated using the two-stream method with those produced using the *disort* (Discrete Ordinates Radiative Transfer) program (Stamnes et al., 1988), assuming a single Henyey–Greenstein phase function. This phase function can be expanded as an infinite series of Legendre polynomials, and the number of terms used in the calculation determines how completely the phase function is described. The number of streams must match the number of terms for the scattering information to be accurately represented in the calculation. We increase the number of terms and ordinates used in the calculation until the addition of more terms does not affect the model spectrum, indicating that we have specified the phase function as accurately as the data can distinguish. We find that the model spectra calculated in this way deviate from those calculated using the two-stream approximation by between $<5\%$ and $\sim 10\%$ depending on the wavelength, emission angle, and atmospheric structure. We use these differences to place uncertainties on our models as follows. We first calculate a *disort* spectrum for the best-fit model found using the two-stream approximation for each atmospheric structure and latitude. We then re-run the two-stream fits with the differences between the *disort* and *two-stream* model spectra as an additional uncertainty term. This term has the effect of weighting different spectral regions based on how robust the model is in that region to the number of streams; incorporating these weights results in minor differences in the retrieved parameters. The final uncertainties on our retrieved parameter values thus reflect both the uncertainties in our data and the systematic error introduced by the use of the two-stream approximation in our calculations.

3.3.2 Parameter Retrieval using MCMC

The various input parameters to the models are described in Section 3.4; the model parameters we retrieve include the vertical distribution (3 parameters), optical depth (1 parameter), and particle size (2 parameters) of each scattering layer in the atmosphere, as well as the degree of methane depletion relative to the base methane profile. The specific atmospheric structures we treat, including the free parameters in each, are outlined in Section 3.4.3 and Table 3.2. For any given model, a subset of the model parameters are fixed, and the actual number of free parameters ranges from 4 to 8 depending on the specific model.

Our parameter retrievals utilize Markov chain Monte Carlo (MCMC) methods for parameter estimation and uncertainties. The goal of MCMC methods is to approximate a physical probability distribution by constructing a Markov chain whose equilibrium distribution is the desired distribution (e.g. MacKay, 2003). For a given k -dimensional vector of parameters θ and data $y = (y_1, \dots, y_n)$, we would like to know $p(\theta|y)$, the posterior probability distribution of each parameter given the data, where

$$p(\theta|y) = \frac{1}{f(y)} p(\theta) p(y|\theta) \quad (3.1)$$

and $f(y)$ is a normalization constant that depends only on the data. Determining the posterior distribution requires a prior distribution $p(\theta)$ incorporating any prior knowledge that

informs the probability distribution, and a likelihood function $p(y|\theta)$. The MCMC algorithm generates a random walk in parameter space that draws a representative set of samples from the posterior distribution. Once these samples have been generated, the probability distribution for each free parameter can be read off the distribution of values drawn for that parameter, after an initial burn-in phase.

We use an affine invariant ensemble MCMC method in which an ensemble of chains is simultaneously constructed, with the subsequent step in each chain dependent on the current position of each individual chain within k -dimensional parameter space (Goodman and Weare, 2010). We employ the Python **emcee** implementation of this algorithm by Foreman-Mackey et al. (2013), which has been used successfully in various astrophysical applications.

We provide a guess for each parameter, and initialize each chain at a different set of parameters drawn randomly from a Gaussian distribution centered at the guess values. Our prior distributions are log-flat and span many orders of magnitude, consistent with a high degree of initial uncertainty in the true parameter values. The Markov Chain random steps seek to maximize the likelihood function, or the likelihood of drawing our data y given our model and a set of parameters θ . In the case of χ^2 fitting, the likelihood function is given by

$$L = \prod_{i=1}^n \left(\frac{1}{2\pi\sigma_i^2} \right)^{1/2} \exp \left(- \sum_{i=1}^n \frac{(y_i - f(x_i))^2}{2\sigma_i^2} \right) \quad (3.2)$$

and

$$\ln(L) = C - \chi^2/2, \quad (3.3)$$

where C is a constant that depends on the data but is independent of the model.

For each fit, we create 150 simultaneous chains. The algorithm typically converges within a few hundred steps, and we run each ensemble for a minimum of ~ 100 steps after convergence to ensure the robustness of the solution. A demonstration of this technique, including chains, their corresponding parameter distributions, and parameter correlations, is shown in Figures 3.3 and 3.2.

3.3.3 The Deviance Information Criterion

While the MCMC algorithm yields accurate parameter estimation and uncertainties for a given model, it does not give a direct metric for comparison between different models. Using a comparison of χ^2 between models can be misleading because it does not take into account model complexity, which is not simply a function of the number of inputs. For the purpose of model comparison, we employ the Deviance Information Criterion (DIC) proposed by Spiegelhalter et al. (2002). The DIC includes a standard term for goodness-of-fit with a penalty term for model complexity, and considers the full posterior distribution of each parameter, allowing comparison of the models themselves instead of their single best-fit manifestations. This metric is particularly convenient because it is simple to calculate from the output of MCMC simulations.

The DIC employs the deviance to measure both goodness of fit and model complexity, where the deviance $D(\theta)$ is defined as the difference in the log-likelihoods between the fitted model and a perfect fit to the data.

$$D(\theta) = -2\ln L(y|\theta) + 2\ln f(y), \quad (3.4)$$

where $L(y|\theta)$ is the likelihood function for the data y given the parameter set θ and $f(y)$ is a function of the data alone, and therefore cancels when considering the difference in deviance between models for the same dataset (Dempster, 1974).

The goodness of fit is given by the posterior expectation of the deviance $\overline{D(\theta)}$, so that smaller values correspond to better fits. The models are penalized for complexity based on the effective number of parameters p_D , defined as the difference between the posterior mean of the deviance $\overline{D(\theta)}$ and the deviance evaluated at the posterior mean of the parameters $D(\bar{\theta})$:

$$p_D = \overline{D(\theta)} - D(\bar{\theta}). \quad (3.5)$$

The DIC is then defined as the sum of these two components:

$$\text{DIC} = \overline{D(\theta)} + p_D = D(\bar{\theta}) + 2p_D. \quad (3.6)$$

These parameters are calculated from the output from our MCMC simulations: $\overline{D(\theta)}$ is the mean of the distribution of likelihood values calculated at values sampled from the k -dimensional probability distribution of parameter values, and $D(\bar{\theta})$ is the deviance calculated at the expectation of the simulated values of θ .

3.4 Atmospheric Models

In this section we discuss in detail the various parameters that enter our atmospheric models, including the choices previous authors have made and the reasoning behind our adopted models. Sections 3.4.1 and 3.4.2 address the particle scattering properties and the treatment of methane. In Section 3.4.3 we review atmospheric structure models that have been used by previous authors to fit observations, and describe the three models we choose to explore in Section 3.4.4.

3.4.1 Particle Scattering Properties

Scatterers in a model atmosphere are described by their size distribution $f(R)$, single-scattering albedo ϖ_0 , scattering phase function $p(\theta)$, and complex refractive index n , which in turn determine the cross-sections for scattering, absorption, and extinction. Cold (<100 K) methane ice, which dominates the scattering in ice giant planets, has a wavelength-dependent refractive index which is in the vicinity of $1.4+0i$ in the near-infrared (Satorre et al., 2008; Martonchik et al., 1984), and we adopt this value in our models. The single-scattering albedo predicted by Mie theory is 1.0 for conservative scattering; we use the value of $\varpi_0 = 0.75$ empirically determined from limb-darkening observations (Sromovsky

et al., 2007a). While this estimate may be biased by the use of older methane absorption coefficients less appropriate for Uranus’ atmospheric conditions, Irwin et al. (2011; 2012b) derived comparable values based on Uranus’ H-band spectra, using the updated methane coefficients of Karkoschka and Tomasko (2010) and the recent line data from Campargue et al. (2012).

The simplest distribution of particle sizes is a delta function at a specific particle radius. However, the modified gamma distribution describes the size spectra of condensing aerosols particularly well (Williams, 1985), and is often used in this context. For a particle size population with mean and variance μ and σ , this distribution has the form

$$f(r; k, \theta) = \frac{r^{k-1} e^{-\frac{r}{\theta}}}{\theta^k \Gamma(k)} \quad (3.7)$$

where the scale $\theta = \sigma/\mu$, the shape parameter $k = \mu^2/\sigma$, and $\Gamma(k)$ is the gamma function evaluated at k . The form of this distribution is shown for the combinations of input parameters used in this work in Figure 3.4. We use this function to model our particle sizes, with average radius values fixed at $0.1 \mu\text{m}$ for the upper atmosphere, and in the $0.6\text{--}1.2 \mu\text{m}$ range at deeper levels, consistent with physical predictions. Pollack et al. (1987) predict, based on photochemical and microphysical modeling, that stratospheric scattering particles are likely to be dominated by ethane, acetylene, and diacetylene gasses produced from UV photolysis of methane above the 0.1 mbar level and descending to their condensation pressures of 14, 2.5 and 0.1 mbar for these three species respectively, and are $\sim 0.1 \mu\text{m}$ in size. Deeper in the atmosphere, where hazes are most likely composed of condensed CH_4 or H_2S , particle sizes may be closer to $1.0 \mu\text{m}$.

While the scattering particles may have complicated shapes and phase functions, our observations are not sensitive to these details and we find that a simple scattering phase function is sufficient to fit our data. We specify this phase function with a single asymmetry parameter g that sets the fraction of back- and forward-scattering; a value of $g = 1$ corresponds to pure forward scattering, and $g = -1$ to pure backscattering. The wavelength dependence of g is calculated from Mie theory. The parameter g is strongly dependent on the particle size; the calculated asymmetry parameters for the wavelengths and particle size distributions used in this paper are shown in Figure 3.4.

3.4.2 Temperature and Methane Profiles

Lindal et al. (1987) derived temperature and methane profiles for the outer atmosphere of Uranus consistent with radio occultation observations. These profiles, labeled A–F, are characterized by their deep methane mixing ratio which ranges from $<2\%$ for profile A to 4% for profile F. Sromovsky et al. (2011; 2014) created additional methane profiles (D1, DE, E1, EF, F1, FG, and G) with associated temperature profiles, consistent with the same observations. The wavelength range we are analyzing is less suited to constraining the deep methane mixing ratio than previous observations; we therefore limit our models to three methane profiles (D1, E1, and F1 with deep volume mixing ratios of 2.22%, 3.20% and 4%) with associated temperature profiles.

For each new methane profile, Sromovsky et al. (2011) calculated corresponding values for the helium mixing ratio that both match the occultation observations and achieve methane saturation in the putative condensation region. We use these values in our models; at 0.126, 0.122, and 0.1155 for the D1, E1, and F1 profiles respectively, they are all within $\sim 1\sigma$ of the value of 0.15 ± 0.033 determined earlier by Conrath et al. (1987).

3.4.2.1 Methane Depletion

Recently, numerous authors have found that invoking a greater methane abundance over the equator than the poles is required to fit observations (Karkoschka and Tomasko 2009; Sromovsky et al., 2011; 2014; Irwin et al., 2012a; Tice et al., 2013). Sromovsky et al. (2011) found they were unable to fit both equatorial and polar spectra with the same vertical distribution of methane, and constructed depleted methane profiles with various depletion degrees and shapes to fit the polar data. They argue that depletion must occur only at shallow depths because a latitudinal gradient in mixing ratio at great depths would produce winds inconsistent with what is observed on Uranus. However, this is seemingly at odds with microwave observations that imply depletions and latitudinal differences down to tens of bars (de Pater et al., 1989; Hofstadter et al., 2003). Irwin et al. (2011; 2012a) and Tice et al. (2013) also found evidence for an enrichment of methane at the equator over mid-latitudes, and note that the apparent variation in cloud top pressure with latitude may disappear when this methane gradient is considered.

We model methane depletion using the Sromovsky et al. (2011) “proportionally descended gas” profile. While undepleted profiles have an abrupt transition in methane abundance at a pressure of 1.2 bars where the temperature becomes low enough for methane to condense out, these depleted profiles increase methane gradually with increasing depth by shifting the mixing ratio profile $\alpha(P)$ down to increased pressure levels $P'(\alpha)$ using the equation

$$P' = P \times [1 + (\alpha/\alpha_d)^{vx}(P_d/P_c - 1)] \text{ for } P_{tr} < P < P_d, \quad (3.8)$$

where P_d is the pressure depth at which the revised mixing ratio $\alpha = \alpha(P')$ equals the uniform deep mixing ratio α_d , P_c is the pressure at which the methane condensation temperature is reached, P_{tr} is the tropopause pressure, and vx controls the shape of the profile in the depleted region. We fix the value of vx at 2.0, which Sromovsky et al. (2011; 2014) suggest provides a good fit to the data.

Such a profile smoothly depletes the methane in the upper troposphere (above P_d) without changing the methane abundance in the deeper atmosphere, such as may occur in a circulation system in which dry air from $P < P_c$ descends to a depth of P_d . The depletion of methane below the tropopause brings the average methane abundance below saturation in this region; this inhibits global methane condensation, though clouds may still condense locally. The dry air above P_c required to explain the depletion requires a methane-removal mechanism such as a condensation cloud. These two requirements are reconciled in (a) a scenario in which condensation is occurring in local convective cells in a region of overall downwelling, or (b) a global system in which methane is condensing in equatorial regions, and

the dried-out air above the cloud layer is then distributed to high latitudes by a hemispheric circulation cell, depleting the methane in polar downwelling regions. The latter scenario is discussed in detail by Sromovsky et al. (2011).

Figure 3.5 demonstrates the construction of a depleted methane profile in panel (a), and shows the three methane profiles D1, E1, and F1 with two example depletion depths in panel (b). The methane depletion profile is parameterized by a single value: the depletion depth P_d . However, we note that the model allows depletion depths that may be deeper than our observations are sensitive to, in which case the retrieved depths are heavily dependent on the depletion profile and may not be physically meaningful.

3.4.2.2 Methane Coefficients

Over the past decades, significant advances have been made in our knowledge of methane absorption properties and their extrapolation to the path lengths and temperatures of the Uranian atmosphere, resulting in an ability to fit observed near-infrared spectra increasingly well. Sromovsky et al. (2012a) and Irwin et al. (2012b) assess the ability of different methane coefficients and absorption line shapes to match measured spectra of Uranus' atmosphere. In the H-band spectral region, both groups independently find that recent improvements in line lists greatly improve their ability to fit measured spectra with Uranus atmospheric models. Irwin et al. (2012b) find the best match for the Hartmann et al. (2002) line shape, while Sromovsky et al. (2012a) prefer a far-wing line shape between that of Hartmann et al. (2002) and de Bergh et al. (2011). We adopt the latter line shape, using the correlated- k approximation (Lacis and Oinas, 1991) for improved speed, with the k -coefficients calculated by Sromovsky et al. (2012a). These coefficients are tabulated at a wavenumber interval of 5 cm^{-1} , and our data are binned to match this resolution prior to fitting.

3.4.3 Atmospheric Structure Models

Previous authors have used a variety of atmospheric structures and particle scattering properties to fit spectra of Uranus at near-infrared and optical wavelengths. Model atmospheric structures generally fall into two categories: atmospheres with aerosols confined to vertically-localized layers, and atmospheres full of a diffuse haze that varies in opacity with altitude. These structures are reviewed below before a description of our model structures.

3.4.3.1 Discrete Cloud Models

While atmospheres with a single aerosol layer have been found inadequate at modeling observations, models with two discrete cloud layers have often been used. These are typically parameterized as an upper haze (UH) based between 1.0 and 0.5 bars and a lower tropospheric cloud (TC) below 1.0 bars. Irwin et al. (2012a) note that they are able to fit the H-band spectrum with many different vertical cloud distributions ranging from continuous to discrete, but that the two-cloud model is sufficient and minimizes free parameters and assumptions.

Using such a model with near-infrared data and assuming a continuous distribution of micron-sized particles with a wavelength-independent Henyey–Greenstein phase function with an asymmetry parameter $g=0.7$ and refractive index of $1.4+0i$, Irwin et al. initially found extended clouds with peak opacities at the 2–3 and 8–10 bar levels at equatorial latitudes (2007), though the use of improved methane k -coefficients decreased the significance of the deeper cloud (2012a). They find that very close fits to 1.4–1.6 μm spectra require particles that become less scattering toward the longer wavelengths, and vary the single-scattering albedo smoothly across these wavelengths to fit the data, an approach also employed by Tice et al. (2013). These authors test a range of fixed particle sizes for each cloud, and find a weak preference for 0.1- μm particles in the UH and a strong preference for 1.35- μm particles in the TC, approximating all particle phase functions as Henyey–Greenstein functions with a wavelength-independent asymmetry parameter of $g=0.7$. Sromovsky et al. (2006) also used a two-cloud model to successfully fit near-infrared spectra obtained in 1975 by Fink and Larson (1979), but they note that a six-cloud model that permits a more complex distribution of opacity provides a much better fit to the observations.

3.4.3.2 Diffuse Haze Models

Karkoschka and Tomasko (2009) test a model of discrete condensation clouds against STIS spectroscopic Hubble data. The best-fit two-cloud model had clouds at 1.4 and 3 bars, consistent with the locations of peak opacity found by Irwin et al. (e.g. 2012a). However, they find a much better fit with an atmospheric model of extended haze layers without compact clouds, and argue that the frequent lack of detection of a condensation cloud at 1.2 bars indicates that the observed opacity may be due to a vertically-extended haze of aerosols, with aerosol production occurring near 1.2 bars followed by subsequent descent to lower altitudes on long timescales. Their model consists of low-opacity layers in the stratosphere and upper troposphere (0.1–1.2 bar) and higher-opacity middle and lower tropospheric layers (1.2–2 bars and >2 bars respectively). They adopt stratospheric scatterers with a wavelength-dependent imaginary index of refraction, scattering efficiency, and single-scattering albedo, and tropospheric scatterers with a wavelength-dependent single-scattering albedo and a double Henyey–Greenstein particle phase function with parameters $g_1=0.7$ and $g_2=-0.3$ and a wavelength-dependent weight f_1 that varies from 0.470 to 0.940 as λ increases from 310 to 940 nm. With these particle properties, they find a stratospheric particle size of $\sim 0.1 \mu\text{m}$, with larger ($\sim 1 \mu\text{m}$) particles at deeper levels.

3.4.3.3 Combination Models

Sromovsky et al. (2011) modified the four-layer diffuse model of Karkoschka and Tomasko (2009) to include compact condensation clouds in addition to the haze layers. They replaced the middle tropospheric haze layer with two compact cloud layers and replaced the lower tropospheric haze layer by a compact cloud at 5 bars, which was needed to fit their spectrum near 0.56 and 0.59 μm , though the pressure level and vertical extent of this cloud were not well constrained. They later adapted this model to fit 1.48–1.64 μm near-IR spectra

by neglecting the compact cloud at 1.2 bar because they found that the data could not distinguish individual contributions at this pressure level (Sromovsky et al., 2012a). For tropospheric aerosols, they adopted the particle scattering properties of the Karkoschka & Tomasko (2009) model, but extended the wavelength-dependence of the phase function into the near-infrared assuming 0.8- μm Mie particles.

3.4.4 Our Models

We model our data with three different atmospheric structures based on those described in Section 3.4.3; our models are summarized here. Our temperature and methane profiles and our adopted particle scattering properties are described in Sections 3.4.1 and 3.4.2. We parameterize the vertical distribution of aerosol density within a scattering layer by the fractional scale height H_{frac} , which is the ratio of the scale height of the aerosols to that of the background gas.

3.4.4.1 Two-Cloud Model [2C]

Our two-cloud model is based on the models by Irwin et al. (2012a) and Tice et al. (2013). It consists of a tropospheric cloud (TC) and upper haze (UH). The UH is constrained to lie at altitudes above 1.0 bar, and the particles follow a modified gamma distribution of sizes with mean and variance of 0.1 and 0.005 μm , consistent with the mean particle size preferred by Tice et al. (2013). The TC is a layer of larger particles ($\sim 1 \mu\text{m}$) in the deeper troposphere, below 1.0 bar. Our model differs from that of Irwin et al. (2012a) and Tice et al. (2013) by our choice to vary the particle phase function in wavelength based on Mie theory while keeping a wavelength-independent single-scattering albedo. The free parameters in this model are the base altitude, optical depth at 1.6 μm , and fractional scale height $\{P_{max}, \tau, H_{frac}\}$ of each layer.

3.4.4.2 Diffuse Haze Model [DH]

Our diffuse haze model consists of four continuous hazes with the fixed pressure boundaries used by Karkoschka and Tomasko (2009): 100 mb, 1.2 bar, and 2.0 bar. The aerosols are evenly mixed with gas within each layer ($H_{frac}=1.0$). The uppermost layer consists of small ($\sim 0.1 \mu\text{m}$) particles, while the lower layers contain larger ($\sim 1.0 \mu\text{m}$ particles); the exact particle size distributions used in modeling are described in Section 3.5.1.1. We fit only for the total 1.6- μm optical depth τ of each haze layer, for a total of four free parameters.

3.4.4.3 Modified Diffuse Haze Model [MDH]

Our third model is motivated by the model used by Sromovsky et al. (2012a) to fit near-infrared spectra of Uranus. This model is identical to our diffuse haze model except that we model the bottom layer (below 2.0 bars) as a compact cloud instead of a diffuse haze, and leave its depth P_{bottom} as a free parameter with the compactness requirement

$P_{top} = 0.9P_{bottom}$. This cloud is assumed to have the same scattering properties as the other tropospheric layers.

3.5 Analysis and Discussion

Our analysis is divided into three steps: we first use equatorial data to test various choices for atmospheric structure, methane profile, and particle size. We then fix the atmospheric structure and fit our entire dataset to assess variations in the depths and opacities of the aerosol layers with latitude. Finally, we fix these properties according to the best model fit to the 2010 data at a latitude of 45°N , and use the spectrum of the discrete cloud feature observed in 2011 to fit for its depth and vertical extent. Our methodology and results are presented for the model comparison in Section 3.5.1, for the latitudinal analysis in Section 3.5.2, and for the discrete cloud in Section 3.5.3. A discussion of these results in the context of global circulation models is given in Section 3.5.4, and our conclusions are summarized in Section 3.6.

3.5.1 Compact/Diffuse Profile Comparison

3.5.1.1 Analysis

We perform tests of the atmospheric structure, particle size distribution, and methane profile using equatorial data (between 10°S and 10°N in latitude): for each of the 2C, DH, and MDH models introduced in Section 3.4.4, we perform fits for the three cases of methane profile {D1, E1, F1} (see Section 3.4.2) and four cases of particle size distribution. An overview of the free and fixed parameters of each model is given in Table 3.2. Each model includes two distinct sets of scattering properties for particles in different regions: in the uppermost haze layer, the scattering particles are fixed at a modified gamma size distribution with a mean of 0.1 and a variance of $0.005 \mu\text{m}$, while all other layers contain particle size distributions with variance of 0.3 and means of $\{0.6, 0.8, 1.0, 1.2\} \mu\text{m}$. We test each of these four particle sizes separately, requiring all layers except the upper haze to have the same particle size distribution. We use wavelength-dependent cross-sections and asymmetry parameters derived from Mie theory for each particle size distribution. We assume methane is not depleted in the equatorial region, which was found by previous analyses (e.g. Sromovsky et al. 2012a; Irwin et al. 2012b) and later confirmed by our own analysis.

3.5.1.2 Results

The retrieved parameter values for each tested combination of atmospheric structure, methane profile, and particle size are shown in Figure 3.6, and the corresponding values of the DIC are shown in Figure 3.7. Figure 3.8 plots the data alongside the model spectra corresponding to the best-fit cases of each of the three vertical structures.

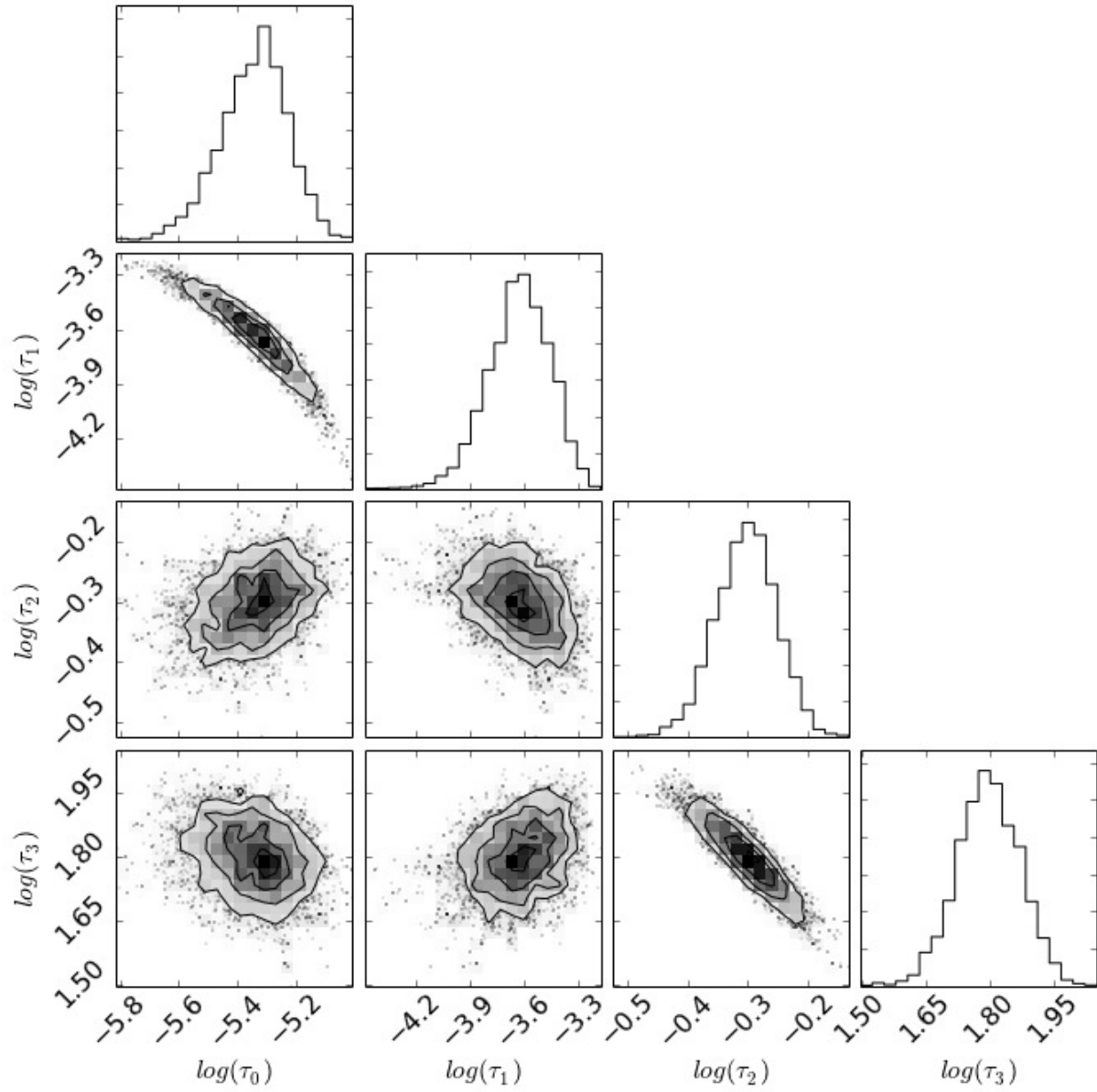


Figure 3.2: Demonstration of parameter correlations from MCMC simulation, for the same run shown in Figure 3.3. Scatterplots show the values taken on by each pair of parameters at every step, and histograms show the derived probability distribution for each parameter as in the previous figure.

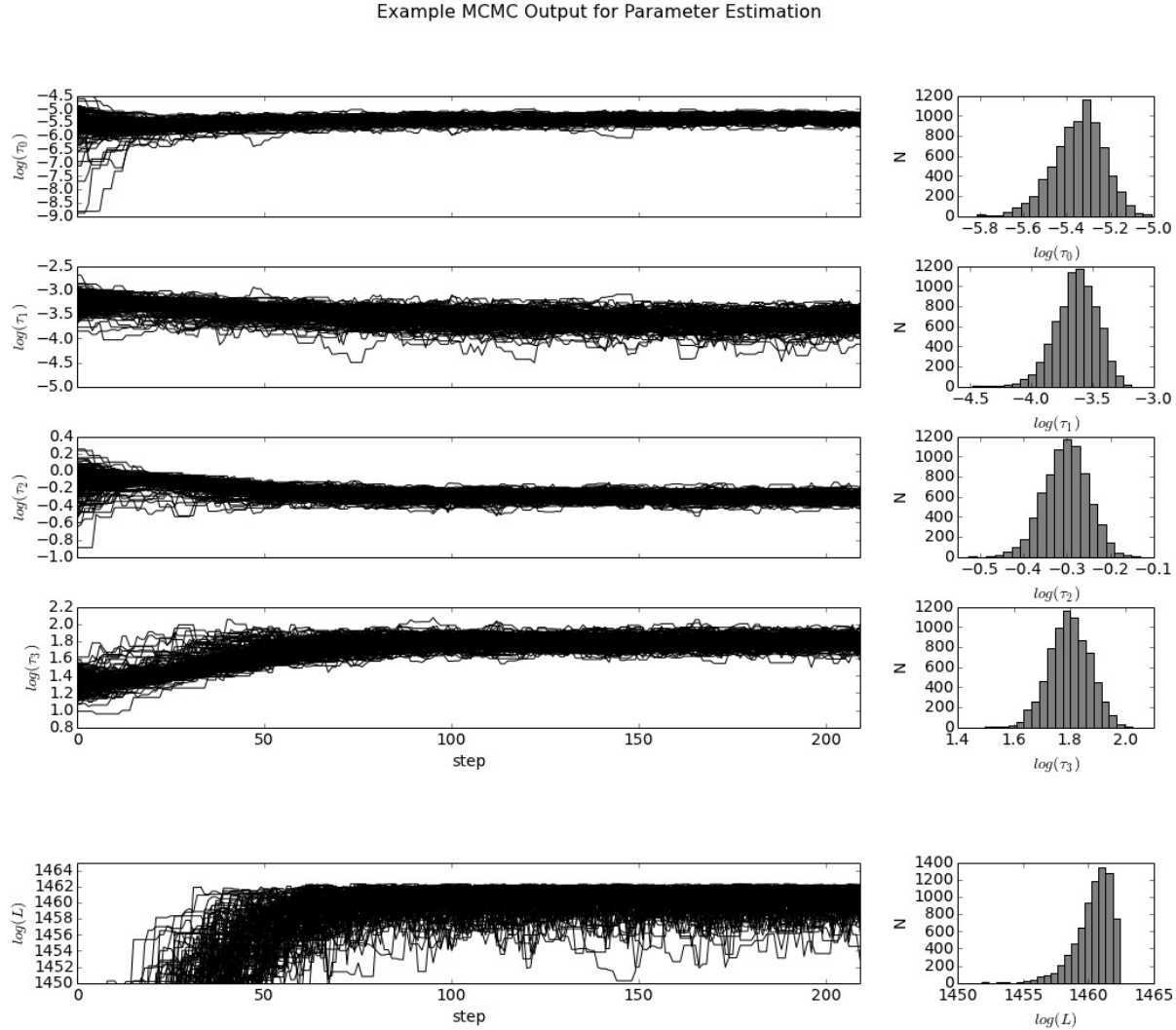


Figure 3.3: Demonstration of the use of Markov Chain Monte Carlo (MCMC) simulation for parameter estimation. Plots on the left show the values taken on by each of 150 walkers at each step for an example simulation using the Diffuse Haze (DH) model, which has four layers with fixed boundaries at $\{0.1, 1.2, 2.0\}$ bars and the optical depth of each layer as free parameters: $\{\tau_0, \tau_1, \tau_2, \tau_3\}$. The values for the likelihood L at every step is shown in the bottom panel. The chains have converged by step 150 in this example; the histograms of the post-convergence chains are plotted to the right. These represent the retrieved probability distribution for each parameter.

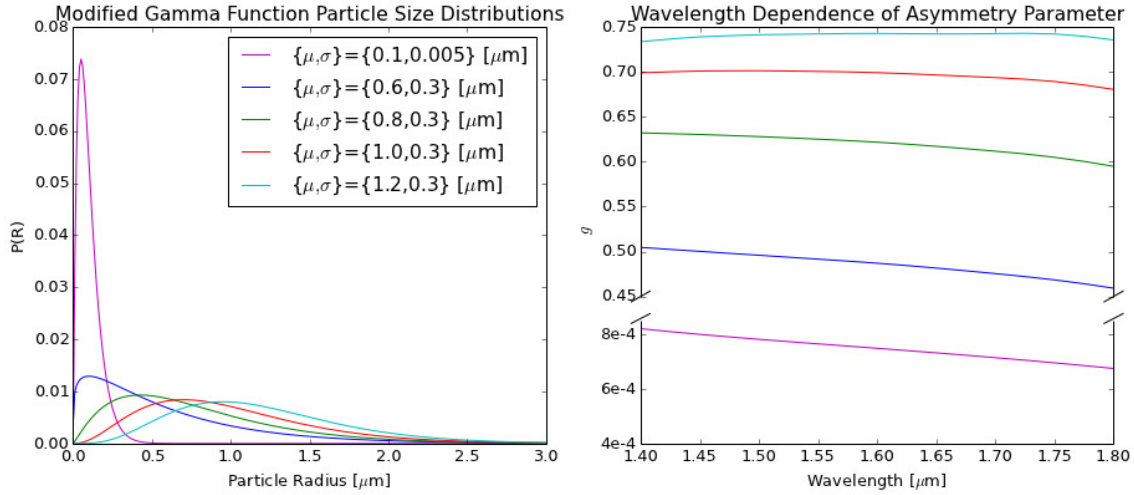


Figure 3.4: Particle size distributions and phase functions. [Left] Modified gamma particle size distributions used in our analysis. [Right] The asymmetry parameter g as a function of wavelength, as derived from Mie theory for the particle size distributions of the corresponding colors in the left plot.

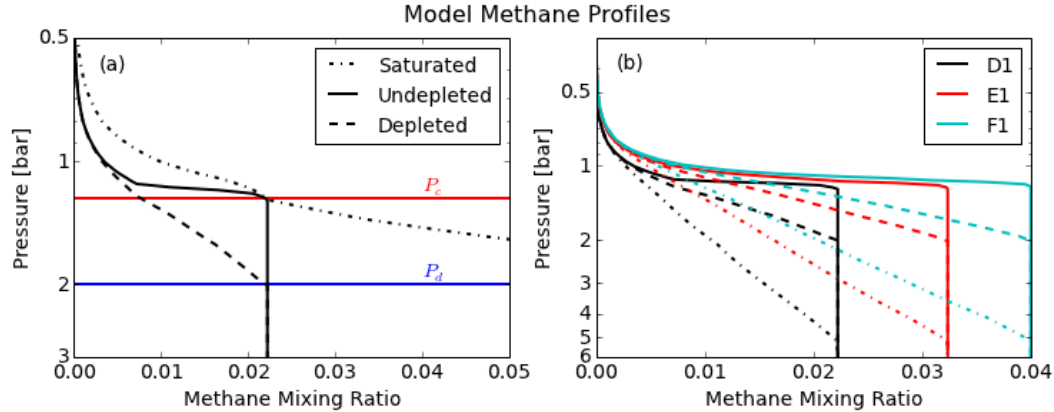


Figure 3.5: Model methane profiles: (a) The saturated methane profile and undepleted profile for the D1 case, with a depleted profile assuming a depletion depth of 2.0 bars, the depth at which the depleted profile reaches the undepleted deep methane mixing ratio. Horizontal lines show the pressure P_c at which the methane condensation temperature is reached, and the depletion depth P_d . (b) The D1, E1, and F1 profiles (Sromovsky et al., 2011). Solid profiles are undepleted, dashed profiles are depleted to 2.0 bars, and dash-dotted lines are depleted to 5.0 bars.

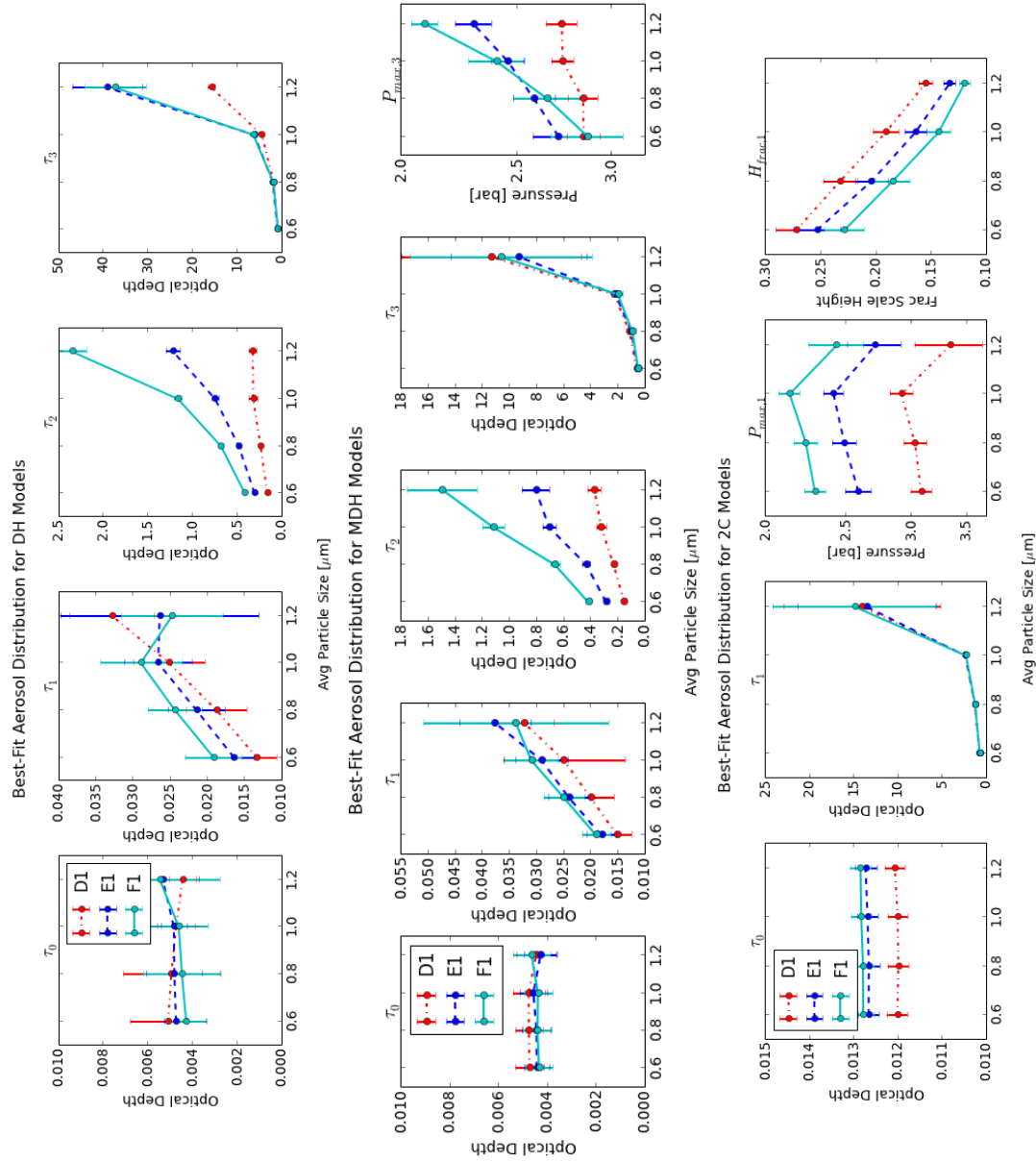


Figure 3.6: Effects of model choices on best-fit parameter values: plotted are the best-fit parameter values and uncertainties for three model atmospheric structures fitted to equatorial spectra. In each plot, the x-axis is the mean tropospheric particle size, and the three colored curves are for the three methane profiles. Optical depths are quoted at $1.6 \mu\text{m}$. Figure 3.7 shows the quality of fit to the data for each of the models shown.

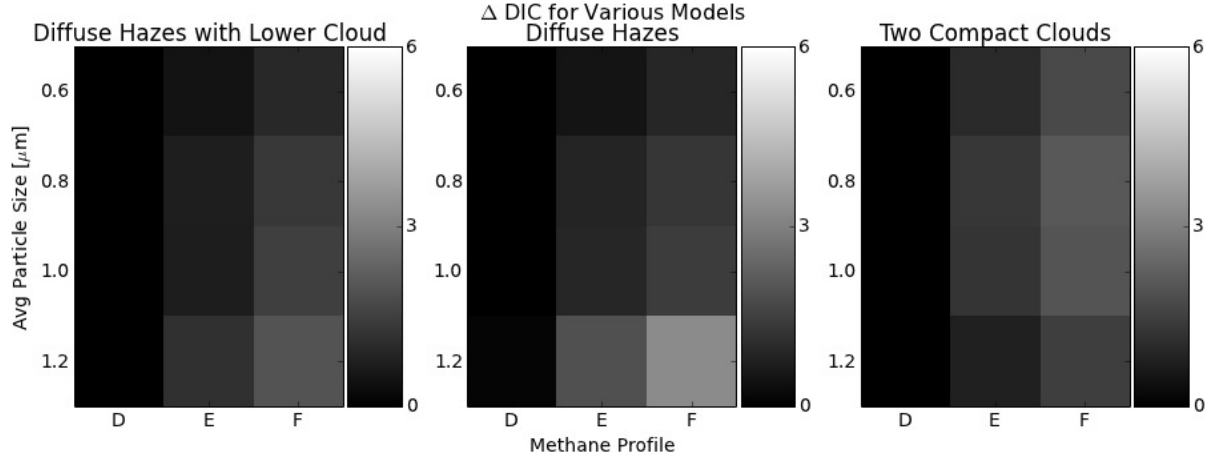


Figure 3.7: Value of the Deviance Information Criterion (DIC) for model comparison, for three atmospheric structures; methane profiles D1, E1, and F1; and particle sizes of 0.6, 0.8, 1.0, and 1.2 μm . Lower values correspond to better models, and the criterion is plotted as a differential above the value for the best-fit model out of all vertical structures, particle sizes, and methane profiles. A differential of 0–2 is not significant, while a value greater than 10 nearly excludes that model; none of the parameter combinations shown are excluded by this criterion.

We find that we are able to get an adequate fit to the data with all three atmospheric structure models: diffuse (DH), compact (2C), and combination (MDH). The different atmospheric structures find very consistent values for atmospheric characteristics that are shared between models. The fits with the DH and MDH models find similar values for the optical depths of all four aerosols layers, even though the lowest layers differ in position and compactness between the models. The MDH and 2C models both include a compact bottom cloud, and the retrieved optical depth, pressure level, and fractional scale height of this cloud are consistent between the models despite their very different structures above 2 bars. These similarities demonstrate that the retrieved vertical aerosol distribution tends toward the same profile regardless of parameterization, giving us confidence in the robustness of the solution.

We find somewhat better fits with the D1 methane profile (2.22% deep mixing ratio) than with the E1 or F1 profiles (3.20% and 4% deep mixing ratios). The D1 profile falls at the lower end of the 2–4% range found by previous authors. However, H-band observations do not provide a strong constraint on this parameter, which is additionally highly correlated with the vertical profile of scattering particles (e.g. Irwin et al., 2012b). Methane is the dominant absorber at most near-infrared and optical wavelengths, including the H-band region considered here, and the ratio of methane to hydrogen is consequently not well measured. The narrow spectral range near 825 nm, where $\text{H}_2\text{--H}_2$ Collision Induced Absorption (CIA) is particularly important, provides unique constraints on the deep methane mixing ratio. Karkoschka and Tomasko (2009) used 2002 STIS observations in this spectral window

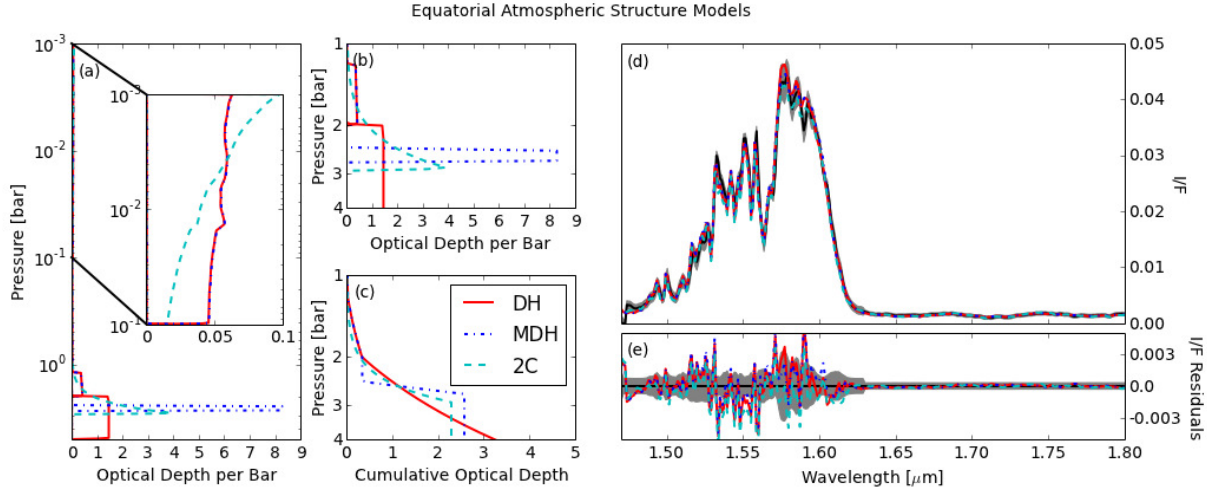


Figure 3.8: A demonstration of each of three atmospheric structure models fit to equatorial data between 10°S and 10°N . The models are for diffuse hazes only (DH), diffuse hazes with a compact bottom cloud (MDH) and a two-cloud model (2C); all models shown use a methane profile with a deep volume mixing ratio of 2.22% (profile D1), and a mean particle size of $1.0\ \mu\text{m}$. The full profiles are shown in (a), with a zoom-in of the 1–4 bar region shown in both $1.6\text{-}\mu\text{m}$ optical depth per bar (b) and cumulative optical depth at $1.6\ \mu\text{m}$ (c). The corresponding model spectra and residuals are shown in (d) and (e), where data are shown in black and the uncertainties are represented by the shaded region.

to derive an equatorial deep volume mixing ratio of methane near 3%. Sromovsky et al. (2011; 2014) re-analyzed this dataset and a subsequent dataset from 2012 to infer a deep volume mixing ratio of methane near 4%. Tice et al. (2013) later used SpeX observations covering this window to derive a much lower mixing ratio, though the observations were very noisy in the relevant regime. All of these values are within the range found by Lindal et al. (1987) to be consistent with Voyager data, and Rages et al. (1991) found that the F profile in particular was needed to match Voyager observations at $0.619\ \mu\text{m}$.

We are also able to fit our data with the higher-methane F1 profile, though use of a different methane profile changes the retrieved optical depths of the various scattering layers (see Figure 3.6). In particular, the choice of methane profile has a significant effect on the retrieved location of the lower cloud; fits with the F1 profile find this cloud near 2.3 bars, while fits with the D1 profile locate it closer to 3 bars. These depths are both consistent with previous two-cloud models of the Uranian atmosphere using the recent sets of methane coefficients, which have consistently found the equatorial altitude of the bottom cloud in the 2–3 bar range (Karkoschka and Tomasko, 2009; Irwin et al., 2012b; Tice et al., 2013). In Section 3.5.2.2 we discuss the effect of methane profile choice on qualitative trends with latitude.

We are able to fit the observations with all particle sizes in the $0.6\text{--}1.2\ \mu\text{m}$ range. However, we note that the choice of particle size does have a strong effect on the retrieved parameter

values, even when the fit quality is comparable. This effect can be seen in Figure 3.6 and is particularly pronounced in the optical depth of the 1.2–2 bar region, where larger particles correspond to higher retrieved optical depths due to their more forward-scattering phase functions.

3.5.2 Latitudinal Trends

3.5.2.1 Analysis

A knowledge of latitudinal trends in atmospheric characteristics provides important constraints on circulation models. Irwin et al. (2007) obtained the first latitudinally-resolved near-IR (1–2.5 μm) spectra of Uranus; using a model with a continuous distribution of hazes, they found two main peaks in the opacity: a deeper cloud that is thickest at the equator and thins toward the poles, and an upper layer extends from mid-southern to mid-northern latitudes and also clears toward the poles. Sromovsky et al. (2007a) imaged Uranus in seven near-IR bands with adaptive optics; they confirm that the deep cloud opacity decreases sharply toward the North pole, finding that essentially no cloud material is required to fit their observations beyond 50°N. Karkoschka and Tomasko (2009) detected latitudinal variability in 2002 HST-STIS observations at 820 nm, determining that the variations were dominated by changes in methane abundance in the 1.2–3 bar region rather than changes in aerosol opacities. Their findings, consistent with later work (e.g. Sromovsky et al., 2011), suggest that methane is increasingly depleted toward high latitudes. This result agrees with microwave observations of the deep atmosphere, which find the greatest volatile concentration in the equatorial region (de Pater et al., 1989; Hofstadter and Butler, 2003).

Recent analyses have considered latitudinal trends in both methane distribution and cloud level (Sromovsky et al., 2011; 2012a; Irwin et al., 2012a; 2012b; Tice et al., 2013) and find that these parameters affect near-infrared observations in similar ways and are difficult to distinguish in observations at these wavelengths. Some of these studies indicate that both parameters vary with latitude, with the main cloud deck moving to higher altitudes and thinning toward the poles while the methane relative humidity decreases from equator to pole.

We use our spatially-resolved observations to investigate trends in the vertical distribution of methane and aerosols with latitude. For these fits we adopt our 2C atmospheric structure model, the D1 methane profile with a deep volume mixing ratio of 2.22%, and a mean particle size of 1.0 μm in the troposphere. In addition, we introduce a methane depletion pressure P_d parameterizing the depth of methane depletion at a given latitude (Section 3.4.2.1). We perform fits with and without allowing depleted methane, and compare the effect on fit quality and on the retrieved values of the other parameters. We initially fit for the depth, opacity, and fractional scale height of both cloud layers. From these first fits, we found that the fractional scale height and location of the upper haze were poorly constrained by our models, with marginal but consistent preference across latitudes for a haze that begins at 1.0 bars or deeper with a fractional scale height between 1 and 2. We therefore fixed this layer with a base at 1.0 bars and a fractional scale height of 1.5 for our

final parameter retrievals. This approach is similar to that of Tice et al. (2013), who chose to fix some of the upper haze properties for similar reasons.

We consider spectra covering latitudes from 80°S to the north polar region, in increments of 10°. However, our simulations did not converge on solutions for the most polar latitudes, and we present results only from latitudes of 70°S to 80°N.

3.5.2.2 Results

Retrieved trends in aerosol and methane distribution with latitude are presented in Figures 3.9 and 3.10 and in Table 3.3 for two-cloud models with and without methane depletion, assuming $\sim 1\text{-}\mu\text{m}$ particles and the D1 methane profile (2.22% deep VMR). We find that methane depletion is better able to reproduce the observations at latitudes polewards of 30° in both hemispheres than changes in the tropospheric cloud depth $P_{max,TC}$, as illustrated by the improved fit demonstrated in Figure 3.9. Changing the amount of methane above the tropospheric cloud layer and changing the depth of this cloud layer both affect the methane column above the cloud, and therefore alter the model spectrum in similar ways, making it challenging to separate these two parameters (Section 3.5.2.1). We do find these parameters to be correlated in our retrievals, but find that while we detect no latitudinal variations in the tropospheric cloud depth beyond the level of the uncertainties, there is a clear equator-to-pole trend in the methane depletion. This result is demonstrated in Figure 3.11, which plots the joint probability distribution of these two parameters for each latitude bin.

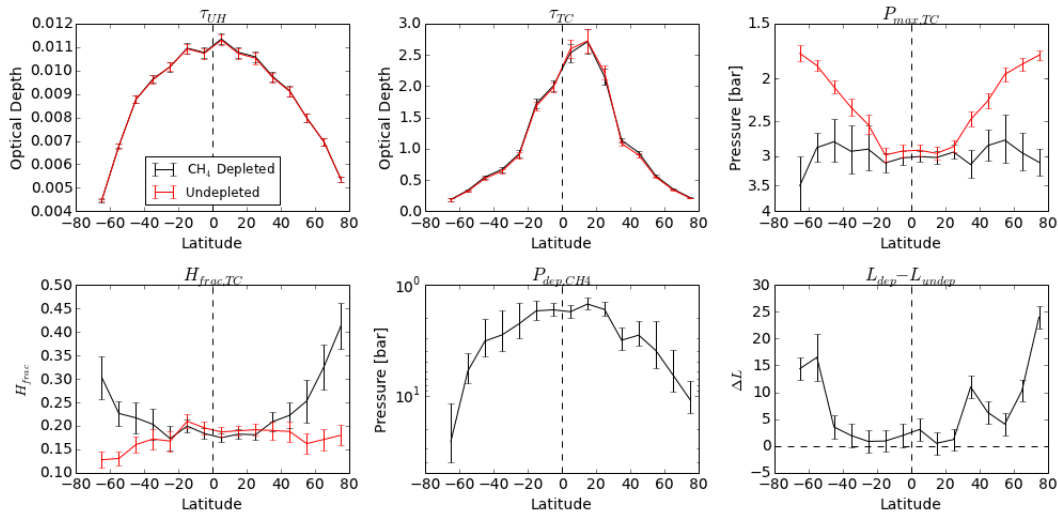


Figure 3.9: Latitudinal trends in fitted parameters for a two-cloud model, including the $1.6\text{-}\mu\text{m}$ optical depth τ for the upper haze (UH) and tropospheric cloud (TC), the fractional scale height H_{frac} and altitude of the TC, and the methane depletion depth. Results are shown with and without allowing for methane depletion, and the final plot shows the improvement to the value of the likelihood function L when depletion is allowed.

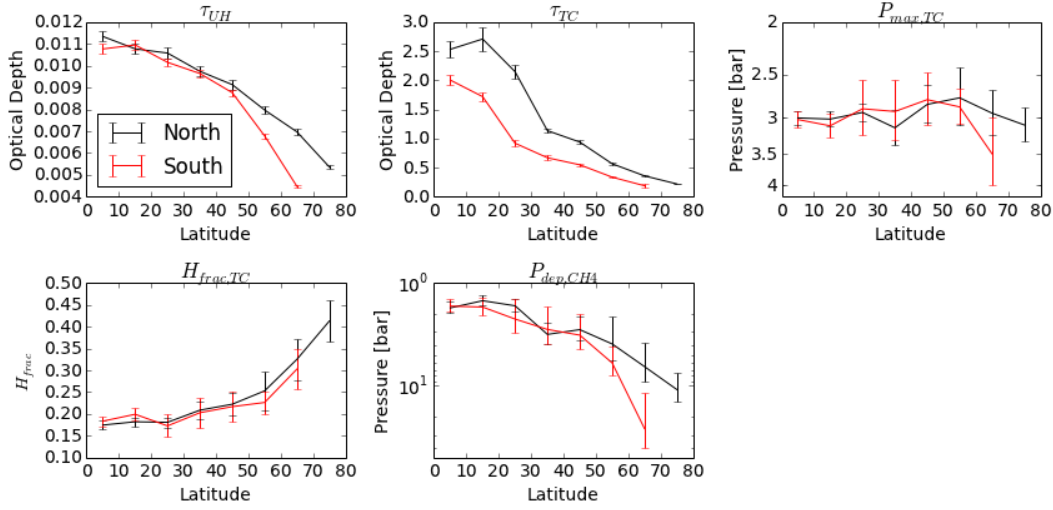


Figure 3.10: Latitudinal asymmetries: variations in fitted parameters with latitude; data are the same as the depleted-methane case presented in Figure 3.9, with northern and southern latitudes over-plotted to facilitate a comparison between hemispheres.

The optical depths of both cloud layers match between the models at all latitudes, but the location and vertical extent of the lower cloud diverge at latitudes beyond $\sim 30^\circ$ for models with and without depletion. Fits with an undepleted model for methane find that the lower cloud becomes higher, with the cloud altitude rising steeply from near 3 bars at the equator to < 2 bars by 60° . However, when we include methane depletion as a free parameter, we find that the depth of this lower cloud layer is nearly constant in latitude. While Irwin et al. (2012b) also find more methane in equatorial over polar regions, they find that the lower cloud deck still becomes higher in the atmosphere with higher latitudes even when methane relative humidity is allowed to vary.

We find that methane becomes sharply depleted to increasing depths toward the polar regions, potentially down to tens of bars within 30° of the poles. This is consistent with the recent work of Sromovsky et al. (2014), who also measure an associated poleward lowering of their $m2$ cloud layer near 1.2 bars. In the methane-depleted polar regions, the air is too dry for significant methane condensation to occur at the 1.2-bar level, except in localized upwelling regions. Because our models only extend down to 8 bars, fitted depletion depths greater than this are heavily dependent on the adopted depletion profile shape.

The broad shapes of the latitudinal trends are common between both hemispheres, but we find some significant asymmetries. Parameter values are plotted to facilitate comparison between hemispheres in Figure 3.10. Both aerosol layers have a higher opacity in the northern hemisphere than at equivalent southern latitudes, and the density of both layers peaks north of the equator: between 0 – 10° N for the upper haze and 10 – 20° N for the tropospheric cloud. The most prominent asymmetry is in the methane distribution, where we find much stronger depletion poleward of 40° in the southern hemisphere than in the north. Irwin et al. (2012b)

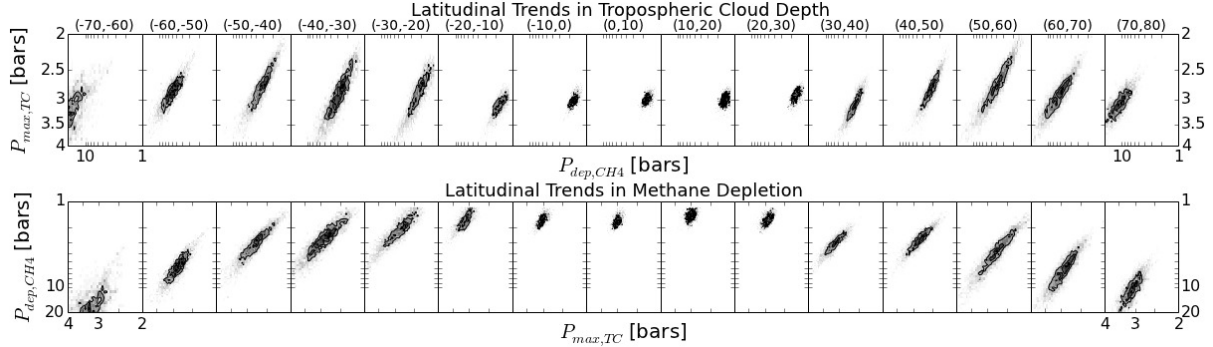


Figure 3.11: 2D probability distributions for methane depletion and tropospheric cloud depth, with 30%, 60% and 90% contours. In the top row, cloud depth is plotted against methane depletion for each latitude bin; the bottom row shows the same set of distributions with x and y axes reversed. The plot for each latitude shows the correlation between the two parameters; a greater depletion depth is correlated to a greater cloud depth, and vice versa. This is because the degree of methane depletion and the depth of the tropospheric cloud affect the spectrum in similar ways through their impact on the methane column above the cloud layer. The plots of the probability distributions as a function of latitude demonstrate that we can clearly distinguish between changes in these two parameters, despite the correlation. The top panel shows that we find no significant latitudinal changes in the tropospheric cloud depth, while the bottom panel illustrates a clear trend in the methane depletion from equator to poles.

also find a greater methane enrichment in the northern hemisphere in 2010, as do Tice et al. (2013), who find the maximum methane enrichment center at $4 \pm 2^\circ\text{S}$, noting that this is nearly 10° north of the enrichment found by Karkoschka and Tomasko (2009), which they suggest may be a real and seasonal change. Our data, taken one year after those used by Tice et al. (2013), find a greater enrichment of methane in the northern hemisphere with a peak enrichment just north of the equator, consistent with this trend.

The region near 45°N is characterized by a denser and higher tropospheric cloud, and a significantly less depleted methane profile, than the surrounding regions. These effects may also be present at the circumpolar zone at 45°S but on a much smaller scale. In the northern region, we find a potential reversal of these trends in the latitude band just equatorward of the bright band. We show a zoom-in of this reversal in Figure 3.12, where we have subtracted out a straight line through the parameter values as a function of latitude in the $25\text{--}65^\circ\text{N}$ region to accentuate these variations.

The higher opacities and methane abundance in the northern hemisphere over the south, and in the northern circumpolar band in particular, are also consistent with other post-equinox observations and may represent a seasonal trend (Irwin et al., 2012b; Tice et al., 2013). Over the 2002–2012 decade surrounding the equinox, Sromovsky et al. (2014) also noted a significant darkening at mid-southern latitudes and brightening at their northern counterparts, at wavelengths probing molecular gas absorption.

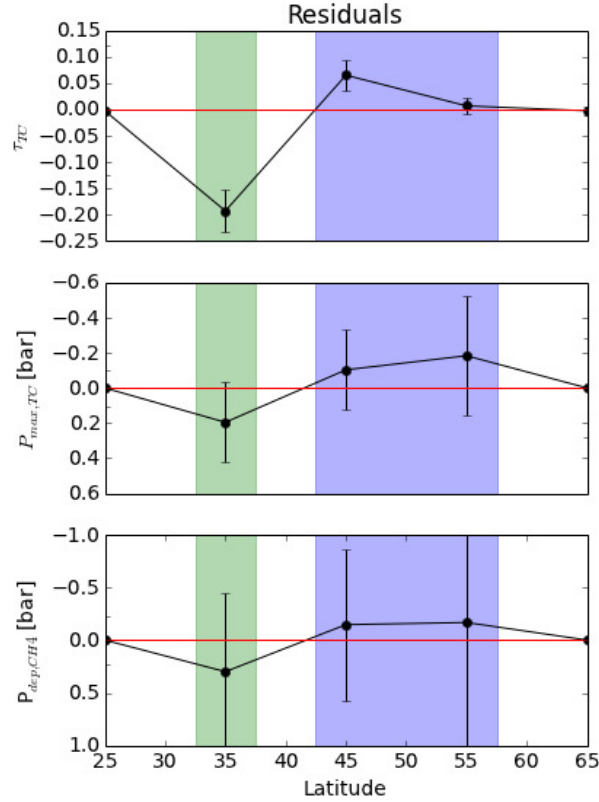


Figure 3.12: Residuals in parameter values at mid–northern latitudes from a straight line through the 25–65° region, for a model that includes methane depletion. The highlighted green and blue regions indicate where we see respectively a local minimum and maximum of bottom cloud opacity and depth, and methane abundance. While only the optical depth shows a statistically–significant deviation in this region, the matching trends in the cloud depth and methane depletion depth profiles are suggestive of a real feature at these latitudes.

As discussed in Section 3.5.1.2, there is strong evidence that the equatorial region may have a methane deep volume mixing ratio close to 4%. To test the effect of this methane abundance, which is higher than that of the D1 profile used in our fits, we duplicated the latitudinal fits with the F1 profile (4% VMR). The retrieved optical depths of the TC and UH were nearly identical across all latitudes, with the main difference arising in the depth of the TC and the degree of methane depletion. The use of the higher methane abundance raised the level of the TC from around 3 bars to closer to 2.2, while increasing the depth of high latitude depletion. The trends with latitude in all parameters remained the same. We therefore consider our results for latitudinal trends robust, with some uncertainty in the aerosol layer positions and methane depletion depth due to uncertainty in the methane profile.

3.5.3 Discrete Cloud Feature

3.5.3.1 Analysis

Unlike Neptune, which is peppered with bright, ever-changing cloud features, Uranus is relatively devoid of discrete cloud detections. While cloud activity has been repeatedly observed at Uranus’ northern mid-latitudes (e.g. Karkoschka, 1998; Sromovsky et al., 2000), the southern hemisphere beyond 45°S was thought free of cloud activity until a recent reanalysis of Voyager 2 data by Karkoschka (2015) revealed dozens of discrete features at these latitudes. Until this past year, the brightest cloud feature ever observed on Uranus was detected in 2005 with Keck II imaging and adaptive optics (Sromovsky et al., 2007b); this feature, located at mid-northern latitudes, was constrained to lie in the 300–500 mb range. In August 2014, vigorous storm activity of unprecedented brightness was seen in Uranus northern hemisphere reaching up to ~330 mbar (de Pater, et al., 2015). A long-lived bright southern feature called the “Berg” was seen to drift from mid to equatorial latitudes, rising from near 3.5 bars to around 2 bars over three years, with pieces extending as high as ~0.6 bars (de Pater et al., 2011). Recently, Sromovsky et al. (2012b) used multi-wavelength observations to constrain the depth of a bright cloud feature and its companion near 25°N to 350–600 mb and 1.0–1.3 bar, respectively.

Sromovsky et al. (2007b; 2011) argue that the position of many of the observed features so far above the 1.2-bar methane condensation level indicates that they are almost certainly composed of methane ice condensed at depth and lofted to the observed pressure levels. They postulate that this lofting could result from a deep convective event, or from local vertical displacement and condensation of atmospheric gas in the vicinity of vortex features.

In 2011 we observed a discrete cloud feature near 45°N. We extract the spectrum of this feature by calculating the reflectivity within a circular aperture centered on the feature. We find a range of aperture radii within which the choice of radius does not have a significant effect on the retrieved cloud spectrum, and choose an intermediate radius from this range for the extraction. The feature is extended, covering 50–100 pixels, and is slightly more extended in the latitudinal than the longitudinal direction.

To determine the altitude and vertical extent of this feature, we first fixed the background atmosphere at the model derived from our 2010 observations with the derived parameters for the latitude and emission angle covered by the feature. We confirm that this model provides an excellent fit to featureless regions of Uranus’ disk in the same dataset.

We model the cloud feature with single- and double-component models, where we require the feature to be composed of one or two vertically-compact ($P_{top} = 0.9P_{bottom}$) layers, and fit for the pressure level and optical depth of these layers.

3.5.3.2 Results

We find that a model with two components gives an improved fit to the spectrum of the discrete cloud feature observed in 2011 over a model with only a single component, indicating a moderate vertical extent. The single-component model finds the main cloud opacity near 0.65 bars, while the double-component finds the cloud opacity focused near 0.5 and 1.3 bars.

The atmospheric profiles and model spectra for each of these models are plotted in Figure 3.13, and the parameters are given in Table 3.4.

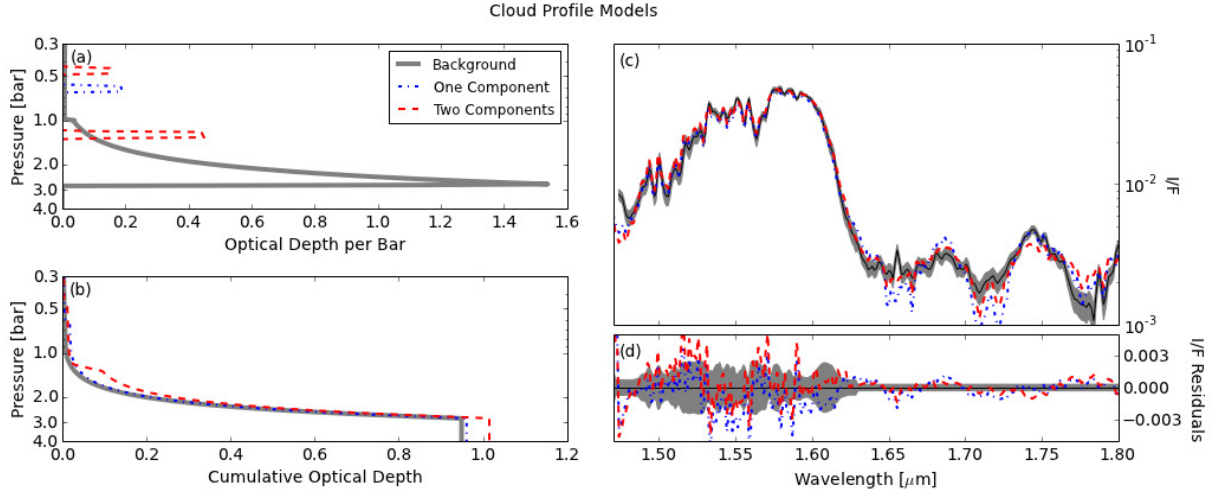


Figure 3.13: Discrete cloud feature profiles and model spectra: (a) optical depth of background model and of the cloud components in the single- and double-component models; (b) cumulative optical depth for both models plotted over that of the background; and (c & d) the corresponding model spectra and residuals. Data are shown in black, and uncertainties are represented by the shaded region.

Although our K-band OSIRIS observations of Uranus contain very low signal and we do not include them in our fits, the lack of detection of this cloud feature at these wavelengths constrains the depth of the feature. Due to the high methane absorption at these wavelengths, such observations cannot probe beneath the top ~ 1 bar of the atmosphere. Though there is no detection of the feature in our OSIRIS data, the cloud is faintly discernible in K-band Keck imaging data with the NIRC2 instrument on the same night. This suggests that the bulk of the scattering particles is located below 1.0 bar with a potential small component at higher altitudes, consistent with our results from the double-component model.

Above ~ 1.2 bars, methane is expected to be the most abundant condensible species in Uranus' atmosphere. Just below this level, where conditions do not permit methane condensation, the most likely condensation species may be H_2S (de Pater et al., 1991). With a base pressure at 1.2–1.4 bars, the vertical location of this cloud is therefore consistent with H_2S at the cloud base and methane in the upper region, with both species lofted upwards by a convective upwelling event. If the true base pressure is on the shallow end of our uncertainties, the cloud may be composed entirely of methane that condenses at the base of the cloud and is subsequently lofted upwards within the troposphere.

3.5.4 Circulation Models

Circulation models for Uranus proposed in recent years include an upwelling of methane-rich gas at low latitudes, a condensation of methane in the cooler troposphere, and descent of the now methane-depleted gas back to the deep atmosphere at high latitudes (Karkoschka and Tomasko, 2009; Sromovsky et al., 2011; Irwin et al., 2012a). This picture gives a straightforward explanation for the enrichment of methane in the upper atmosphere in the equatorial regions, but is unable to explain the existence of clouds at the depths and latitudes where they are observed.

Sromovsky et al. (2014) recently proposed a 3-layer circulation model in which the standard Hadley cell is shallow and sits on top of a counter-rotating cell at a depth of ~ 1.5 bars; they invoke a third cell below 10 bars with upwelling at low latitudes for consistency with microwave observations. In this model, the bright circumpolar bands are attributed to H_2S condensation clouds forming below 1.5 bars. However, such a model would inhibit equatorial condensation cloud formation below 1.5 bars, which is precisely where the global condensation cloud layer is inferred from spectral modeling.

Though the current models give explanations for some gross latitudinal trends, they do not explain hemispheric asymmetries, nor the particular location of the bright bands at $40\text{--}60^\circ$. Depletions down to 10 bars or more, as we find here and as have been previously indicated (Sromovsky et al., 2014), must be associated with deep circulation cells, but microwave observations have revealed a symmetric deep atmosphere (Hofstadter et al., 2003; 2007). In addition, there is an inconsistency between the deep latitudinal variations revealed by microwave observations (de Pater et al., 1989; Hofstadter et al., 2003), and models of deep depletion gradients that predict wind speeds much higher than we observe (Sromovsky et al., 2011). A more complete understanding of Uranus' atmospheric circulation is clearly needed to simultaneously explain the range of observations.

If cloud features are formed in local convective upwelling events, previous authors have noted that the asymmetries in cloud occurrence between the hemispheres may be caused by the inhibition of convective cloud formation due to methane depletion (Irwin et al., 2012b; Sromovsky et al., 2014). Though the presence of depletion in both polar regions complicates this connection, evidence for a deeper depletion in the southern hemisphere offers a possible explanation for the dearth of cloud features at high southern latitudes. If the convective events producing these clouds originate at depths greater than a few bars, the southern hemisphere may be too deeply depleted to produce clouds while the northern hemisphere may contain enough methane at these depths to form them. The cloud feature we detected, which we believe originates at a depth of around 1.3 bars, is located at a local maximum of methane abundance at 45°N .

In the region just south of the bright northern band, we detect a dip in the opacity of the bottom cloud. This appears to be accompanied by an extra-deep methane depletion and a somewhat deeper cloud depth, though the deviations in these parameters are not statistically significant (see Figure 3.12). This dip is present more strongly in the latitudinal trends derived by Irwin et al. (2012b) for observations during the same year, suggesting that it is a real feature. If the circumpolar band arises from a region of local upwelling,

this dip may indicate a region where the methane-depleted gas descends back into the deep atmosphere, suggesting a localized region of counter-circulation. Flasar et al. (1987) also suggested an upwelling at $\pm 30^\circ$ between 0.06 and 1 bars from Voyager IRIS measurements of lower temperatures at these latitudes, and Hofstadter and Butler (2003) noted that at the time the -45°S region was radio-dark, a potential indication of upwelling at depths of 5–50 bars.

3.6 Conclusions

In the following subsections, we present the analysis of high-spectral-resolution near-infrared observations of the atmosphere of Uranus. Using radiative transfer modeling, we investigate the structure and composition of the upper atmosphere at northern and southern latitudes and at the location of a discrete cloud feature.

3.6.1 Aerosol Structure

We find that models composed of extended scattering hazes and those containing compact clouds both provide a good fit to equatorial data. The best-fit cases of each model find a similar vertical profile of aerosol opacity whether this profile is composed of compact layers or diffuse hazes, and we therefore consider the vertical aerosol profile robust and not heavily model dependent given the vertical resolution of our observations. Our two-cloud model fits indicate that the lower cloud is moderately compact ($H_{frac} \sim 0.20$) while the density of the upper haze relative to the background gas increases with altitude ($H_{frac} > 1.0$). This is consistent with the scenario described by Pollack et al. (1987) where the constituents of the upper haze are photochemically produced in the upper stratosphere and subsequently descend, condensing near 0.1–10 mbar.

3.6.2 Latitudinal Trends in Aerosols

The optical depths of both layers in our two-cloud model decrease from equator to pole; the density of the lower cloud is sharply peaked at equatorial latitudes, while the upper haze exhibits a more gradual trend. The northern hemisphere has denser aerosols than the southern at equivalent latitudes, and the highest optical depth in each aerosol layer is reached north of the equator by up to 20° . Irwin et al. (2012b) also find a greater opacity in the northern hemisphere in both cloud layers in 2010, as well as a lower cloud layer that peaks north of the equator by $\sim 10^\circ$.

3.6.3 Methane Depletion

We find methane to be undepleted in the equatorial region between 20°S and 30°N , with depletion increasing with latitude to a depth of tens of bars by $\sim 60^\circ$ in both hemispheres, consistent with the recent results of Sromovsky et al. (2014). If we fix the methane profile

across all latitudes, we find that the lower cloud shifts rapidly to higher altitudes toward the poles. However, models that include a latitudinally-varying methane abundance provide a better fit to the data and find that the altitude of the lower cloud is the same at all latitudes. We find a greater methane abundance in the northern hemisphere than the southern, again consistent with the results of Irwin et al. (2012b).

3.6.4 Circumpolar Bands

In the bright zones near 45°S and 45°N , we find that the lower cloud is denser and higher than in the surrounding regions. These effects are more pronounced in the north than in the south, consistent with the observed fading of the southern band and brightening of the northern since the spring equinox in 2007 (Sromovsky et al., 2009; Irwin et al., 2012a). The methane abundance also reaches a local maximum around 45°N , an effect that we do not see in the southern hemisphere. In the northern hemisphere, we see weak evidence for an associated band near $30\text{--}45^{\circ}\text{N}$ where the aerosols are thinner and deeper and methane is particularly depleted, suggestive of a region of local counter-circulation, with upwelling near 45°N and subsequent downwelling $\sim 10^{\circ}$ to the south.

3.6.5 Cloud Feature

We determine that the cloud feature observed at mid-northern latitudes in 2011 has a moderate vertical extent, with a base around 1.3 bars and extending up to the 0.5 bar level. This structure is consistent with a scenario in which a convective upwelling event lofts particles from their condensation levels to higher altitudes, indicating a composition of methane above ~ 1.2 bars with a possible H_2S contribution at deeper altitudes.

3.6.6 Global Circulation

The asymmetries between the hemispheres, including more methane, denser aerosols, and a brighter circumpolar band in the northern hemisphere, are all consistent with previously-noted seasonal trends as solar illumination falls increasingly on northern latitudes (Irwin et al., 2012a; Sromovsky et al., 2014).

The polar depletion in methane, and the accompanying decrease in aerosol optical depth, are consistent with polar downwelling down to at least a few bars. However, it is difficult to simultaneously explain the peak in aerosol opacity and methane abundance near the equator with the presence of the bright bands and cloud features at high latitudes. A better understanding of the compositions and mechanisms producing these different features would yield insight into the global dynamics at work throughout Uranus' upper atmosphere. Obtaining this information requires more observations of the Uranian atmosphere at wavelengths that probe multiple altitudes and over a longer timeline; such data would place additional constraints on models, and bring us closer to a circulation model that is consistent with the full set of observations.

Table 3.2: Atmospheric Structure Model Parameters

	Model 2C	Model DH	Model MDH
<i>Upper Haze</i>	Optical Depth	Free	Free
	Bottom Pressure [bars]	Fixed at 1.0	Fixed at 0.1
	Top Pressure [bars]	None	None
	Fractional Scale Height	Fixed at 1.5	Fixed at 1.0
	Mean Particle Size [μm]	Fixed at 0.1	Fixed at 0.1
<i>Upper Middle Haze</i>	Optical Depth	Free	Free
	Bottom Pressure [bars]	Fixed at 1.2	Fixed at 1.2
	Top Pressure [bars]	Fixed at 0.1	Fixed at 0.1
	Fractional Scale Height	Fixed at 1.0	Fixed at 1.0
	Mean Particle Size [μm]	Fixed at 0.6, 0.8, 1.0 or 1.2	Fixed at 0.6, 0.8, 1.0 or 1.2
<i>Lower Middle Haze</i>	Optical Depth	Free	Free
	Bottom Pressure [bars]	Fixed at 2.0	Fixed at 2.0
	Top Pressure [bars]	Fixed at 1.2	Fixed at 1.2
	Fractional Scale Height	Fixed at 1.0	Fixed at 1.0
	Mean Particle Size [μm]	Fixed at 0.6, 0.8, 1.0 or 1.2	Fixed at 0.6, 0.8, 1.0 or 1.2
<i>Lower Cloud</i>	Optical Depth	Free	Free
	Bottom Pressure [bars]	None	Free
	Top Pressure [bars]	Fixed at 1.0	Fixed at 0.9* P_{bottom}
	Fractional Scale Height	Free	Fixed at 1.0
	Mean Particle Size [μm]	Fixed at 0.6, 0.8, 1.0 or 1.2	Fixed at 0.6, 0.8, 1.0 or 1.2

Table 3.3: Two-Cloud Model Parameters at all Latitudes

Latitude [°]	τ_{UH}	τ_{TC}	$P_{max,TC}$ [bar]	$H_{frac,TC}$	P_{dep,CH_4} [bar]
-70 to -60	$0.00447 \pm 7e-05$	0.19 ± 0.03	3.5 ± 0.5	0.30 ± 0.05	26^{+11}_{-18}
-60 to -50	0.0068 ± 0.0001	0.34 ± 0.02	2.9 ± 0.2	0.23 ± 0.03	$6.0^{+2.0}_{-2.0}$
-50 to -40	0.0088 ± 0.0002	0.55 ± 0.03	2.8 ± 0.3	0.22 ± 0.03	$3.2^{+1.0}_{-1.0}$
-40 to -30	0.0096 ± 0.0002	0.67 ± 0.04	2.9 ± 0.4	0.20 ± 0.03	$2.8^{+0.9}_{-1.0}$
-30 to -20	0.0102 ± 0.0002	0.92 ± 0.06	2.9 ± 0.3	0.17 ± 0.03	$2.2^{+0.7}_{-0.9}$
-20 to -10	0.0110 ± 0.0002	1.72 ± 0.07	3.1 ± 0.2	0.20 ± 0.01	$1.7^{+0.3}_{-0.4}$
-10 to 0	0.0108 ± 0.0002	2.00 ± 0.09	3.0 ± 0.1	0.18 ± 0.01	$1.7^{+0.2}_{-0.2}$
0 to 10	0.0113 ± 0.0002	2.5 ± 0.1	3.0 ± 0.1	0.17 ± 0.01	$1.7^{+0.2}_{-0.2}$
10 to 20	0.0108 ± 0.0002	2.7 ± 0.2	3.0 ± 0.1	0.18 ± 0.01	$1.5^{+0.2}_{-0.2}$
20 to 30	0.0106 ± 0.0002	2.1 ± 0.1	2.9 ± 0.1	0.18 ± 0.01	$1.7^{+0.2}_{-0.2}$
30 to 40	0.0097 ± 0.0002	1.14 ± 0.04	3.1 ± 0.2	0.21 ± 0.02	$3.2^{+0.7}_{-0.8}$
40 to 50	0.0091 ± 0.0002	0.94 ± 0.03	2.8 ± 0.2	0.22 ± 0.03	$2.8^{+0.6}_{-0.8}$
50 to 60	0.0080 ± 0.0002	0.57 ± 0.02	2.8 ± 0.3	0.25 ± 0.05	$3.9^{+1.0}_{-2.0}$
60 to 70	0.0070 ± 0.0002	0.359 ± 0.008	2.9 ± 0.3	0.33 ± 0.05	$6.5^{+2.0}_{-3.0}$
70 to 80	0.0054 ± 0.0001	0.220 ± 0.005	3.1 ± 0.2	0.41 ± 0.05	11^{+3}_{-4}

Table 3.4: Discrete Cloud Feature Parameters

Model	Optical Depth	P_{max}
1-Component	0.0120 ± 0.0004	0.647 ± 0.006
2-Component	0.0074 ± 0.0004	0.49 ± 0.02
	0.059 ± 0.006	1.33 ± 0.10

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Part II

Io

Chapter 4

Near-Infrared Monitoring of Io & Detection of a Violent Outburst on 29 August 2013

We present initial data from our campaign to monitor Io in the near-infrared, beginning in August 2013, using 3.8- μm adaptive optics imaging at Gemini N and 2-5 μm disk-integrated spectroscopy at NASA’s IRTF. Conducted during 2013-2014, these observations were coincident with the ISAS/JAXA EXCEED mission’s continuous monitoring of the Io plasma torus and will enable the speculated effects of volcanic outgassing on the torus to be observed directly, in addition to enabling an assessment of the frequency and properties of large-scale outbursts. On 29 August 2013 we detected a powerful eruption (designated 201308C) on Io at $223.5 \pm 2.6^\circ\text{W}$, $29.1 \pm 1.8^\circ\text{N}$. Emitting between 15 and >25 TW, this event was one of the most powerful eruptions ever seen on Io and falls into the rare “outburst” class. This was the third eruption of this type seen on Io in August 2013, an unprecedented occurrence. Also unprecedented was the charting of the decay in thermal emission over the subsequent days and weeks. Modeling of the outburst spectrum places a lower bound of 1200-1300 K on the eruption temperature, and is suggestive of temperatures 1900 K or higher, typically associated with ultramafic lava composition. The eruption was likely a highly energetic, high-volume lava fountain event.

4.1 Introduction

As the only object outside Earth definitively known to host active silicate volcanism, Io provides a crucial component to our understanding of volcanic activity throughout our solar system, past and present, as well as on extrasolar planets. Since the discovery of Io’s volcanic activity by the *Voyager* spacecraft in 1979 (Morabito et al., 1979; Smith et al., 1979), observers have sought to constrain the styles and distribution of this activity from space- and ground-based observations.

Understanding volcanic activity on Io on local and global scales requires detailed ob-

servations of individual active sites over a range of timescales, as well as consistent global monitoring to characterize the distribution of activity of various styles. Volcanism on Io ranges from insulating flows and plume activity that persist for decades, to enormous lava lakes exhibiting periodic overturn behavior, to rare and short-lived fire-fountaining events (Davies 2007). The highest-energy events are termed outbursts, and are defined as events that double Io’s 4.8-5.0 μm flux (Blaney et al., 1995; Spencer & Schneider, 1996).

The dominant lava composition on Io is an outstanding question which is difficult to address without in situ measurements. However, outburst events provide rare opportunities to gain insight into this issue because the high temperatures that are observed can be diagnostic of magma composition. Magmas on Io were initially believed to be sulphur-dominated (Lunine & Stevenson, 1985), until measurements of temperatures >1000 K suggested that some events have a silicate composition like we see on Earth today (e.g. Veeder et al., 1994; Blaney et al., 1995; Davies, 1996; Spencer et al., 1997). Initial analyses of *Galileo* data by Davies et al. (1997) showed that temperatures indicative of silicate volcanism were present, and McEwen et al. (1997) demonstrated that silicate lava composition is widespread on Io. McEwen et al. (1998) were the first to show evidence for lava temperatures in excess of the liquidus temperature of basalt (1475 K), suggesting that magnesium-rich ultramafic lavas may be erupting on Io. High-energy eruptions of ultramafic composition are believed to be characteristic of the Precambrian era of Earth’s early history, when the mantle was hotter than it is today. If such eruptions are indeed taking place on Io, these events can provide an active analog for this period of Earth’s history (Matson et al., 1998).

NASA’s *Galileo* spacecraft carried out a visible and short wavelength infrared Io observation program between 1996 and 2001. Outbursts were seen by the *Galileo* Near Infrared Mapping Spectrometer (NIMS) and Solid State Imaging experiment (SSI) at Pillan (Keszthelyi et al., 2001; Davies et al., 2001), by SSI at Tvashtar Paterae (summarized by Milazzo et al., 2005), and by NIMS at $\sim 132^\circ\text{W}$, 39°N (Lopes et al., 2004), designated “Thor”. Many high-energy eruptions have also been detected from the ground with adaptive optics, including the Surt eruption in 2001 which emitted 78 TW, the highest energy ever measured for an Ionian event (Marchis et al., 2002). Howell et al. (2001) reported an extremely high-energy (63 TW) event near Gish Bar Patera. All outburst detections through 2001 are tabulated by Veeder et al. (2012); despite the extreme energies involved in individual events, they find that outburst eruption phases contribute at most $\sim 4\%$ to Io’s total thermal emission over time.

Ground-based multi-year monitoring campaigns have played an important role in characterizing Io’s volcanic activity, and in detection and analysis of outburst events. Between 1979 and 1981, Sinton et al. (1983) observed Io during 37 nights at 2.2, 3.8, and 4.8 μm in disk-integrated photometry. They detected ongoing outbursts during eight of these nights and reported decay in the 4.8- μm emission during some events over as short a timescale as a few hours. Veeder et al. (1994) monitored Io in disk-integrated photometry at 4.8, 8.7, 10, and 20 μm on 55 nights over 10 years between 1983-1993. During this period they detected two high-temperature outbursts, and determined that the likelihood of observing an outburst on any given night is roughly 4%. Spencer et al. (1997) monitored Io at 1-5 μm in disk-integrated photometry frequently from 1995-1997 and detected several events fainter

than a traditional outburst, lasting days to weeks, as well as two major outbursts. Rathbun and Spencer (2010) present ~ 100 nights of sunlight and eclipse observations over a 10-year period including observations in support of the New Horizons mission; rough spatial information is obtained from eclipse and occultation observations. During this time they detected three very bright events, which decayed over a timescale of days. They demonstrate that the sites that sustain a high level of volcanic activity over many years (e.g. Loki Patera, Kanehekili/Janus Paterae) also exhibit significant time variability.

Together these programs have yielded important statistical information on the frequency of outbursts and the variability of Io's disk-integrated thermal emission over timescales from weeks to years. No dedicated Io monitoring program to date has been conducted with the high spatial resolution provided by adaptive optics on 8-10 m telescopes, which is generally required for monitoring the activity at specific sites.

The results of these campaigns all indicate that major outburst events can appear and decay in a matter of hours to weeks, and therefore to truly characterize Io's volcanic activity requires frequent observation; even weekly monitoring will miss a sizable number of major events. Describing the eruption style of an outburst requires capturing the initial stages of the event, when the hottest temperatures are present. These timescales indicate that the initial stages may be as short-lived as a few hours, so that capturing them requires fortuitous timing.

Accurate characterization of Io's volcanic variability is particularly relevant during the period from the Fall of 2013 through the Spring of 2014. During this time, the ISAS/JAXA EXCEED (Extreme Ultraviolet Spectroscope for Exospheric Dynamics) mission onboard the SPRINT-A Earth-orbiting satellite will be continuously monitoring the Io plasma torus in the UV (Murakami et al., 2012; Ueno et al., 2011). The plasma torus is a ring of ionized material orbiting Jupiter, believed to be sourced by volcanic by-products from Io. The processes involved in the creation and evolution of the torus are not well understood, but the plasma exhibits considerable and rapid time variability. From ground-based near-infrared monitoring of Io's thermal emission, one could construct a timeline of Io's volcanic activity during the EXCEED mission; correlations between Io's thermal emission and variations in the plasma torus brightness would shed light on the mechanisms and timescales that transfer particles from Io's interior into the torus.

In support of this mission, and to continue addressing the questions surrounding Io's volcanic activity, we have initiated monitoring campaigns at the Gemini North telescope and NASA's Infrared Telescope Facility (IRTF), beginning in late August of 2013. In Section 4.2 we introduce our campaign, including general design (Section 4.2.1), outburst detection criteria (Section 4.2.2), and our techniques and preliminary data from each facility (Sections 4.2.3 & 4.2.4). In Sections 4.3 & 4.4, we present the detection and characterization of an energetic lava fountaining event that we observed from its early stages through its rapid decay over the subsequent days. We detected the event on UT 2013 August 29, and denote it 201308C as the third outburst in August 2013, following the previous events at Heno and Rarog Paterae (de Pater et al., 2014a).

4.2 Monitoring Program: Observations and Techniques

In August 2013 we began a program monitoring Io in the near-infrared in order to (1) determine the frequency and duration of volcanic outbursts; (2) understand the eruption styles of outbursts; and (3) construct a timeline of volcanic activity on Io during the time period of the EXCEED observations.

4.2.1 Program Design

Addressing these goals requires frequent monitoring at multiple near-infrared wavelengths. Constructing a timeline of volcanic activity and determining the outburst frequency require observations spaced close enough to give a statistical sample of volcanic activity of different scales, while evaluating outburst duration requires multiple observations over the course of a single outburst, which may be as short-lived as a few hours or days. Constraining eruption style requires an estimate of temperature and areal coverage, which relies on spectroscopic information, while placing the physical location of the volcanic site requires the high spatial resolution that on ground-based instruments is only provided by adaptive optics on 8-10 m telescopes. Additionally, as outbursts can evolve significantly on a timescale of hours, there is usually only a single opportunity to observe the most violent and high-temperature phase of the outburst, so traditional follow-up observations cannot be relied on to obtain this information.

Ideally we would observe Io nightly with high spatial and spectral resolution in order to simultaneously determine the locations of all active volcanic sites and estimate the associated temperatures and areas. Our goal in designing our monitoring program was to permit frequent observation by minimizing the amount of time spent on any given night, while simultaneously ensuring that we will have the basic information needed to constrain the location and energy of an outburst in the event of a detection.

Following these objectives, we have been observing Io with both the Gemini North telescope and NASA's IRTF since August 2013. With Gemini N we use the Near-Infrared Imager (NIRI; described in Section 4.2.3) with adaptive optics system ALTAIR to image Io in L'-band; the use of adaptive optics allows us to constrain the locations of active hot spots to within a few degrees in latitude and longitude. We bootstrap flux calibrations from previous data (see Section 4.2.3), eliminating the need for standard star observations so that a single observation requires less than 20 minutes of telescope time. With NASA's IRTF we use the SpeX instrument to obtain a disk-integrated spectrum of Io between 2.1-5.0 μm . In Section 4.2.4 we demonstrate that a volcanic outburst is unambiguously detected even in a disk-integrated spectrum, constraining the temperature of the event. While the SpeX observations lack the resolution to identify the location of an outburst, they indicate which hemisphere the event occurred on and can inform follow-up observations with adaptive optics. We have developed outburst-detection criteria specific to our SpeX observations that rely on the shape of Io's spectrum rather than the absolute flux density (see Section 4.2.4).

This eliminates the need for a photometric standard star, though we do require observations of a bright star for telluric correction, and a single observation requires ~ 30 minutes of telescope time.

In the following sections, we describe the reasoning behind the criteria used to decide whether there is an outburst occurring on Io, demonstrate the techniques used in our monitoring program on both facilities, and discuss our reduction and calibration procedures. Our first four SpeX observations were coincident with Gemini N observations, allowing us to calibrate our interpretation of these and subsequent spectra.

4.2.2 Outburst Identification Criteria

An outburst on Io is typically defined as an event that doubles Io’s 4.8-5.0 μm flux (Blaney et al., 1995; Spencer & Schneider, 1996). Io’s typical 5- μm flux is dominated by reflected sunlight with a small but measurable component from thermal emission, so that an outburst can be thought of as a single event whose 5- μm thermal emission matches or exceeds the reflected sunlight from the entire disk at this wavelength. As neither of our observing campaigns measure Io’s absolute 5- μm flux density, we develop criteria based on this definition that are measurable by our program.

Our IRTF outburst criterion relies only on the shape of Io’s 2-5 μm spectrum. Moving longward from 2.1 μm , Io’s spectrum transitions from being heavily dominated by reflected sunlight at short wavelengths, to being strongly impacted by time-variable thermal emission from volcanic activity at wavelengths towards 5 μm , as was demonstrated by Veeder et al. (1994). The thermal emission from eruptions in the 600-1200 K range characteristic of volcanic events on Io peaks between 2.4-4.8 μm ; such emission has a much higher fractional impact on the longer-wavelength regime, where reflected sunlight is less dominating. To quantify the impact of an outburst on the shape of Io’s spectrum, we look at the relative brightness of Io between characteristic short- and long-wavelength regions of the spectrum. At longer wavelengths, the shape of the 3.7-4.2 μm region is dominated by SO_2 frost absorption, and varies as a function of longitude based on the distribution of frost (Carlson et al., 1997; Douté et al., 2001). We thus choose the 4.8-5.0 μm window as an indicator of long-wavelength brightness. For the short-wavelength window, we find that the 2.3-2.4 μm region has the lowest night-to-night fractional brightness variability. We define a 5- $\mu\text{m}/2\text{-}\mu\text{m}$ flux ratio as the ratio between the median values in these two spectral windows. Even though the 2.3-2.4 μm window is the least variable of the 2-5 μm range, Io’s hemisphere-integrated albedo still varies as a function of longitude by a few percent at 2.2 μm due to the distribution of SO_2 frost (de Pater et al., 2014b); we therefore expect night-to-night variability at this level. We note that a very hot eruption would increase Io’s flux at both short and long wavelengths, so that an event that doubles Io’s 5- μm flux would not necessarily be expected to double the 5- $\mu\text{m}/2\text{-}\mu\text{m}$ flux ratio.

We determine outburst identification criteria based on the 5- $\mu\text{m}/2\text{-}\mu\text{m}$ flux ratio for the IRTF observations, and based on the L’-band flux density for the Gemini observations. We create these criteria to be consistent with the standard outburst definition, via model Io spectra for a range of activity levels, including the cases of no volcanic activity, moderate

activity, and ongoing outbursts at representative temperatures of 1000 K, 1250 K, and 1500 K over emitting regions scaled to double Io's disk-integrated $5\text{-}\mu\text{m}$ flux. All models include reflected sunlight and a 150 K surface. From these models we read off the $5\text{-}\mu\text{m}/2\text{-}\mu\text{m}$ flux ratios, and the L'-band flux density, and identify values for these two metrics that indicate an outburst. Our models are plotted in Figure 4.1, and the flux densities at $5\text{ }\mu\text{m}$ and L' as well as the $5\text{-}\mu\text{m}/2\text{-}\mu\text{m}$ ratio are tabulated for each model in Table 4.1. Based on this information, we determine the following criteria for outburst detection: an L'-band flux density above 500 $\text{GW}/\mu\text{m}/\text{sr}$ for thermal emission from a single volcanic site, or a disk-integrated $5\text{-}\mu\text{m}/2\text{-}\mu\text{m}$ flux density ratio above 0.1. In Section 4.3.4 we discuss the values of these metrics for the observations presented in this paper, and confirm that they correctly indicate the presence or absence of an outburst.

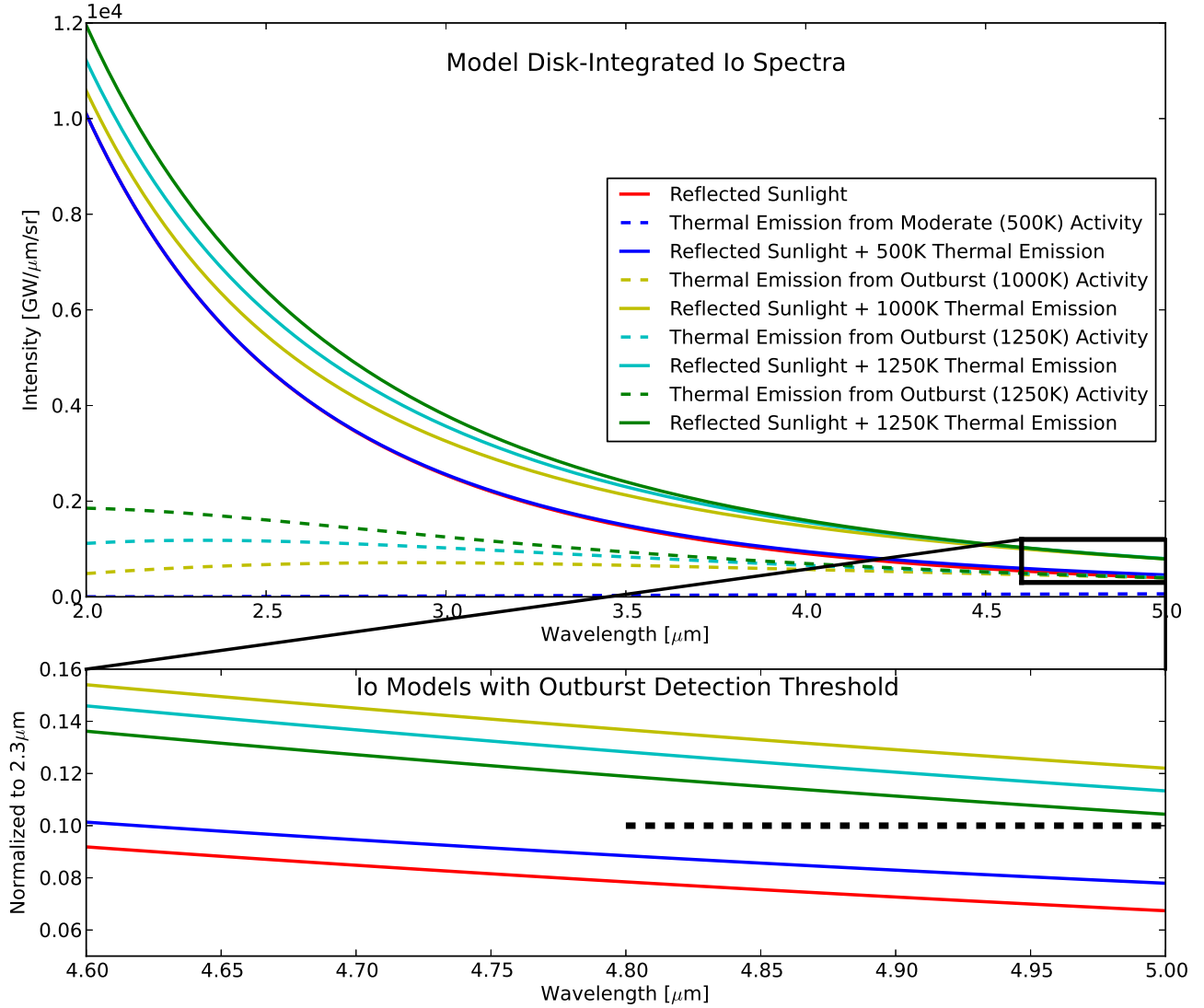


Figure 4.1: Model Io Spectra with Outburst Activity (Top) Model disk-integrated spectra of Io with reflected sunlight and a 150K surface, including volcanic activity at 500K for the Moderate case, and 1000K, 1250K, and 1500K for the Outburst cases. A zoom-in of the boxed region is shown below. (Bottom) A close-up view of the model Io spectra in the long wavelength region scaled to the $2.3\mu\text{m}$ window to indicate the $5\mu\text{m}/2\mu\text{m}$ flux ratio; spectra above the dashed line are indicative of ongoing outbursts, demonstrating the successful identification of model spectra via our criteria.

4.2.3 Gemini Monitoring

We use the Near-Infrared Imager (NIRI; Hodapp et al., 2003) combined with the ALTAIR adaptive optics system on the Gemini North telescope to monitor Io at high spatial resolution. The detector is a 1024x1024 ALADDIN InSb array, which we use with the f/32 camera for a platescale of $0.022''/\text{pixel}$, corresponding to ~ 45 pixels across the disk of Io, or 80 km/pixel at disk center. Our spatial resolution, defined as the full width at half maximum of the point spread function, is generally 4-5 pixels, or $\sim 0.1''$. We observe in natural guide star mode, using Io itself for wavefront sensing. We image Io briefly in reflected sunlight at nine different detector locations with the L' filter, which has a central wavelength of $3.78 \mu\text{m}$ and covers the $3.43\text{--}4.13 \mu\text{m}$ range. Standard reduction procedures are applied, including flat-fielding and bad pixel removal, and a sky frame produced by median-averaging the images is subtracted from the data. The nine images are then aligned and median-averaged to produce a final image for each night.

To permit observations on non-photometric nights and to eliminate time-consuming photometric star observations, we bootstrap flux calibrations from calibrated data (published in de Pater et al., 2014b) at a matching viewing geometry from the NIRC2 instrument on the W.M. Keck telescope based on regions of Io's disc with low volcanic activity. Although the emission from volcanically-active regions is highly time-variable, the reflected sunlight from non-active areas is relatively constant in time.

Our flux-calibration procedure involves selecting a non-active region of Io's disk in our data and in the calibration images, and scaling the data by the ratio of measured flux densities, accounting for the changing geocentric and heliocentric distance of Io. These calibrations are complicated by the fact that no region on Io is fully free of low-level volcanic activity, nor from the wings of the point-spread functions from nearby events. We therefore repeat this procedure with a range of sizes and positions for the calibration region, and adopt the median measurement of the ratio for our flux calibration and the standard deviation of the measurements as our flux calibration uncertainty. Based on our initial observations, we find a calibration uncertainty of 5-10% depending on the level of volcanic activity on a given night, with a typical uncertainty of 6%. Figure 4.2 shows the calibrated L'-band images from eleven nights of observation in August and September of 2013, and the details of these observations are listed in Table 4.2.

From the flux-calibrated images, we estimate the flux density of individual hot spots via aperture photometry, using a compact aperture to mitigate contamination from the reflected-sunlight background and from other hot spots on the disk. We then correct for flux lost to the wings of the point-spread function (PSF) by applying the same aperture and background radius to stellar observations and determining the fraction of total flux recovered, following the procedure of Gibbard et al. (2005). We observe a standard star only every ~ 10 nights of observation for PSF estimation. The use of adaptive optics stabilizes the PSF by minimizing the effects of atmospheric variability, but we may still expect it to exhibit minor variation from night to night. To quantify the uncertainty introduced by this, we apply the flux-correction procedure based on stars observed on a few different nights with different observing conditions, and evaluate the spread of correction factors derived. The

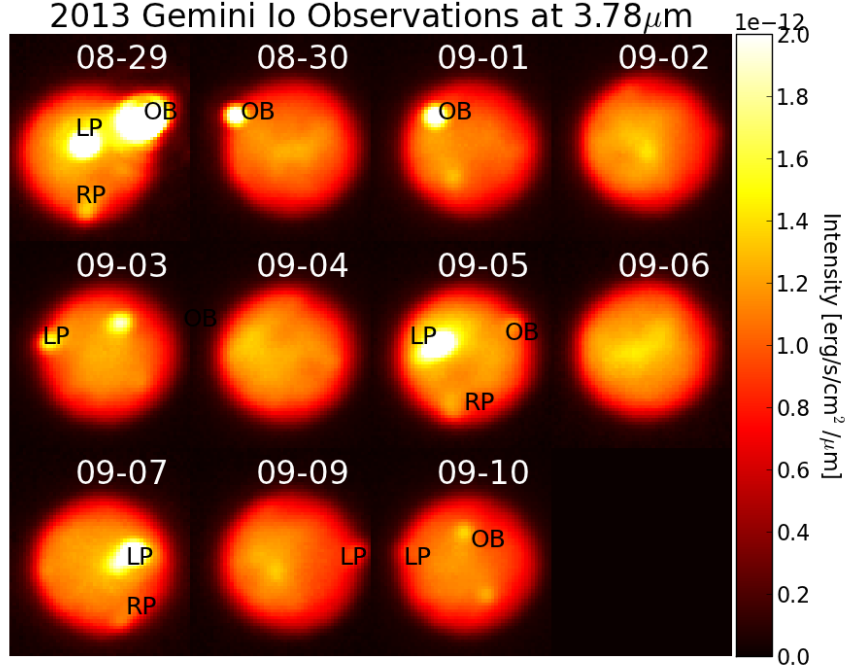


Figure 4.2: Observations of Io in 2013 with adaptive optics on Gemini N at $3.8\mu\text{m}$ (L'). The outburst (OB), Loki Patera (LP), and Rarog Patera (RP) are indicated, and images are rotated so that Io’s north pole points upwards.

uncertainties depend on aperture radius chosen, but are typically of order 10-20%. After correcting for PSF losses in this way, the flux density derived for a given hot spot has almost no dependence on which aperture radius is chosen, and we therefore consider the correction robust. The final uncertainties on our measured hot spot flux densities are the quadrature sum of our basic flux calibration errors and the errors in the PSF flux loss correction factor.

We are interested in knowing, in addition to flux densities, the exact latitude and longitude of each individual hot spot in order to place it in the context of activity at that site over time. Hot spot locations are determined by fitting a 2D gaussian to each spot, and then mapping the fitted location to its position on a map derived by de-projecting the image based on the sub-observer latitude and longitude and the north polar position angle during observation¹. This mapping depends on a determination of the position of the center of Io’s disk; we estimate this to be accurate to slightly better than half a pixel. The uncertainties on our calculated latitudes and longitudes are based on a position uncertainty of 0.5 pixels, and are higher for sources closer to the limb. The positions and L' -band flux densities for hot

¹ssd.jpl.nasa.gov/horizons

spots observed with Gemini N in 2013 between 29 Aug and 10 Sep are presented in Table 4.3.

4.2.4 IRTF SpeX Monitoring

We use the SpeX near-infrared spectrometer on NASA’s IRTF (Rayner et al., 2003) in spectroscopic mode to monitor Io. We use a 1.6” slit to cover Io completely, and observe in low-resolution mode ($R \sim 2000$) covering 2.1-5.0 μm . We observe Io and a nearby bright star for telluric correction and dither both targets along the slit for sky-subtraction. Calibrations utilize the SpeX standard calibration macros, which obtain flat fields as well as arc lamp spectra for wavelength calibration. We use procedures from the data reduction tool package Spextool (Cushing et al., 2004) for reduction, wavelength calibration, and spectral extraction for the star and Io. Median spectra of the star and Io are constructed for each night, and errors on these spectra are derived based on the spread in the individual spectra that are combined into each median spectrum, after identification and removal of integrations with anomalously low signal due to occasional guiding errors where the target has drifted off the slit. The dates and times of our first four nights of observation are given in Table 4.2. Figure 4.3 shows raw extracted spectra for these nights in Panel a, and illustrates the various stages of data calibration in the subsequent panels.

Following extraction of the target spectra, the bandpass in each echelle order is extracted from the flat fields, and the target spectra are corrected for echelle blaze² (Panel b). The spectra are then binned to a constant $\Delta\lambda/\lambda$ interval accounting for spectral regions covered by two echelle orders, and regions of high telluric absorption are removed (Panel c). We then correct for moderate telluric absorption via a bright nearby star and account for the difference in airmass between the star and Io using the extinction parameters tabulated by Tokunaga et al. (2002) for the Mauna Kea site (Panels d & e). The agreement between spectra taken on the latter three nights is demonstrated in Panel e. Discrepancies are more significant in spectral regions of higher atmospheric absorption, due primarily to an imperfect atmospheric correction. Panel f shows the same spectra in units of I/F, and Panel g shows the spectra after flux calibrating based on simultaneous Gemini observations, as described below. The high signal in the August 29 spectrum is due to the volcanic outburst described in Section 4.3.1; the slightly higher signal in the September 5 spectrum is due to emission from Loki Patera, which was particularly bright on this night.

The observations of Io are corrected for its changing geocentric distance prior to comparison with one another. Because our observations were closely spaced in time, the heliocentric distance did not vary enough between observations to have a significant effect on the spectra and is therefore neglected.

We estimate the fraction of flux from the targets lost to the regions of the PSF falling outside of the slit by observing Io and our telluric star with both 1.6” and 3.0” slits. We find that while the larger slit increases the retrieved flux density of each source by $\sim 10\%$, it only

²In an Echelle spectrograph, the observed spectral window is dispersed into multiple different orders which fall onto different regions of the detector and therefore must be corrected individually. (Michelson, 1898)

affects the tellurically-corrected Io spectrum by $<1\%$ at all wavelengths, and we therefore do not apply any slit loss correction.

The observations on 2013 August 29 & 30 and September 3 & 5 were simultaneous with adaptive optics observations with Gemini N at $3.78\ \mu\text{m}$ (L'), and we are therefore able to flux-calibrate the spectra on these dates by scaling them to match the Gemini photometry over the bandpass of this filter. Absolute flux calibration is not done on other nights since we do not observe a photometric standard star. This shortens our total observation time significantly because standard stars with recorded magnitudes out to $5\ \mu\text{m}$ are rare and generally too faint and far from our target to also be used for telluric correction.

We investigate whether the SpeX instrument introduces a bias into our spectra using calibrated images of Io taken with the SpeX guiding camera in the K and M' wideband filters centered at 2.2 and $4.7\ \mu\text{m}$ respectively, and the Long6 narrowband filter at $3.3\ \mu\text{m}$. We compare the flux densities derived from the images with the flux densities of the calibrated spectra over the bandpasses of the filters ($2.03\text{-}2.36\ \mu\text{m}$ for K; $4.56\text{-}4.80\ \mu\text{m}$ for M'). The agreement is at the 5% level; we add this uncertainty in quadrature into our error bars on the flux-calibrated spectra.

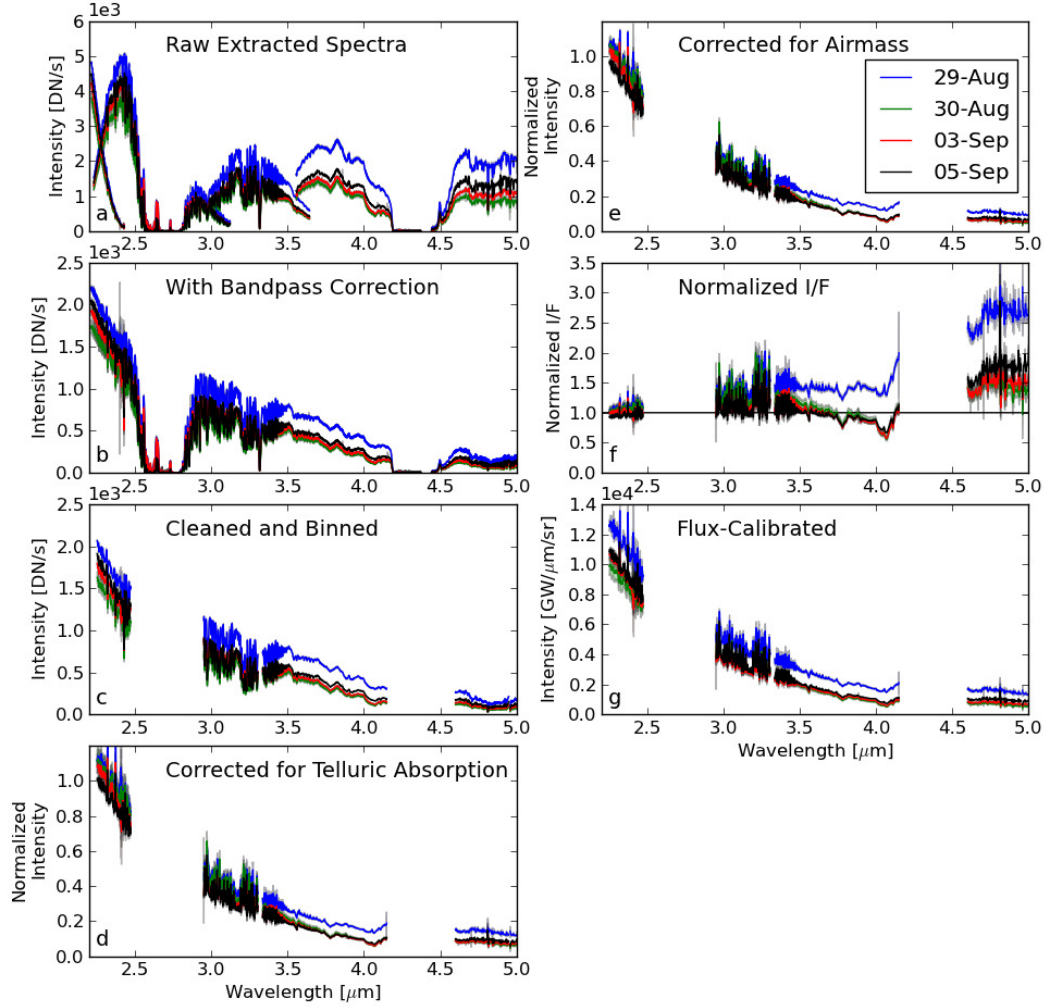


Figure 4.3: SpeX observations of Io on four different dates at successive stages of reduction and calibration, to demonstrate our procedures: (a) Io spectra extracted via standard methods, (b) after bandpass correction in each of six echelle orders, (c) with binning and high-atmospheric-absorption regions removed (d) after telluric correction by a standard star, (e) after telluric correction where an airmass correction has been applied to the star and Io, (f) in I/F, and (g) flux-calibrated to $3.8\mu\text{m}$ based on simultaneously Gemini observations. Note that on August 29 an outburst was occurring, and on September 5 Loki Patera was particularly bright; these events are reflected in the relative magnitudes of the spectra.

4.3 Results: Activity at Volcanic Sites

4.3.1 201308C

On UT 29 August 2013, we detected a high-energy outburst (denoted 201308C) while observing Io simultaneously with ALTAIR/NIRI at Gemini N and SpeX at the IRTF. The timing was fortuitous: the simultaneous observations were planned as part of a follow-up program observing the outbursts at Heno and Rarog Paterae detected on August 15 (de Pater et al., 2014a).

Following the initial detection on August 29, three subsequent observations were made with the same two instruments together, followed by observations of the eruption on several nights with Gemini N alone. The number and frequency of our observations give us an unprecedented timeline of the evolution of a major volcanic event on Io on a timescale of days to weeks. The spectroscopic observations on the night of the detection provide constraints on the highest temperatures present during the initial stages of this violent eruption. The simultaneous Gemini N observations allow us to confirm the existence of the outburst, flux-calibrate the spectrum, and derive the areal coverage of the emitting region, as well as fix the position of the event on Io’s surface. The observations of de Pater et al. (2014a) on August 20 did not show activity at the site of the outburst, indicating that we are indeed seeing the event in its early stages.

4.3.1.1 Flux Densities and Outburst Evolution

After the initial detection of the outburst on UT Aug 29, we observed the outburst site again on Aug 30 and Sep 1, 3, and 10 with adaptive optics and 3.8- μm imaging at Gemini N and extracted the flux density of the site on each night via the method described in Section 4.2.3. The results are tabulated in Table 4.3 and plotted in Figure 4.4. For the initial outburst observation, we find a 3.8- μm flux density of $\sim 700 \text{ GW}/\mu\text{m}/\text{sr}$, which had dropped off to $\sim 10 \text{ GW}/\mu\text{m}/\text{sr}$ by Sep 10 less than two weeks later.

For observations of a flat target on the surface, such as a lava flow or lava lake, one must correct the detected flux density by the cosine of the emission angle to obtain the physical emitted flux. However, such a correction may not be appropriate for emitting material launched into the air, where the visible area is not diminished by viewing geometry. Such is the case for violent lava fountaining, which we believe is occurring in the 201308C event; though the first two observations of this event were on Io’s limb, we do not make an emission angle correction. We note that while the short-wavelength region of the spectrum is dominated by the high temperature erupting lava, the longer-wavelength component is more heavily affected by the lava flow component, whose detected flux density is sensitive to the emission angle and may therefore be severely diminished by the near-limb geometry. As a result, our detected thermal emission spectrum may be biased towards the shorter wavelengths relative to the physical emission.

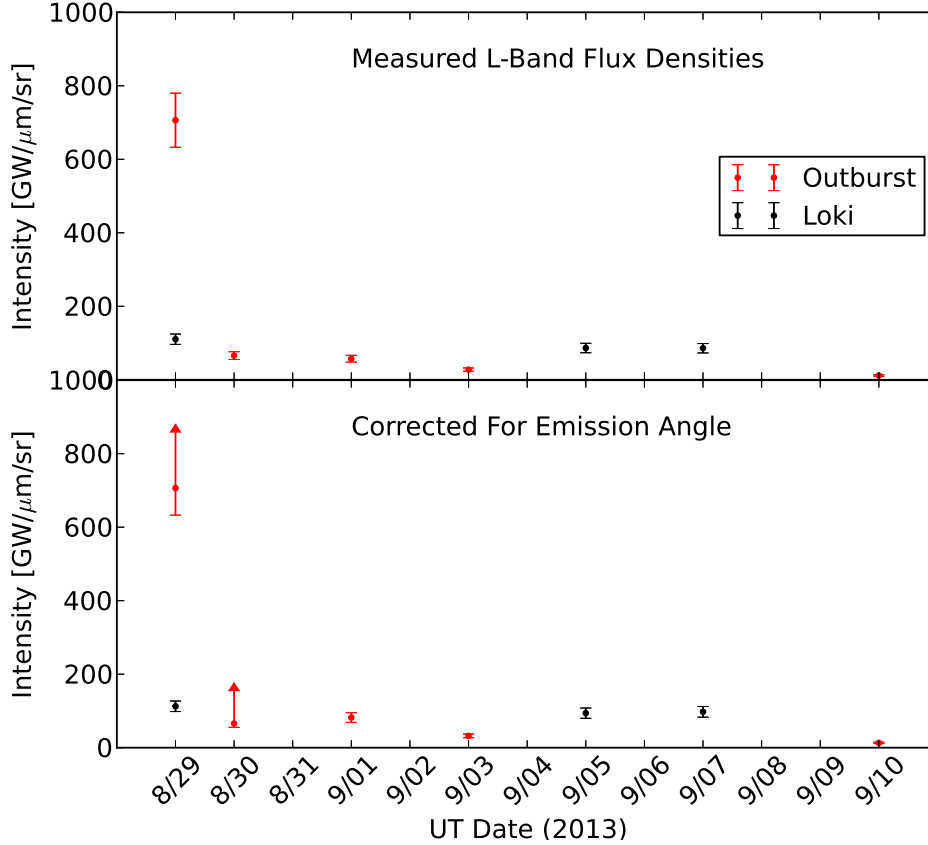


Figure 4.4: L-band ($3.78\mu\text{m}$) flux densities as a function of time for the outburst and Loki Patera, before and after an emission angle correction. The first two outburst observations are shown as lower limits because they were too close to Io’s limb to make a good estimate of emission angle.

4.3.1.2 Temperature and Area Models

We calculated temperatures and areal coverages for the outburst on August 29 from our IRTF spectra. As seen in the spatially-resolved Gemini images (Figure 4.2), both Loki Patera and the outburst were active on the disk on this night, and the thermal emission from both sites contribute to Io’s disk-integrated thermal emission. To extract the thermal emission from the outburst alone, and to remove the reflected-sunlight component of the spectrum, we subtract the flux-calibrated spectrum of Io on September 5, when Loki Patera was visible and still highly active but when the outburst had subsided considerably; the resultant spectrum is shown in Figure 4.5. The extraction of the outburst spectrum from a disk-integrated observation was made possible by the simultaneous adaptive optics Gemini images, which provide flux calibration and enable us to confirm that no volcanic sites changed significantly between the two subtracted observations. We do not account for any change

in thermal emission from Loki Patera between these dates; our Gemini observations are consistent with a constant L'-band emission from Loki Patera between the two observations (see Table 4.3), and the change in L'-band emission using our best-fit values is below 3% of the total thermal emission. As Loki Patera is a relatively low-temperature source, its emission at 2-3 μm is minimal, and neglecting any change in its thermal emission does not impact the peak temperatures we measure for the outburst.

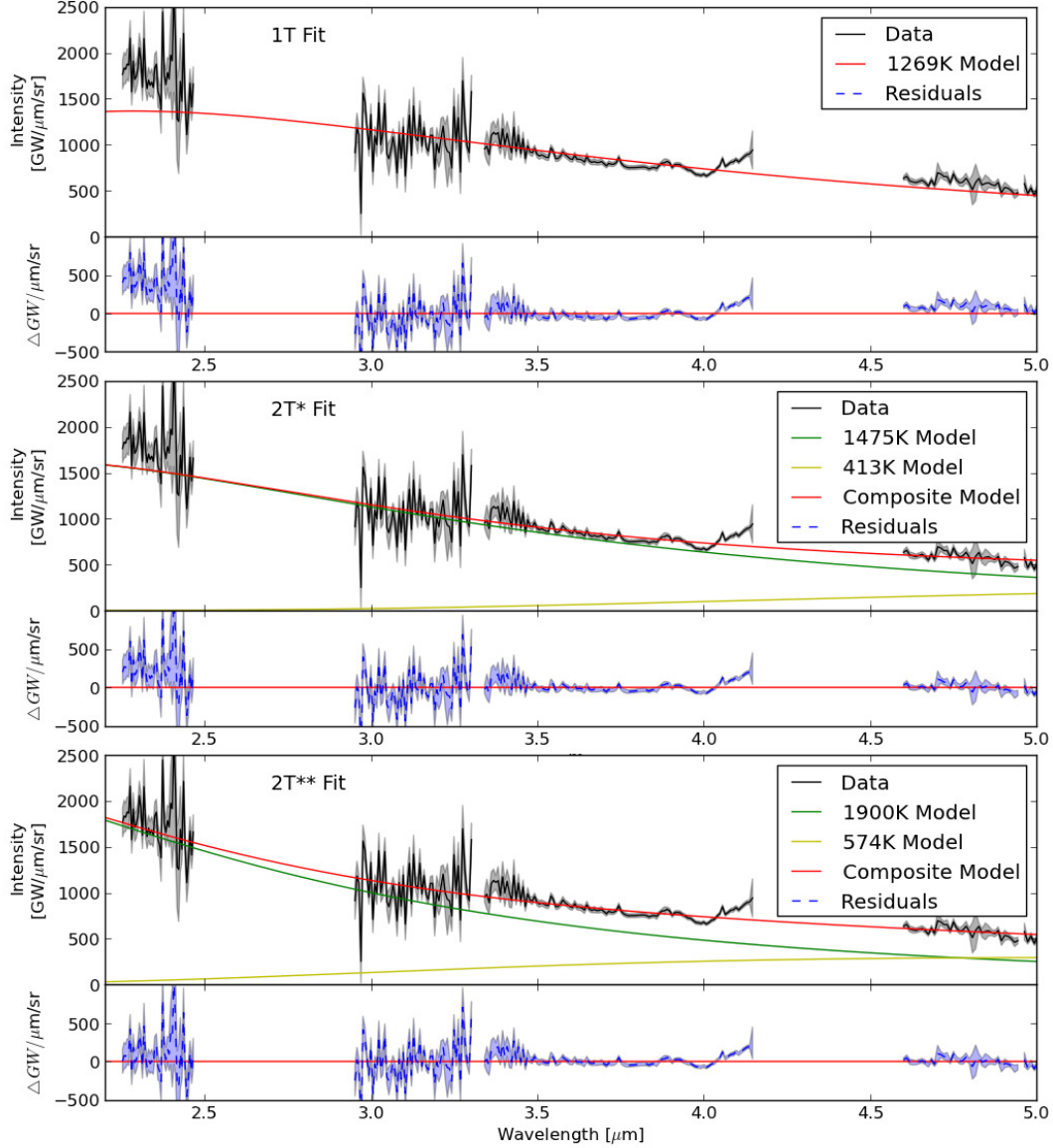


Figure 4.5: Thermal emission IRTF spectrum of the August 29 outburst with models over-plotted. The 1T fit displays a single-temperature fit to the data, and the bottom two panels show two-temperature fits where the upper temperature is fixed at 1475 K (2T*) and 1900 K (2T**)

We use an MCMC simulation to determine the temperatures and associated emitting areas in blackbody models with both one and two temperature components. The likelihood function maximized by the MCMC algorithm is based on the χ^2 statistic, where we define χ^2 as

$$\chi^2 = \sum_i \frac{(f_i - f_{mi})^2}{\sigma_i^2} \quad (4.1)$$

where f_i is the i th data point, f_{mi} is the i th model point, and σ_i is the uncertainty on the i th data point. We fit single-temperature (1T) models with a range of temperatures, leaving emitting area as a free parameter, and two-temperature (2T) models with a grid of temperatures, allowing the emitting areas for both components to vary freely. The best-fit parameter values and $1-\sigma$ uncertainties are calculated from the MCMC simulation, and represent the peak and 68th percentile of the posterior distribution. For each model we calculate a reduced χ^2 value (Avni, 1976), defined as

$$\hat{\chi}^2 = \chi^2/n, \quad (4.2)$$

where χ^2 is defined in Equation 4.1 and n is the number of degrees of freedom, or the number of data points minus the number of input parameters in a given model. Our models have between 1-3 free parameters, while the number of data points is ~ 300 ; the value of n is therefore essentially constant between models. We additionally calculate the Kolmogorov-Smirnov (K-S) statistic for each model, which finds the distance of the distribution of residuals from a Gaussian distribution. The distribution of residuals is generally Gaussian in shape for each model, with a possible tail to one side. This statistic therefore allows us to investigate whether the largest deviations occur symmetrically or preferentially to one side.

For the 201308C outburst, the values of $\hat{\chi}^2$ for a range of temperatures are shown for both models in Figure 4.6. Our 1T fits strongly prefer a temperature near 1270 K; the best-fit model is shown in Figure 4.5. For the 2T fits, the best fits are found for models with an upper temperature above 1700 K. However, as demonstrated in Figure 4.6, our data are not able to discriminate well between temperatures above this value. The spectra for eruptions with temperatures beyond this value peak short of $2 \mu\text{m}$, the lower end of our observing range; models with higher temperatures can fit the data equally well when the emitting area is allowed to vary. We examine the $\hat{\chi}^2$ and K-S contours in parameter space, and estimate a lower temperature limit based on the outermost contour that follows the shape of the minimum value surface. These contours are highlighted in Figure 4.6; based on this metric, we find a lower limit on the eruption temperature of 1200-1300 K.

In general, a 2T model is able to fit the outburst spectrum much better than a 1T model. The 2T scenario is also more representative of lava fountains observed on Earth, where a high-temperature erupting component and a lower-temperature flow are both present.

We investigate in more detail the particular cases that represent physical scenarios on Io. If lava of a basaltic composition is erupting and has not had time to cool, we would expect an upper temperature of 1475 K, the liquidus temperature of basalt. Similarly, if ultramafic lavas are erupting, we would expect an upper temperature of 1900 K. Higher temperatures than this would be unprecedented in Io and terrestrial volcanism, and would

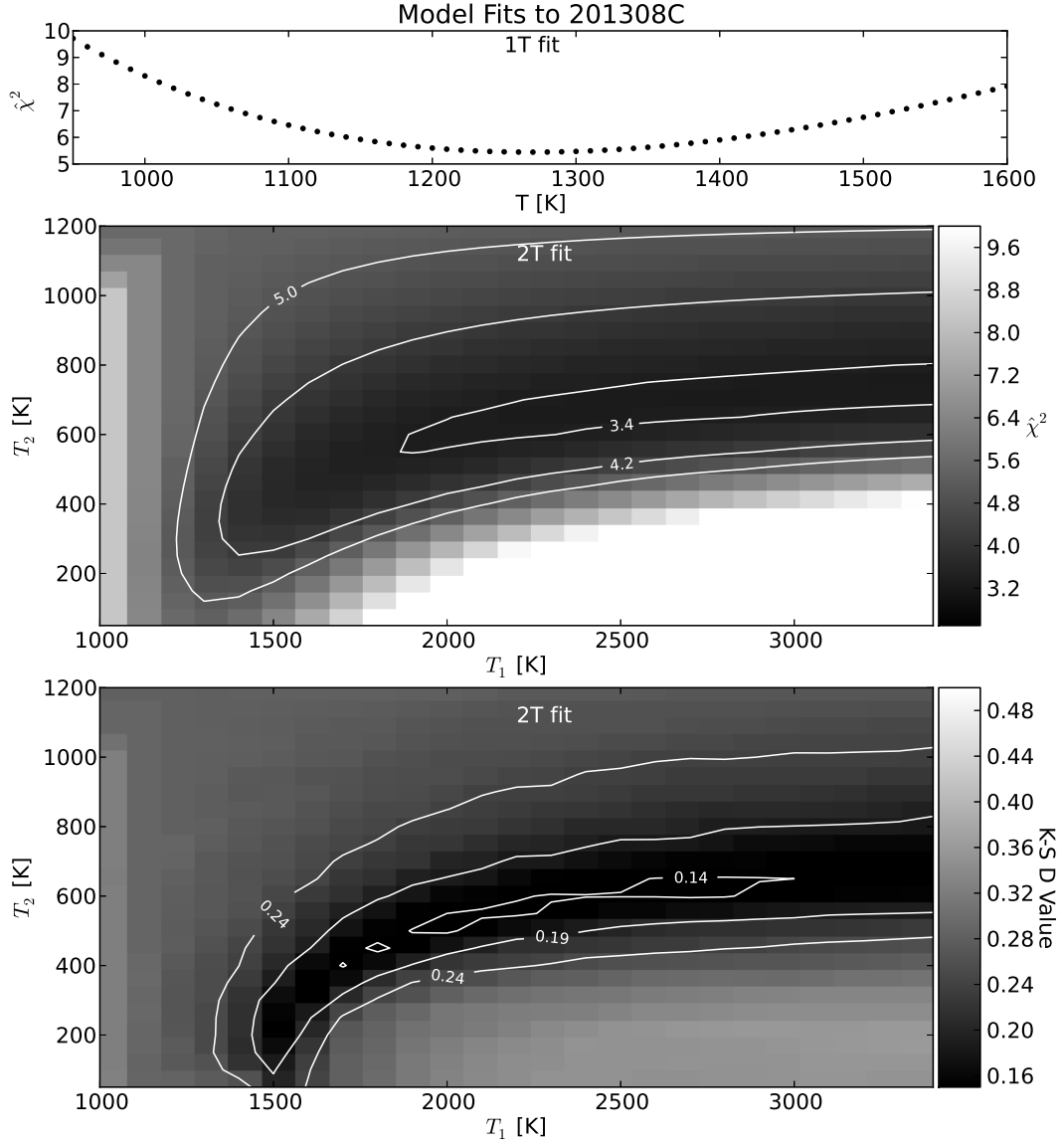


Figure 4.6: Values of the goodness-of-fit metrics $\hat{\chi}^2$ and the K-S statistic for various models fit to the outburst spectrum. In all fits, the temperatures are fixed at the indicated values, while the size of emitting region(s) is allowed to vary freely. Three constant-value contours are plotted for each statistic for the 2T fit: an inner contour near the minimum-value surface, the outermost contour that still follows the shape of the minimum-value surface, and a mid-point between the two.

suggest an exotic composition (e.g. Kargel et al., 2003) that is hard to explain given the understanding of the composition and state of Io’s interior (Keszthelyi et al., 2007). For these two cases, which we designate our 2T* and 2T** fits respectively, instead of fitting on a grid of temperatures, we fix the upper temperature at the defined value and fit directly for the lower temperature and the two emitting areas. These fits are performed using Markov Chain Monte Carlo simulations via the Python **emcee** implementation by Foreman-Mackey et al. (2013), and find both the best-fit parameters and their uncertainties.

The 2T* fit yields temperatures of 1475 K and 410 ± 20 K over areas of 57.5 ± 1.0 km² and 5500 ± 1700 km² respectively, for a total power of 24.5 ± 1.5 TW. We note that the low-temperature area required by this fit is extremely high for an outburst in its initial stages, and still does not give a close fit at short wavelengths. The 2T** fit yields temperatures of 1900 K and 575 ± 15 K over areas of 23.5 ± 0.5 km² and 1160 ± 60 km² respectively, for a total power of 24.5 ± 0.5 TW. We show the best-fit model spectra in Figure 4.5, and tabulate the associated parameters in Table 4.4.

With a best-fit temperature above 1700 K and a lower temperature limit of 1200-1300 K, our 2T model fits are suggestive of temperatures associated with super-heated or ultramafic magma, but we are not able to confidently discriminate between this scenario and basaltic lavas that have not yet cooled. Regardless of lava composition, all model fits indicate that we are observing a violent lava fountaining event with one of the highest energies and temperatures ever detected on Io. The power output and temperature are comparable to those of the Tvashtar outburst in 1999-2000 (24 TW; $T > 1300$ K), with a power only a factor of three below the 78 TW emitted by Surt in 2001 (Marchis et al., 2002).

4.3.1.3 Io Flow Model

We also fit the data with the more sophisticated Io Flow Model (IFM) of Davies (1996). The IFM was created to model lava fountain and lava flow thermal emission and has been used successfully to infer the physical properties of lava eruption and emplacement for lava fountains, lava flows and overturning active lava lakes on Io and Earth (Davies, 1996, 2007; Davies et al., 2001). The IFM calculates the expected distribution of temperatures given input parameters such as the thermo-physical and cooling characteristics of the lava and the environment into which the lava is erupted, in this case basalt erupting in the Ionian surface environment (see e.g. Davies, 2007). Varying the duration and scale of activity, we iteratively fit the integrated thermal emission spectra produced by the model to the observed spectrum to retrieve eruption parameters such as the rate of areal coverage (m²/s), the age in hours of the oldest emitting surface, and the lowest lava surface temperature present. The lava is assumed to erupt at a temperature of 1475 K, the liquidus temperature of basalt.

The best-fit IFM for 201308C yields a large isothermal area of 64 km² which is instantaneously emplaced at 1474 K, the maximum possible temperature for basalt and Ionian conditions. The total power output in this model is 17 TW. It is difficult to imagine what could cause such a phenomenon; such a thermal signature might be caused by the complete removal of the crust on a lava lake exposing incandescent lava, but even at the most active lava lakes on Earth, the temperature distribution is never this isothermal even during active

resurfacing. No lava lake has been seen in this location before, and the high emission angle makes it unlikely that a lava lake in a pit would be seen. The model fit implies that there exist higher-temperature areas contributing to the thermal emission, although with the high degree of scatter in the data between 2 and 2.5 μm , refining this temperature limit is not possible.

However, by considering the uncertainty in the data it is possible to obtain a model fit. By fitting the full range of radiance values using the lower radiance limit (data - uncertainty) for intensities at wavelengths shorter than 3.5 μm and the upper range of uncertainties (data + uncertainty) for our data at wavelengths at or longer than 3.5 μm , the IFM yields a total emitting area of 79.5 km^2 with a temperature range from 1291 to 1475 K, and a total power output of 15 TW. This ‘minimum temperature’ spectrum is plotted with the best-fit IFM in Figure 4.7, and the full set of derived physical properties for both versions of the fit are presented in Table 4.5. The age of the oldest surface is only a few seconds, implying an extremely high areal coverage rate, in excess of 20 km^2/s . A simple 1T fit to the same spectrum yields similar numbers: a temperature of 1356 K, an area of 78.5 km^2 , and a total power output of 15 TW.

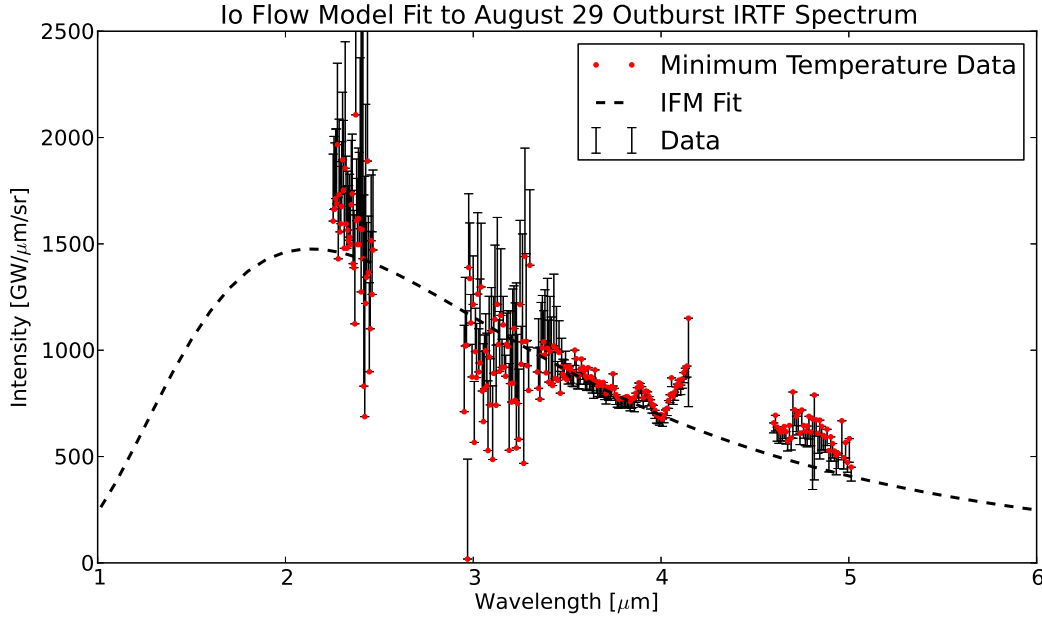


Figure 4.7: August 29 outburst IRTF spectrum (black) with minimum temperature spectrum shown in red; this spectrum selects the upper limit on the flux densities for wavelengths $< 3.5 \mu\text{m}$ and the lower limit on the flux densities for wavelengths $> 3.5 \mu\text{m}$, based on the data uncertainties. The Io Flow Model fit to the minimum temperature spectrum is plotted as a dashed line.

By looking at the lower flux density limit at longer wavelengths and the upper limit at shorter wavelengths, we retrieve the lowest temperature consistent with our observations.

The IFM fits indicate that the lower-limit peak temperature is in the 1300-1350 K range. This is consistent with the 2T fits, which place this lower limit at 1200-1300 K.

4.3.2 Loki Patera

As one of the sites that has hosted a consistently high level of volcanic activity for decades, Loki Patera is one of the most well-studied single volcanic sites on Io. It is postulated to be a 21,500 km² lava lake with a periodically over-turning crust (Rathbun et al., 2002; Davies et al., 2012; Veeder et al., 2011; Matson et al., 2006). During overturn events, a spike in Loki Patera’s flux density and temperature is observed; at other times, thermal emission is dominated by the large expanse of cooling crust.

On Aug 29 and Sep 5 & 7 we detected a bright hot spot in the southeast corner of Loki Patera, part of the patera floor thought to be occupied by a lava lake. This region of the patera floor is also where the highest temperatures were seen by Galileo NIMS (Davies, 2003), and is proposed to be where the lava lake resurfacing cycle began during the Galileo epoch (Davies, 2003; Matson et al., 2006; Rathbun and Spencer, 2006). A faint hot spot just to the southwest of Loki Patera on Io’s surface also became active in the first few days of September, between our Aug 29 and Sep 5 observations (see Figure 4.2).

We extract the 3.78- μ m flux densities of Loki Patera from Gemini photometric observations and correct them for emission angle. The results are tabulated in Table 4.3 and plotted in Figure 4.4. We find a flux density of ~ 100 GW/ μ m/sr on all three nights, with a slightly higher flux density observed on August 29; these values are consistent with the level of activity typically seen at Loki Patera (Davies et al., 2012).

4.3.3 Rarog & Heno Paterae

On August 15, two outbursts were detected near Rarog and Heno Paterae (de Pater et al., 2014a), and the observations presented in this paper were initially scheduled to provide follow-up observations to chart their evolution. We observed the sites of these outbursts on UT Aug 29, Sep 5, and Sep 7 at 3.78 μ m; the locations are shown in Figure 4.2. We found that this pair of outbursts had diminished significantly in L’-band intensity, from ~ 600 GW/ μ m/sr on August 15 to ~ 20 GW/ μ m/sr on August 29 and down to ~ 10 GW/ μ m/sr by Sep 7. We note that on the September dates in particular, the sites were very faint and exhibited an elongated shape, although we were not able to resolve the pair. As such, flux determinations were challenging and our uncertainties are quite high ($\sim 50\%$, see Table 4.3).

4.3.4 Testing Outburst Detection Criteria

We applied the outburst detection criteria defined in Section 4.2.2 to all observations presented here. From the measured flux densities of the hot spots observed with Gemini, only the outburst passes the requirement of 500 GW/ μ m/sr L’-band thermal emission with a flux density of 700 GW/ μ m/sr; no other hot spot exceeds ~ 100 GW/ μ m/sr. From the

SpeX observations, the August 29 disk-integrated spectrum exceeds the threshold $5\text{-}\mu\text{m}/2\text{-}\mu\text{m}$ flux ratio of 0.1 with a ratio of 0.13, while the ratios of 0.07, 0.08, and 0.09 on the subsequent observations fall below this threshold. We therefore confirm that our criteria correctly identify the presence or absence of an outburst in these observations. Figure 4.8 compares the observed spectra with our model spectra in the $4.6\text{-}5.0\text{ }\mu\text{m}$ region and indicates the outburst detection threshold.

4.4 Discussion

4.4.1 August 29 Outburst

The outburst 201308C detected on August 29 is an example of a rare, vigorous, and high-temperature volcanic event on Io. The combination of spatial, spectral, and temporal resolution have allowed us to constrain the eruption style, the temperature and areal coverage, and the time evolution of the event. 201308C is located at $223.5\pm 2.6^\circ\text{W}$, $29.1\pm 1.8^\circ\text{N}$. From a study of *Voyager* and *Galileo* images, the only surface feature in this vicinity is a patera designated P171 (Radebaugh, 2005) with an outer dark floor and an inner bright floor (Williams et al., 2011). The location of P171 at 222°W , 31°N is consistent with the outburst location, and may have also been the source of a small hot spot designated I32A, identified by Lopes et al. (2004) in NIMS data obtained in October 2001 (Veeder et al., 2014).

The IRTF thermal emission spectrum is best fit by models with temperatures above 1700 K. However, the spectrum is also consistent with a range of eruption temperatures from ~ 1200 K to well beyond 2000 K. We are therefore unable to discriminate between basaltic composition (< 1475 K) and superheated or ultramafic magmas (> 1475 K), but we cannot rule out either scenario. In either case, these temperatures indicate high-temperature, newly-exposed magma.

As demonstrated by our models, the $2\text{-}5\text{ }\mu\text{m}$ region of the spectrum does not provide information on eruption temperatures above 1700 K, where the emission spectrum peaks short of the observed region. To constrain these extremely high temperatures and convincingly distinguish between silicate and ultramafic magma compositions would require an observation in the $1\text{-}2\text{ }\mu\text{m}$ window, where we would detect either the peak or the sharp short-wavelength drop-off in the emission.

To put these Ionian eruptions in context with other volcanic events on Io and Earth, we plot the data in two different ways, alongside events with a broad range of styles of volcanic activity from data collected for Earth and Io (Davies et al., 2010). Figure 4.9 shows the $5\text{-}\mu\text{m}$ radiant flux as a function of the $2\text{-}\mu\text{m}$ radiant flux, and Figure 4.10 shows the $2:5\text{-}\mu\text{m}$ radiant flux ratio versus the total radiant flux density (kW/m^2). As our observations span the $2.1\text{-}5.0\text{ }\mu\text{m}$ region only, the plotted $2\text{-}\mu\text{m}$ values are interpolated based on our best-fit models; reference points on the figure are also similarly interpolated when measurements did not include 2 and $5\text{ }\mu\text{m}$.

In Figure 4.9, the farther a point plots to the right relative to the $2\text{-}\mu\text{m} = 5\text{-}\mu\text{m}$ radiant flux line, the greater the proportion of high-temperature areas to cooler areas. Lava fountains

and active lava lakes plot near or to the right of this line, while hot spots dominated by relatively cool crust plot to the left. This figure shows the immense variety in the scale of volcanic activity on Io, spanning over six orders of magnitude. Figure 4.10 removes the scale of the activity by considering the relative brightness at 2 and 5 μm . The 2:5- μm radiant flux ratio is a measure of the effective temperatures of emitting areas; the greater the ratio, the higher the temperature. Hence if the eruption covers a large area, such as for the outburst seen at Surt (Marchis et al., 2002), it will show up farther to the right in Figure 4.9, while the most vigorous eruptions regardless of areal size (i.e. emphasizing temperature rather than size) appear near the upper right of Figure 4.10. These two plots demonstrate that lava flows and quiescent lava lakes with insulating crusts (QL and IFL in Figure 4.10) have a low 2:5- μm ratio, while highly-energetic eruptions such as active, overturning lava lakes and open channel flows (C) and lava fountains (F) have much higher radiant flux densities due to the large, high-temperature areas exposed. Previous Io outburst eruptions are shown as red circles in Figure 4.10; each eruption is identified separately in Figure 4.9. To avoid confusion, we note that the 2- μm to 5- μm radiant flux ratio discussed here refers to the thermal emission from an individual volcanic site, while the 5- μm /2- μm flux ratio discussed in Section 4.2.2 refers to Io’s disk integrated intensity, which is generally dominated by reflected sunlight.

The 201308C event, as well as the Rarog Patera and Heno Patera outbursts that took place earlier in August 2013 (de Pater et al., 2014a), plots in both figures in the same region as the most energetic lava fountain episodes previously seen on Io. The total emitted power emitted over all wavelengths for 201308C is between 15 and >25 TW, more powerful than the Rarog and Heno outbursts combined (14 TW), and only a factor of a few below the violent eruption at Surt in 2001 (78 TW), which was the most energetic outburst yet seen (Marchis et al., 2002).

In the case of 201308C, the 2:5- μm ratio is the highest yet observed on Io, suggesting that the extreme energetics of the eruption exposed a proportionally larger area at or close to the actual eruption temperature than any previously quantifiable eruption. The eruption apparently has been observed very close to its onset, possibly close to the peak effusion rate, before substantial cool areas from clastogenic flows have developed.

Regarding these comparisons, we emphasize that this detection was made with the eruption site on Io’s extreme limb, and the actual power from the event could be much higher than calculated if it contained significant contribution from surface flows, which would be nearly invisible at such a high emission angle. These cooler surfaces, if present and seen with a more direct viewing geometry, would have increased the 5- μm radiant flux and reduced the 2:5- μm radiant flux ratio.

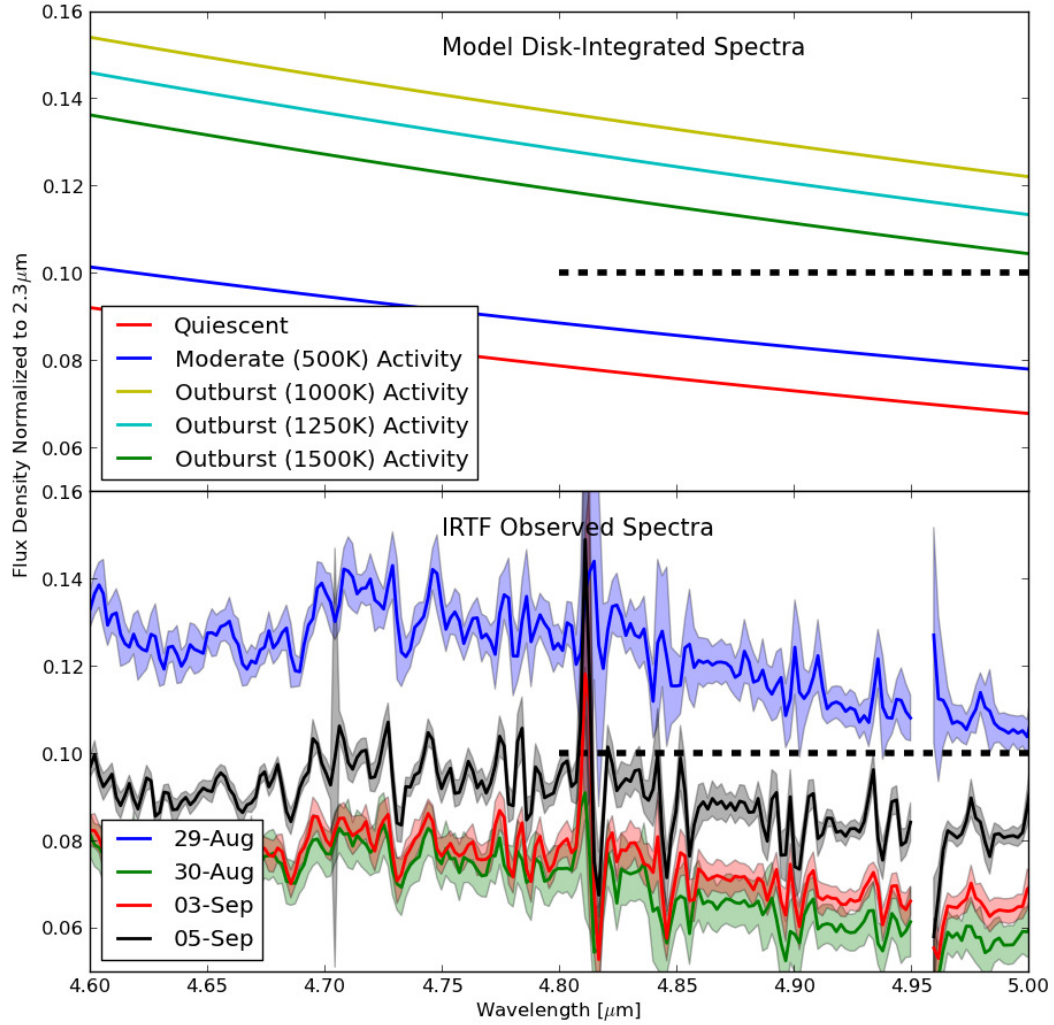


Figure 4.8: Outburst Identification in Models and Data: (Top) Model disk-integrated spectra for various level of volcanic activity, scaled to the $2.3\text{-}\mu\text{m}$ window to indicate the $5\text{-}\mu\text{m}/2\text{-}\mu\text{m}$ flux ratio. The dashed line indicates the outburst detection threshold. (Bottom) Observed disk-integrated spectra. Of the observations shown, only the August 29 spectrum captured an ongoing outburst, which is successfully identified by our criterion.

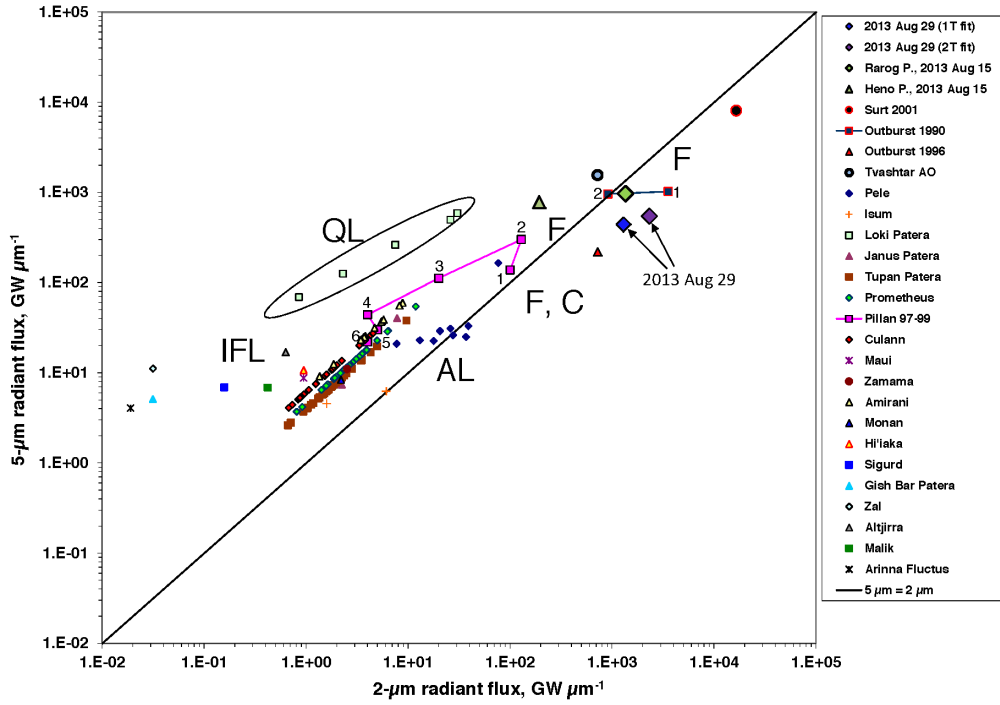


Figure 4.9: Plot of $5\text{-}\mu\text{m}$ versus $2\text{-}\mu\text{m}$ radiant fluxes for different volcanic events on Io. The points for 201308C as well as the other August 2013 outbursts (de Pater et al., 2014a) at Rarog and Heno Paterae (green diamond & triangle) place them among the most energetic eruptions ever witnessed on Io, i.e. lava fountain episodes that took place at Surt, Tvashtar, Pillan, and events in 1990 and 1995. Key: F = lava fountains; C = open channel flows; AL = active lava lakes; QL = quiescent lava lakes and flows; IFL = flows with insulated crusts. Numbers (e.g. 1990 eruption) refer to a chronological sequence of those observations. The $2\text{-}\mu\text{m}$ radiant flux for 201308C is interpolated based on best-fit 1T and 2T models; some reference points are similarly interpolated to the plotted wavelengths. Base image from Davies et al. (2010).

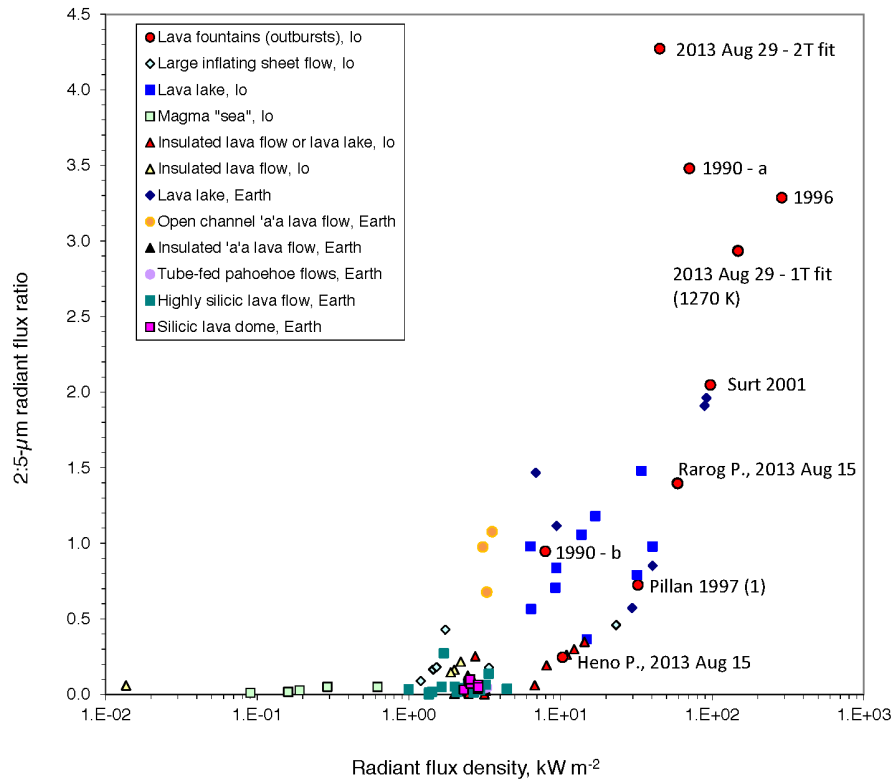


Figure 4.10: Plot of the 2:5- μm radiant flux ratio is a function of the radiant flux density for different styles of volcanic activity on Io and Earth. Outburst 201308C is the most extreme event in terms of radiant flux ratio yet observed, which indicates the extreme vigor of the eruption. The 2- μm radiant flux for 201308C is interpolated based on best-fit 1T and 2T models; some reference points are similarly interpolated to the plotted wavelengths. Base image from Davies et al. (2010), with added Heno and Rarog Paterae data from de Pater et al. (2014a).

4.4.2 Implications

This outburst completes an unprecedented trio of volcanic outbursts observed on Io in August of 2013, following the detections at Rarog and Heno Paterae earlier in the month (de Pater et al., 2014a). All three events are believed to be violent lava fountain episodes typically observed less than once a year (Veeder et al., 2012; Davies, 1996). In addition, all three events had subsided to barely-observable levels within weeks of their detections.

The close spacing and short timescales of these events indicate that either this trio marked an unusually extreme period in Io’s volcanic activity level, or that short-lived high-intensity outbursts may be far more common than has been deduced from previous observations. If the latter is the case, more frequent observation of Io would be required over a long time baseline to re-assess the occurrence of such events on Io and estimate the frequency of events missed by an observing program.

If indeed such a close cluster of events is unusual for Io, these detections may have important implications for the EXCEED mission and the multi-wavelength ground support observations of the torus and neutral cloud. Lava fountaining episodes, such as we believe to be taking place here, are often associated with large plumes of outgassed and ejected material. Such a plume would provide a burst of new material into Io’s atmosphere and subsequently the neutral cloud and plasma torus, potentially resulting in a detectable change in any of these components (Brown and Bouchez, 1997; Mendillo et al., 2004). The timing of these events only a few months before the beginning of the EXCEED mission and related ground-based campaigns means that the effects of such a plume could be observed in the coming months. If no such effects are observed, this information may also help constrain the processes linking Io’s volcanic activity to neutral cloud density and torus variability.

Table 4.1: Io Model Parameters

Model	Temperature	3.8- μm Thermal Emission	5- μm Total Emission	5- μm /2- μm Flux Ratio
	[K]	[GW/ μm /sr]	[GW/ μm /sr]	
Quiescent	-	-	400	0.07
Moderate Activity	500	40	460	0.08
	1000	610	800	0.13
Outburst	1250	730	800	0.12
	1500	790	800	0.11

Table 4.2: 2013 Io Observations

UT Date	UT Time ^a	Wavelength [μm]	Longitude [$^{\circ}\text{W}$]	Instrument
08-29	15:35	3.8	305	Gemini NIRI
	16:14	2.1-5.0	311	IRTF SpeX
08-30	15:14	3.8	146	Gemini NIRI
	16:04	2.1-5.0	153	IRTF SpeX
09-01	15:12	3.8	192	Gemini NIRI
09-02	15:15	3.8	36	Gemini NIRI
09-03	15:27	3.8	241	Gemini NIRI
	15:52	2.1-5.0	245	IRTF SpeX
09-04	14:50	3.8	79	Gemini NIRI
09-05	15:07	3.8	285	Gemini NIRI
	15:50	2.1-5.0	291	IRTF SpeX
09-06	15:11	3.8	129	Gemini NIRI
09-07	15:25	3.8	334	Gemini NIRI
09-09	15:47	3.8	24	Gemini NIRI
09-10	15:36	3.8	226	Gemini NIRI

(a) Time at start of observation.

Table 4.3: Hot Spot Locations and 3.8- μm Flux Densities

Site	UT Date	Latitude [°N]	Longitude [°W]	Flux Density ^a [GW/ μm /sr]	Flux Density ^b [GW/ μm /sr]
Outburst	Aug 29	28.3 $\pm$ 2.8	220.5 $\pm$ 10.0	706 $\pm$ 74	<i>c</i>
	Aug 30	29.2 $\pm$ 1.4	214.3 $\pm$ 5.2	66 $\pm$ 10.5	<i>c</i>
	Sep 1	29.2 $\pm$ 1.6	224.5 $\pm$ 2.0	57 $\pm$ 9	82 $\pm$ 13
	Sep 3	29.2 $\pm$ 1.6	224.0 $\pm$ 1.6	28 $\pm$ 4	32 $\pm$ 5
	Sep 10	27.8 $\pm$ 4.0	222.2 $\pm$ 4.0	12 $\pm$ 2	13 $\pm$ 2
	<i>best-fit</i>	29.1 $\pm$ 1.8	223.5 $\pm$ 2.6		
Loki Patera	Aug 29	12.2 $\pm$ 1.4	302.8 $\pm$ 1.4	110 $\pm$ 14	113 $\pm$ 14
	Sep 5	10.8 $\pm$ 1.4	306.0 $\pm$ 1.5	86 $\pm$ 13	94 $\pm$ 14
	Sep 7	11.6 $\pm$ 1.4	303.9 $\pm$ 1.6	86 $\pm$ 13	98 $\pm$ 15
	<i>best-fit</i>	11.5 $\pm$ 1.4	304.1 $\pm$ 1.5		
Rarog/Heno Paterae	Aug 29			18.4 $\pm$ 3.5	
	Sep 5			6.8-12.3	
	Sep 7			6.0-13.8	

(a) Before emission angle correction

(b) After emission angle correction

(c) Too close to the limb to estimate emission angle correction factor; the uncorrected flux density may be considered a lower limit.

Table 4.4: 201308C Outburst Models

Fit ^a	Temperature [K]	Area [km ²]	Power [TW]	$\hat{\chi}^2$	K-S D-value
1T	1270 $\pm$ 10	102 $\pm$ 3	15.0 $\pm$ 0.2	2.7	0.27
2T*	410 $\pm$ 20	5500 $\pm$ 1700	24.5 $\pm$ 1.5	3.7	0.22
	1475	57.5 $\pm$ 1.0			
2T**	575 $\pm$ 15	1160 $\pm$ 60	24.5 $\pm$ 0.5	3.4	0.17
	1900	23.5 $\pm$ 0.5			

(a) 1T is a single-temperature fit; 2T* is a two-temperature fit with a fixed upper temperature of 1475 K; 2T** is a two-temperature fit with a fixed upper temperature of 1900 K.

Table 4.5: Io Flow Model Derived Properties for 201308C

IFM Fit	Data Set	Min Temp Analysis
Total power [TW]	17	15
dA/dt [m ² /s]	7.3x10 ⁹	2.4x10 ⁷
Total area [km ²]	64	80
Oldest surface temperature [K]	1474	1291
Oldest surface age [s]	<1	3.4
2- μ m radiant flux [GW/ μ m]	5720	4593
5- μ m radiant flux [GW/ μ m]	1266	1284
2:5- μ m flux ratio	4.52	3.58
Flux density [kW/m ²]	268	190

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Chapter 5

Time Variability of Io's Volcanic Activity from Near-IR Adaptive Optics Observations on 100 Nights in 2013-2015

Jupiter's moon Io is a dynamic target, exhibiting extreme and time-variable volcanic activity powered by tidal forcing from Jupiter. We have conducted a campaign of high-cadence observations of Io with the goal of characterizing its volcanic activity. Between Aug 2013 and the end of 2015, we imaged Io on 100 nights in the near-infrared with adaptive optics on the Keck and Gemini N telescopes, which resolve emission from individual volcanic hot spots. During our program, we made over 400 detections of 48 distinct hot spots, some of which were detected 30+ times. We use these observations to derive a timeline of global volcanic activity on Io, which exhibits wide variability from month to month. The timelines of thermal activity at individual volcanic centers have geophysical implications, and will permit future characterization by others. We evaluate hot spot detection limits and give a simple parameterization of the minimum detectable intensity as a function of emission angle, which can be applied to other analyses.

We detected three outburst eruptions in August 2013, but no other outburst-scale events were observed in the subsequent ~ 90 observations. Either the cluster of events in August 2013 was a rare occurrence, or there is a mechanism causing large events to occur closely-spaced in time. We also detected large eruptions (though not of outburst scale) within days of one another at Kurdalagon Patera and Sethlaus/Gabija Paterae in 2015. As was also seen in the *Galileo* dataset, the hot spots we detected can be separated into two categories based on their thermal emission: those that are persistently active for 1 year or more at moderate intensity, and those that are only briefly active, are time-variable, and often reach large intensities. A small number of hot spots in the latter category appear and subside in a matter of days, reaching particularly high intensities; although these are not bright enough to qualify as outbursts, their thermal signatures follow the same pattern, suggesting that a similar mechanism may be responsible for these events though at a smaller scale.

Two eruptions seen at Kurdalagon Patera in January and April 2015 occurred simultaneously with a brightening of the neutral cloud and plasma torus which are sourced from Io's atmosphere. A plume at Kurdalagon Patera, such as was seen by *New Horizons* in 2007, could have been responsible for the influx of material that caused these brightenings.

5.1 Introduction

Since before the Voyager fly-bys, Io has been recognized as an unusual and dynamic object (Cruikshank and Murphy, 1973). Io's locked eccentric orbit causes high internal heating generated by tidal forcing from Jupiter (Peale, 1979). The high heat flow of ~ 2.5 W/m² (Matson et al., 1981; Veeder et al., 2012), 30 times that of Earth, causes extreme volcanic activity on this rocky body only slightly larger than Earth's moon. Hundreds of active volcanic sites hosting a wide variety of volcanic styles generate thermal signatures that are easily detected from the Earth in the near-infrared, and resolved by telescopes equipped with adaptive optics (Marchis et al., 2000). Large eruptions can exhibit rapid variability on a timescale of hours (Blaney et al., 1995; Rathbun et al., 2014), and may change in power output by orders of magnitude over just a few days (de Pater et al., 2014a; de Kleer et al., 2014).

The extreme conditions on Io make it a unique target for gaining insight into numerous processes that operate throughout the Solar System and beyond. Volcanic plumes reaching more than 100 kilometers above Io's surface have been detected by spacecraft (Strom and Schneider, 1981; Geissler et al., 2008), and contribute to the Solar System's only sulfur-based atmosphere (e.g. Lellouch et al., 1990; Spencer et al., 2005), which is lost at a rate of 1 ton/second to a neutral cloud and dynamic plasma torus in the Jovian system (Schneider and Baganel, 2004). Magmas of an ultramafic composition - containing less silica and more heavy metals than the basalts common on Earth today - have been tentatively detected (McEwen et al., 1998; de Kleer et al., 2014). Volcanic activity of this style was widespread on Earth and the other rocky bodies in early Solar System history when planetary interiors were hotter, making Io a potential active analog for studying these processes (Matson et al., 1998).

Obtaining a complete picture of the variability and spatial distribution of Io's volcanic activity requires observations with high temporal and spatial resolution, covering multiple near-infrared wavelengths so that temperatures and power outputs can be calculated. The *Galileo* mission provided the first and most extensive characterization of Io's volcanic activity over a multi-year period from 1995-2003 (e.g. Lopes-Gautier et al., 2004; Veeder et al., 2012). Since the beginning of this mission, other space- and ground-based observations have provided snapshots of Io's global activity. Occultation photometry provided the first resolved ground-based observations of individual active sites (Spencer et al., 1997), and has been used extensively to capture Io's activity level during time periods surrounding spacecraft encounters (e.g. Rathbun et al., 2010). The advent of adaptive optics on 8-10 m telescopes has made it possible to observe more and fainter thermal sources. Marchis et al. (2005) characterized activity on Io at all longitudes during 10 nights of observation

at the Keck telescope in December 2001; data at multiple near-infrared wavelengths were used to determine the temperatures and power outputs of many of the sites. The *New Horizons* fly-by of the Jupiter system provided a unique snapshot of Io’s volcanism; night-side observations at 1-2.5 μm with the LEISA instrument measured the hot component of many volcanic eruptions (Spencer et al., 2007; Tsang et al., 2014). Thermal emission is difficult to detect at these wavelengths when Io is in sunlight, and such measurements are hence rare from the ground. Simultaneous measurements with MVIC detected plume activity, while the high cadence of the LORRI instrument confirmed that the detected volcanoes did not exhibit variability on a timescale of seconds to minutes, though one site (E. Girru) changed in intensity in a matter of hours to days, and was seen across multiple wavelengths and instruments (Rathbun et al., 2014; Tsang et al., 2014).

We have obtained a new dataset covering volcanic activity on Io from August 2013 through December 2015 based on near-infrared adaptive optics images taken on 100 nights during this time period. These data represent the highest-cadence coverage of Io’s volcanism at high spatial resolution over such a time period to date, allowing for a unique characterization of the variability of activity on timescales from days to years. Our program, introduced in de Kleer et al. (2014), is optimized for maximal time coverage at 3.8 μm , and the majority of our observations are therefore taken at only one or two wavelengths and constraints on temperature and power are only possible for $\sim 30\%$ of hot spot detections. Previous ground-based programs and *New Horizons* have measured global activity at multiple wavelengths, but these observations typically cover only single or sporadic points in time. While the full time baseline of the *Galileo* observations spans nearly a decade, high resolution observations from dedicated Io fly-bys were rare, and are generally unable to constrain time variability at the scale of days or weeks that we sample. In addition, the consistent spatial resolution of our observations make it easier to separate real variability from observational biases.

We describe the observations and data reduction and calibration procedures in Section 5.2, followed by our hot spot photometry methods in Section 5.3. In Section 5.4 we present a timeline of 3.8- μm activity on Io and discuss activity at individual sites of interest. Implications of our results are discussed in Section 5.5, and our conclusions are summarized in Section 5.6. Appendix A.1 contains an extensive analysis of the detection limits and intensity and position uncertainties for this type of observation based on simulated data. Details on our observations and hot spot photometry are tabulated in Appendix A.2.

The spatial distribution of volcanic activity on Io is an important constraint on models of tidal heat dissipation in Io’s interior. The spatial distribution of the hot spots detected in this dataset is the subject of a companion paper (de Kleer and de Pater, 2016a).

5.2 Observations and Data Processing

We imaged Io in the near-infrared (1-5 μm) on 100 nights between August 2013 and December 2015 with adaptive optics at the Gemini N and Keck telescopes. The use of adaptive optics provides the spatial resolution to identify and extract the flux densities of individual volcanic hot spots. The details of the instruments and observations are given in

Table A.1 and described below, and example data from each instrument are shown in Figure 5.1. The complete dataset used in this analysis is shown in Figure 5.2.

5.2.1 Keck II NIRC2

With the Keck II telescope we aim to image all Ionian longitudes every year to track global variability from year to year. The observations presented here are made up three epochs: Aug 2013–Mar 2014 (10 observations), Oct 2014–Jan 2015 (6 observations), and Mar 2015–Dec 2015 (10 observations). Our observations covered all Ionian longitudes during each of these epochs. However, conditions were poor during multiple nights in the 2013-2014 epoch, and data at some longitudes are unusable. Data from some dates in August 2013 were previously published in de Pater et al. (2014a), and are included here in the context of the full dataset.

We observe Io with the NIRC2 imager combined with the adaptive optics system in natural guide star (NGS) mode, using Io itself for wavefront sensing. The NIRC2 detector is a 1024x1024 Aladdin InSb array, which we use with the narrow camera to obtain a $0.00994''/\text{pixel}$ platescale (de Pater et al., 2006). Io's angular size ranges from $0.8\text{--}1.2''$ depending on its distance from Earth, corresponding to $30\text{--}45\text{ km/pixel}$ at disk center. We image Io in reflected sunlight in a variety of wide- and narrow-band filters between $1.21\text{ }\mu\text{m}$ (J-cont) and $4.67\text{ }\mu\text{m}$ (Ms). We observe a nearby photometric standard star which we use for flux calibration, for point spread function (PSF) estimation, and to correct for atmospheric absorption. We observe both targets at three locations on the detector and construct a sky frame by median-averaging these frames.

We apply standard data reduction procedures for flat-fielding, bad pixel removal, and sky subtraction, and include a rectification of the images to correct for known spatial distortion using dewarp routines¹. Target images within a filter are aligned and median-averaged after reduction and sky-subtraction.

5.2.2 Gemini N NIRI

With Gemini N we observed Io briefly over a range of Ionian longitudes on 74 nights between August 2013 and April 2015. We image Io in the K-cont and L' and filters (2.27 and $3.78\text{ }\mu\text{m}$, respectively) with the Near-Infrared Imager (NIRI; Hodapp et al., 2003) combined with the ALTAIR adaptive optics system in NGS mode, using Io itself for wavefront sensing. The detector is a 1024x1024 Aladdin InSb array, which we use with the f/32 camera for a platescale of $0.022''/\text{pixel}$, corresponding to ~ 45 pixels across the disk of Io, or $\sim 80\text{ km/pixel}$ at disk center. Our spatial resolution at L', defined as the full width at half maximum of the point spread function, is generally $4\text{--}5$ pixels, or $\sim 0.1''$. We image Io in reflected sunlight at nine detector locations and construct a sky frame by median-averaging the images. We occasionally observe a standard star as well, which we use only for PSF estimation. We apply standard data reduction procedures, including flat-fielding, bad pixel removal, and

¹provided by Brian Cameron of the California Institute of Technology

sky-subtraction. The nine images are then aligned and median-averaged to produce a final image for each night.

Reduced images from both telescopes in a variety of filters are shown in Figure 5.1.

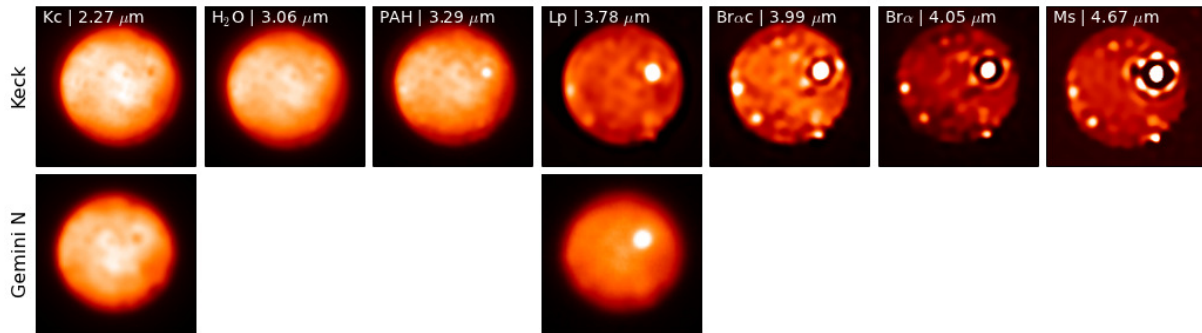


Figure 5.1: Example observations from the Keck and Gemini N telescopes. The two datasets are from 2015 Jan 12 and 14 for Keck and Gemini N respectively, and are selected for similar activity level and central meridian longitude, to facilitate comparison. Images are labeled with filter name and central wavelength.

5.2.3 Flux Calibration

The Keck observations are flux calibrated using observations of bright photometric standard stars taken on the same night as the target observations. The star counts are extracted from the reduced images via standard aperture photometry, and the Io images are flux calibrated based on the known stellar magnitudes (Leggett et al., 2003; 2006), interpolating between recorded values for narrowband filters and correcting for the airmass difference between the star and Io.

To determine the accuracy of the flux calibration each night, the flux density from reflected sunlight is measured on a region of Io's disk free from volcanic activity. While the emission from volcanically-active regions is highly time-variable, the reflected sunlight from non-active areas is relatively constant in time, after correcting for the sun-Io distance. A reference value for the flux density of Io's disk is determined for each filter based on observations on the most photometric nights. The calibrated background levels for this set of observations only differ by a few percent from one another. If the background level on a given night differs significantly ($> 10\%$) from this reference value, the entire image is scaled so that the disk background matches the reference value. Of the 26 nights of Keck observations, 19 had good observing conditions and were calibrated to the star; of these, 8 nights were particularly photometric and constituted the referenced set. The remaining 7 nights required correction due to poor weather or lack of a standard star observation.

On most nights, we do not observe a standard star with Gemini N, and we calibrate our Gemini N images using the Keck reference set by the same method described above. The uncertainty in this calibration method is due primarily to Io's non-uniform albedo, as well as

background contamination by bright hot spots whose PSF wings may raise the background level of the entire disk. Based on these effects, we derive a typical uncertainty of 6% in the photometry resulting from this procedure. This procedure and the derivation of uncertainties is described in further detail in de Kleer et al. (2014), where the program at Gemini N is introduced.

5.2.4 Navigation

We determine the latitude and longitude of each hot spot detection by navigating the images as follows. To determine the exact center of Io's disk in the images, we fit a circle matching the angular size of Io at the date and time of observation² to the limb of the disk by eye. We use the sub-observer latitude and longitude and north polar angle² to convert the (x, y) positions of each spot to Ionian (lat, lon) pairs.

The greatest uncertainty in our latitude-longitude estimates arises from the difficulty in determining the exact location of the limb, particularly at longer wavelengths where the disk is dimmer, and when there is a hot spot near the limb that distorts Io's apparent shape. We estimate that the position we find for Io's center based on the limb fit is accurate to 0.5 pixels for data from both telescopes. This is converted to a latitude and longitude uncertainty by shifting the fitted (x, y) position of each hot spot by half a pixel in each direction and calculating the corresponding (lat, lon) position; the resultant uncertainties therefore reflect the fact that position estimates become less precise closer to the limb. Typical uncertainties derived by this method range from $\sim 0.5^\circ$ in Ionian latitude/longitude near disk center to a few degrees near the limb. We evaluate these uncertainty estimates by looking at the actual spread in the positions derived for individual hot spots on multiple images taken on the same night, either in the same filter or different filters. In the Keck images, the spread in positions is typically less than 1.0° in latitude or longitude, and only rises above 3.0° on very rare occasions. This corresponds well with the uncertainties we derive. We cannot apply this analysis to our Gemini N observations where only one image is obtained each night, but we might expect the position uncertainties to be 20% larger than at Keck due to the lower spatial resolution.

In Appendix A.1 we revisit these uncertainties based on an analysis of simulated hot spots inserted into our observations at a range of emission angles and intrinsic flux densities. In some cases, we find that the method above underestimates uncertainties, and we increase errorbars accordingly.

5.3 Analysis

5.3.1 Hot Spot Photometry

We determine the exact position of each hot spot by finding the centroid of the brightest portion of a small sub-image manually chosen to contain only a single hot spot. In cases

² Ephemeris from JPL HORIZONS System: ssd.jpl.nasa.gov/horizons.cgi

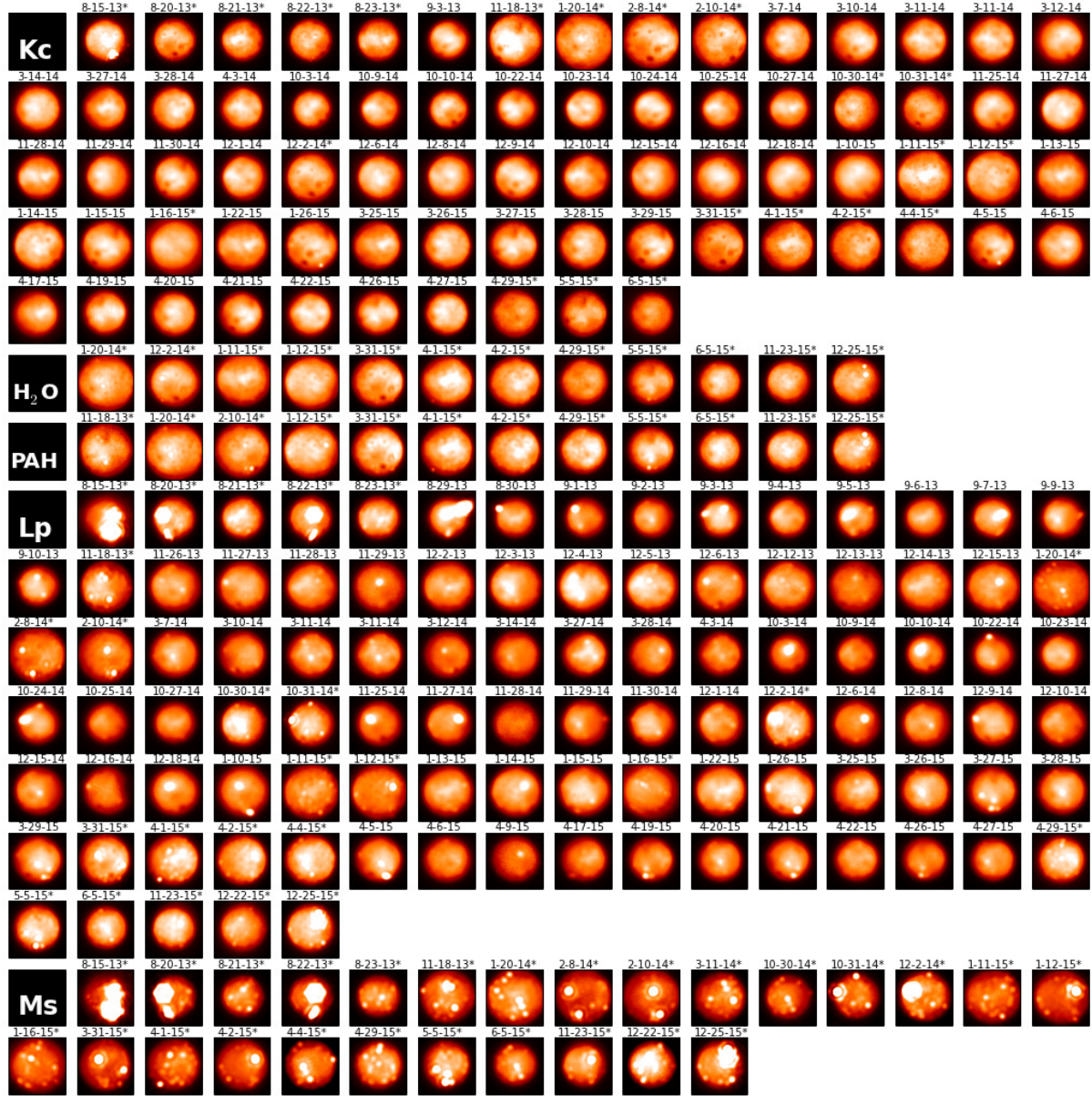


Figure 5.2: All Io images used in this analysis, taken in five filters: Kc ($2.27 \mu\text{m}$), H₂O ($3.06 \mu\text{m}$), PAH ($3.36 \mu\text{m}$), Lp ($3.78 \mu\text{m}$) and Ms ($4.67 \mu\text{m}$). Dates are indicated above images; asterisks next to dates indicate data from the Keck telescope; all other data are from the Gemini N telescope.

of faint hot spots near the limb or very near brighter hot spots, the positions found by this method are skewed by nearby brighter pixels, and the positions are corrected manually by eye.

Io is covered by hot spots whose point spread functions overlap, and an aperture that

collects all of the flux from one hot spot would be contaminated by others, requiring the use of smaller apertures that do not collect all the flux. The stellar PSF is used to estimate the fraction of flux lost due to this small aperture size and a correction factor is applied to the retrieved hot spot flux density, following the method described by Gibbard et al. (2005; for details, see also: de Pater et al., 2014b). The choice of aperture size generally does not impact the extracted flux density beyond the 1σ uncertainties, although smaller apertures lead to greater uncertainties. We therefore consider this correction robust except in cases when weather conditions are poor and the PSF varies in shape over the course of the night.

The uncertainties on the correction factor are determined by calculating the spread in values derived for this factor from multiple star observations in the same filter on a given night. This spread is affected by the choice of aperture size, the weather conditions, and the wavelength of observation. At Gemini N we do not observe a standard star each night of observation, and the aperture-size correction factor is based on a set of stellar observations with the same instrument on different nights, which leads to a larger spread and correspondingly higher flux density uncertainties. The factor we apply to the hot spot photometry is the median of the factors derived for each stellar observation for a given aperture choice, and we incorporate the standard deviation of the stellar correction factors into the uncertainty on the hot spot photometry. The stellar observations are made under a variety of weather conditions, and this spread gives us a conservative uncertainty estimate of $\sim 10\text{-}20\%$.

The hot spot intensities are corrected for geometric foreshortening by dividing by μ , the cosine of the emission angle. The final value for the hot spot intensity is calculated as

$$F_{hs} = F_{hs,counts} \times \frac{R \times L}{\mu} \quad (5.1)$$

where $F_{hs,counts}$ is the measured hot spot intensity in counts, R is the flux calibration factor converting counts to $\text{GW}/\mu\text{m}/\text{sr}$ based on either stellar or background calibration (see Section 5.2.3), and L is the aperture-size correction factor. The uncertainties are then calculated as

$$\left(\frac{\sigma_{F,hs}}{F_{hs}}\right)^2 = \left(\frac{\sigma_R}{R}\right)^2 + \left(\frac{\sigma_L}{L}\right)^2 + \left(\frac{\sigma_\mu}{\mu}\right)^2. \quad (5.2)$$

The uncertainty in the flux calibration σ_R , and on the correction factor σ_L are typically in the 2-10% range, depending primarily on wavelength and observing conditions. The uncertainty on μ is calculated from the uncertainty in the position determined for each hot spot. For positions very near the limb, σ_μ is much larger in moving towards the limb than away from it, and asymmetric uncertainties are given.

5.3.2 Detection Limits and Uncertainties

A robust characterization of the uncertainties on position and intensity retrievals is crucial for hot spot identification and correct interpretation of time variability. We assess the position and intensity uncertainties calculated by the methods described above by retrieving fake hot spots inserted into observations and testing our retrieval accuracy. This analysis is described in detail in Appendix A.1.

The detection limit analysis finds that uncertainties are underestimated for hot spots that are faint and/or near the limb, and the errorbars on these values are increased according to our results from the retrieval accuracy test. Apart from an analysis of the hot spot detection limits of the LEISA instrument on *New Horizons* (Tsang et al. 2014), a quantitative analysis of instrument sensitivities as they relate to hot spot detections has often been lacking. Such studies are critical for understanding hot spot variability and interpreting non-detections.

5.3.3 Temperature and Emitted Power

On nights when a hot spot is detected at two or more wavelengths, its temperature and emitting area are calculated assuming a single-temperature blackbody model. Although an actual eruption emits at a continuous range of temperatures, the data are typically well fit by a single temperature component, and therefore do not merit a more complex model. The fitted values can thus be considered a rough estimate of the dominant temperature component in the eruption. In cases where observations were made at K-cont but no detection was made, the non-detection is taken as a constraint on the fit.

Models are fit to the data using an affine-invariant ensemble Markov Chain Monte Carlo (MCMC) method, via the Python **emcee** implementation (Foreman-Mackey et al., 2013). This method is described in detail in de Kleer et al. (2014), where we used it to fit models to the 2-5 μm spectrum of an outburst on Io. We perform each run with 40 chains and 1000 steps; the chains typically converge after <200 steps. We fit for the temperature and area in log space, and the 1- σ errorbars are quoted directly from the posterior distributions of these properties. The power P is calculated from the area A and temperature T according to the Stefan-Boltzmann Law: $P = A\sigma T^4$, assuming an emissivity of $\epsilon=1$. Figure 5.3 shows example fits for different cases.

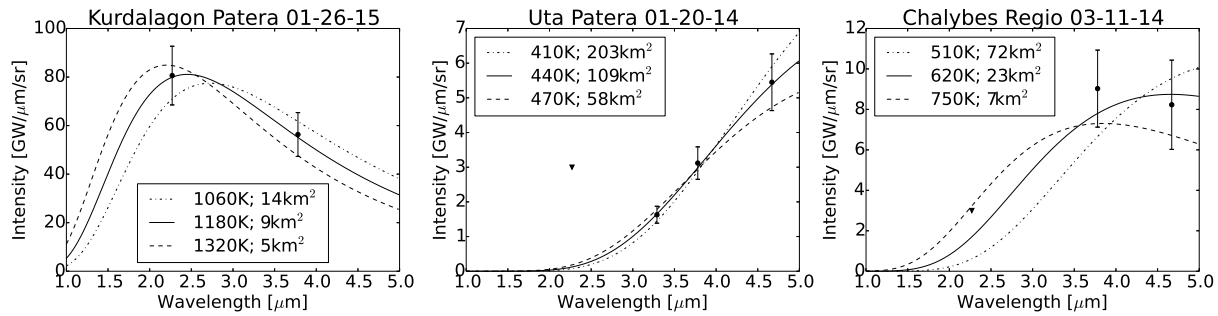


Figure 5.3: Example blackbody fits to three hot spots: (left) high-temperature hot spot; (middle) low-temperature hot spot; (right) poorly-constrained temperature. The solid curve is the best fit, and the two other curves demonstrate the fits corresponding to the 1- σ limits on temperature. Downward arrows are upper limits, and the temperature and area for each fit are indicated.

5.3.4 On L-band Emission as a Tracer of Total Power

In the absence of multi-wavelength data, the temperature and emitting area cannot be calculated from the observations. However, the majority of our data is taken in at least the Kc and L' filters (wavelengths of 2.3 and 3.8 μm), and a detection at L' combined with a lack of detection at Kc places an upper limit on the temperature that is at or below ~ 800 K. In addition, the limited range of plausible eruption temperatures allows for a rough estimate of total power from the L'-band intensity alone. This is demonstrated in Figure 5.4, where spectra at a range of temperatures are shown that all produce the same L'-band intensity. For eruption temperatures above 500 K, the power emitted is within a factor of 3 regardless of the temperature; if we allow eruptions as cool as 400 K, we can only be certain of the power to within a factor of ~ 8 . A temperature of 400 K, or 127°C, is at the low end for temperatures we might expect for sulfur volcanism, and too cool for erupting silicate lavas. This is therefore a conservative lower bound on eruption temperature, and we would expect most eruptions to be hotter. Although cooling lava flows may be even colder than this, such flows must cover vast areas to be detectable at 3.8 μm . In the detections where we have the data to make a temperature measurement, we find the dominant temperature component at the majority of hot spots to be between 500-700 K. This is much lower than the 1475 K of basaltic magma, and is likely dominated by large areas of cooling lava flows.

This demonstrates that even in the absence of multi-wavelength information, we can constrain the total emitted power to within a factor of ~ 5 from the 3.8- μm emission alone. Since the variability of the L'-band intensities can be much higher than this, we see that a comparison of L'-band emission between dates and hot spots can provide at least a crude stand-in for a comparison of total power.

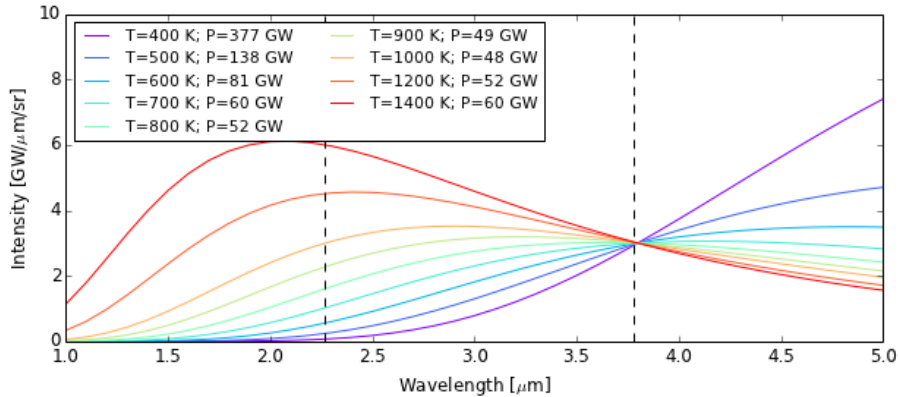


Figure 5.4: Demonstration of thermal emission spectra at a range of plausible eruption temperatures that produce the same 3.8- μm intensity. Although the spectra differ substantially, the spread in total powers is less than a factor of 10. The dashed vertical lines correspond to the central wavelengths of the K-cont and L' filters, at 2.27 and 3.78 μm respectively.

5.4 Results: Time Variability of Volcanic Activity

Between August 2013 and December 2015, we made 409 detections of thermal activity at 48 distinct hot spots. The timeline of 3.8- μm activity is shown in Figure 5.5, and all measured hot spot intensities and positions are given in Table A.2, along with identifications of candidate corresponding surface features. This timeline gives a picture of Io's global activity level over timescales of days to months to years, as well as the variability of individual volcanic sites. Of the 48 sites detected, Loki Patera was detected the most frequently (46 times), followed by Janus Patera (32 times) and Marduk Fluctus (29 times); all three sites were detected every time the observing geometry was favorable. Twelve additional sites were detected ten or more times.

Figure 5.5 includes a timeline of longitudinal coverage during the time period of observation. There were seven ~ 1 -month intervals of complete longitudinal coverage, and one period of partial coverage. Complete coverage specifically means that any eruption during these dates that sustained a 3.8- μm flux density above $\sim 3 \text{ GW}/\mu\text{m}/\text{sr}$ for three weeks or more would have been detected.

The scale of Io's volcanic activity varies widely from month to month, as seen in Figure 5.5. In the month of August 2013 four hot spots were detected (Rarog Patera, Heno Patera, 201308C, Loki Patera) with flux densities an order of magnitude brighter than the brightest event detected in the entire period from Nov 2013–Jan 2014, despite excellent longitudinal coverage during much of the latter interval. In general, we detected significant activity in Aug–Sep 2013 followed by a period from Nov 2013 –Apr 2014 when we detected only moderate activity (no event brighter than $30 \text{ GW}/\mu\text{m}/\text{sr}$ at 3.8 μm). When we began observing again in Oct 2014, Io had multiple regions of high activity, though nothing of an outburst scale; this heightened level of activity continued through the spring of 2015.

Io's volcanoes exhibit a wide range of time-variability signatures, corresponding to a variety of eruption styles (Davies et al. 2010). While some sites maintain a steady level of low-intensity activity for years, others vary by orders of magnitude, or may appear and subside in just a few weeks or less. In the following sections, we describe activity at individual sites of interest, including the brightest observed activity (Section 5.4.1), previously-undetected hot spots (Section 5.4.2); an unusual eruption at Kurdalagon Patera (Section 5.4.3); and activity at Pele, Amirani, and Loki Patera (Sections 5.4.4–5.4.6). The positions stated in bold for each location are an average calculated from our observations based on all hot spot detections attributed to this site (see Table A.2). These locations are shown on a surface map for selected hot spots of interest in Figure 5.6. Hot spots are identified with the most probable associated surface feature using the feature name when possible. The P/PV designations (Radebaugh 2005) are used for unnamed paterae, and patera floor unit ID numbers (Williams et al. 2011a; 2011b) are used when no alternative designation exists.

³http://astrogeology.usgs.gov/search/map/Io/Voyager-Galileo/Io_GalileoSSI-Voyager_Global_Mosaic_1km

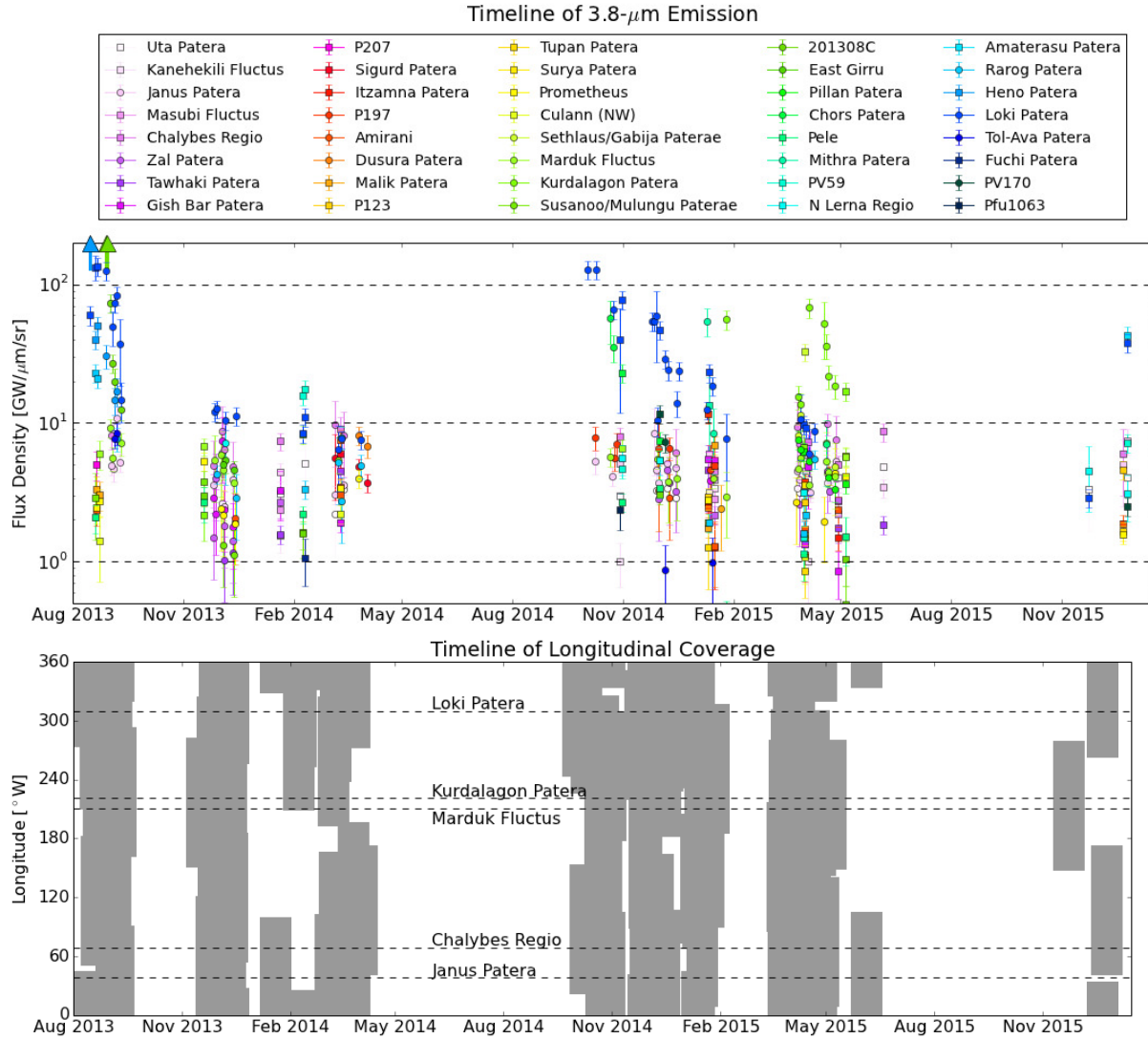


Figure 5.5: [Top] Timeline of 3.8- μ m emission from volcanic activity on Io between August 2013 and December 2015. Squares are detections with Keck/NIRC2, circles are detections with Gemini N/NIRI, and arrows indicate points off the scale of the figure. [Bottom] Timeline of longitude coverage of observations. The longitudes of selected hot spots discussed in the paper are indicated with dashed lines.

5.4.1 Bright Events

Following the three previously-published outburst events in August 2013 (de Pater et al., 2014a; de Kleer et al., 2014), no other outburst-scale events were detected. A high-energy eruption was detected at **Pillan Patera** [12 $^\circ$ S, 245 $^\circ$ W] on Feb 18⁴ (de Pater et al., 2016a). We first detected activity at Pillan Patera on March 27, the first date we observed its lo-

⁴Detected at the IRTF by R. Howell.

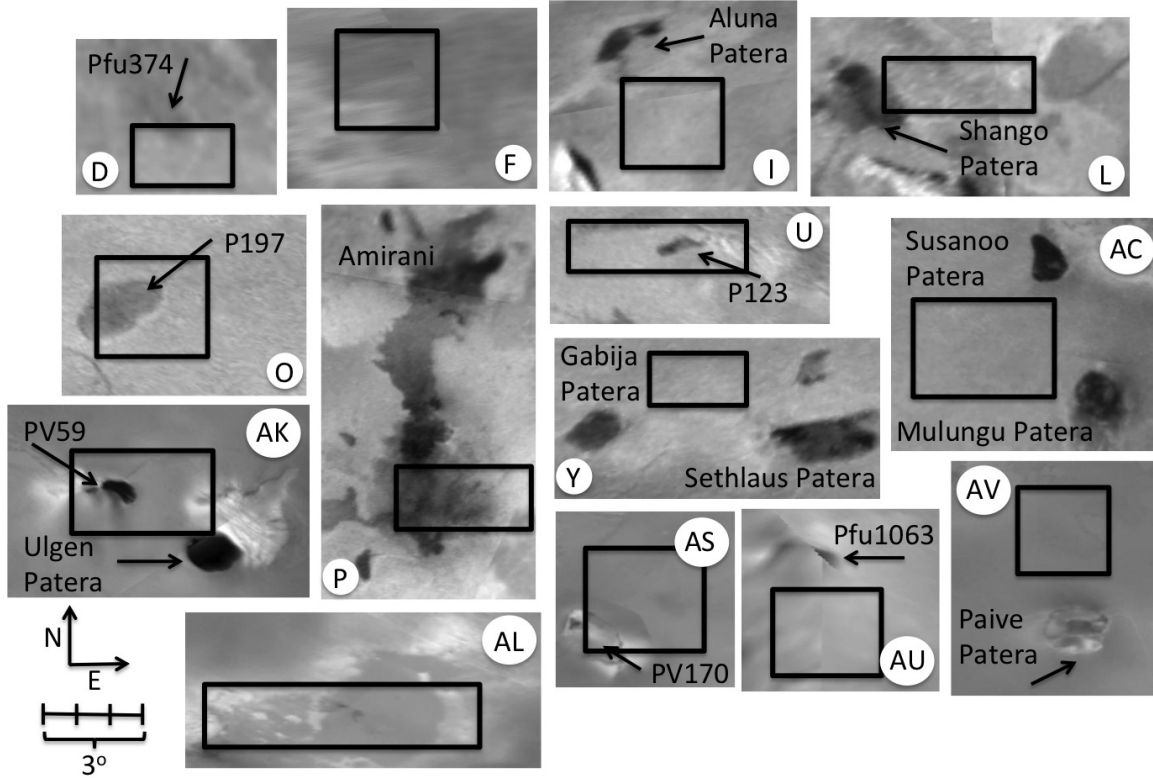


Figure 5.6: Locations of selected hot spots overlain on the USGS merged *Voyager/Galileo SSI* Io surface map³. Size of rectangles indicate uncertainties on detected location, and letters in bubbles correspond to hot spot identifications in Tables A.2 and 5.1. In the cases where the rectangles lie between two sources, emission may be present from both but unresolved.

cation after the eruption. During the subsequent months we observed its steady decline in brightness. We detected three brightening events at Loki Patera, which are the subject of a companion paper (de Kleer and de Pater, 2016b). Apart from the outbursts, Loki Patera, and the eruption at Pillan Patera, the brightest activity detected during this period was at **Kurdalagon Patera** [49°S, 221°W] (~ 68 GW/ $\mu\text{m}/\text{sr}$), **Chors Patera** [65°N, 247°W] (~ 57 GW/ $\mu\text{m}/\text{sr}$), **Mithra Patera** [58°S, 266°W] (~ 55 GW/ $\mu\text{m}/\text{sr}$), **Amaterasu Patera** [39°N, 304°W] (~ 43 GW/ $\mu\text{m}/\text{sr}$), and **Sethlaus/Gabija Paterae** [50°S, 198°W] (~ 33 GW/ $\mu\text{m}/\text{sr}$; intensities given at $3.8 \mu\text{m}$). In all cases, the peak brightnesses were measured at the first detection of activity from these sites, and were followed by a steady decline in brightness (this cycle repeated twice in the case of Kurdalagon). We note that all sites where bright activity was seen, including these four locations, the three outburst events, Loki Patera, and Pillan Patera, fall within a $\sim 100^\circ$ strip of longitude from 200-300°W, despite

our comparable coverage of the two hemispheres. The significance of this spatial grouping is discussed in de Kleer and de Pater (2016a).

5.4.2 New Hot Spots & Hot Spots without Associated Surface Features

We detected several hot spots where activity has rarely or never been seen before, some with no clear accompanying patera in *Galileo/Voyager* surface images. The most distinctive is a hot spot in **Chalybes Regio** [**56°N, 68°W**] which was active for the entire period of observation. There is no clear patera feature in this region (see Figure 5.6F), nor was activity detected here during the *Galileo* or *New Horizons* missions, apart from an HST NICMOS detection⁵ during the *Galileo* mission at $60 \pm 15^\circ\text{N}$, $60 \pm 15^\circ\text{W}$ (Lopes et al., 2007), which is consistent with this location within the large uncertainties. However, de Pater et al. (2014b) detected emission at this site from ground-based observations in 2010, suggesting that activity in this location began between 2007 and 2010 and continued for 5 or more years, either continuously or in episodes.

The location of the hot spot **PV59** [**38°S 290°W**] is well constrained, and is more consistent with the smaller dark-floored patera (PV59) a few degrees northwest of Ulgen Patera than with Ulgen Patera itself (PV56; see Figure 5.6AK). Past activity in this region has been attributed to Ulgen Patera; however, the location of PV59 is also consistent within uncertainties with the activity detected by NIMS and attributed to Ulgen Patera (Lopes et al., 2007), and is also closer than Ulgen Patera to the emission detected by *New Horizons* (Tsang et al. 2014). It is possible that this smaller patera has been the source of some or all of activity previously attributed to Ulgen Patera.

We detected faint activity at the following five hot spots where activity has never, or very rarely, been seen before: **Pfu374** [**25°S 49°W**], which we attribute to a light-floored patera at this location (see Figure 5.6D); **Shango Patera** [**33°N 97°W**]; **Pfu1063** [**41°N, 355°W**], where the emission may originate from a light patera at 43°N , 357°W (see Figure 5.6AU); and **Paive Patera** [**42°S, 0°W**]. Paive Patera was also detected on Io in eclipse in May 2008 (de Pater et al., 2016c). **P207** [**37°S, 91°W**] is a small dark-floored patera, where emission was not detected by *Galileo* but was seen with Keck in 2001 (Marchis et al., 2005).

The activity in **N Lerna Regio** [**57°S, 289°W**] may originate from a patera at this location (see Figure 5.6AL), and was also seen by *Galileo* and *New Horizons*. The hot spot identified as **PV170** [**48°S, 328°W**] may be associated with a bright-floored patera just west of Argos Planum, at 49°S , 330°W (see Figure 5.6AS).

Activity at **East Girru** [**21°N, 234°W**] was detected for the first time by *New Horizons* in 2007 (Tsang et al., 2014; Rathbun et al., 2014). We detected brief activity at this location in December 2013; if this emission originates from the same source, this means that activity started between the *Galileo* mission and 2007, and continued up through 2013, either

⁵J. Spencer and R. Howell

continuously or in sporadic eruptions. We did not detect further activity at this site after December 2013.

5.4.3 Eruption at Kurdalagon Patera

An unusual eruption took place in the spring of 2015 at Kurdalagon Patera. We first detected activity here on Jan 26, 2015; Kurdalagon Patera was bright on this date despite being below detection limits less than two weeks prior. When we next observed Kurdalagon Patera two months later on March 27, the activity level had dropped significantly. However, between Mar 29 and Apr 5 it flared up again to brighter than the January intensity. Following this second event, it steadily declined in brightness through the end of our observations. On the two dates of peak activity, the eruption was detected at both 2.2 and 3.8 μm . The best-fit eruption temperatures in both cases are near 1200 K, although we note that a correction was applied for geometric foreshortening, which can overestimate the short-wavelength flux density and hence temperature if actively erupting magma is responsible for a significant fraction of the thermal emission. A timeline of the eruption is shown in images in Figure 5.7 and plotted in Figure 5.8; this latter figure includes the multi-wavelength detection and best-fit temperature estimates.

At the start of the second eruption, we observed the regions containing Kurdalagon Patera and Sethlaus/Gabija Paterae on March 31 and April 1. Due to their close proximity and the limb viewing geometry, it is difficult to separate their emission with confidence. However, on March 31, Kurdalagon Patera was at $\mu=0.25$, while Sethlaus/Gabija Paterae were just on the far side of the limb, and we therefore attribute all emission on this date to Kurdalagon Patera. The following night, Kurdalagon was just on the limb while Sethlaus/Gabija Paterae were closer to $\mu=0.25$, and we attribute the emission on that date to the latter sources. In addition, if a cosine law for geometric foreshortening is relevant in these cases, the change in detected intensity over the course of our observation is more consistent with these identifications. However, it is possible that both sites contributed to the emission detected on both dates.

These timelines indicate that the peak eruption intensities at these sites occurred within just a few days of one another. In the three days prior, Kurdalagon Patera was at moderate intensity and Sethlaus/Gabija Paterae was increasing in brightness after a first detection on March 27. These two sites are separated by 500 km on Io's surface. Nearby sites erupting within days of one another have been seen in the past on Io; this phenomenon is discussed in Section 5.5.6.

5.4.4 Diminished Activity at Pele

Pele [18°S, 255°W] was consistently active on Io's disk throughout the *Galileo* mission (Davies et al., 2012), and maintained this level of activity through at least 2002, although its intensity dropped to 25% of its former level in 2011-2014 (de Pater et al. 2016b). In 2013-2015, Pele was consistently detected by Keck at low intensity whenever the geometry was favorable, but fell consistently below the detection threshold at Gemini N. These low

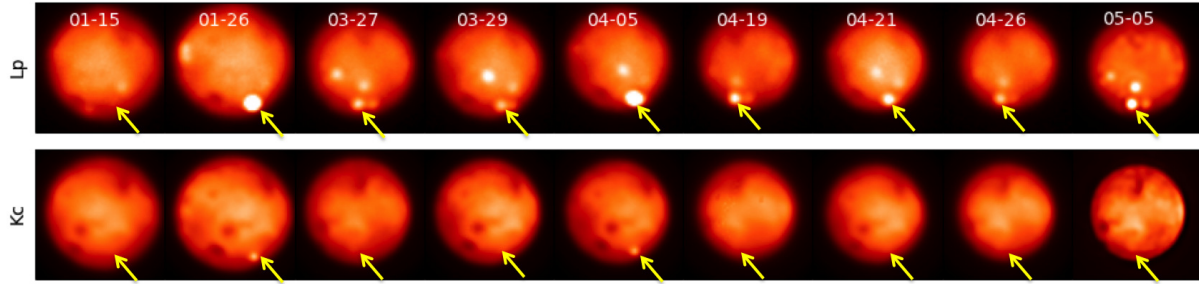


Figure 5.7: Observations of the progression of eruptions at Kurdalagon Patera in 2015. Arrows indicate location of Kurdalagon Patera.

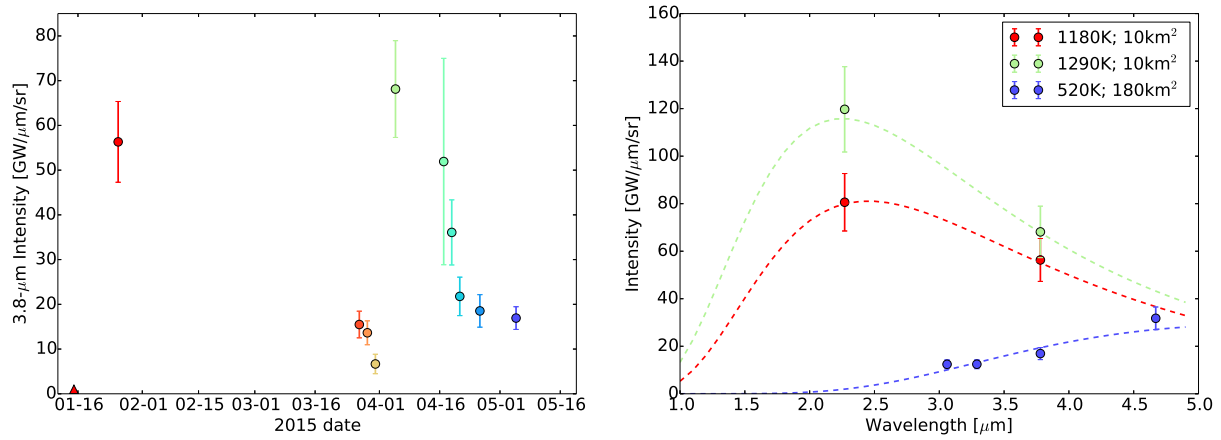


Figure 5.8: (Left) Timeline of 3.8- μm emission at Kurdalagon Patera in 2015. (Right) Best-fit temperature models on the dates when activity was detected at multiple wavelengths. Colors of points correspond between the two plots.

flux densities confirm that Pele's period of low activity that began by 2011 continued through the end of 2015.

5.4.5 Variability at Amirani

Amirani [21°N , 114°W] is the largest active lava flow field in the Solar System, and was detected consistently as a thermal source by *Galileo* NIMS. Davies et al. (2014) analyzed variability in emission at Amirani from NIMS observations, noting that the position of effusive activity changed over time, with a decreased intensity in 2001, which these authors attribute to magma depletion following an outburst event in February 2001 (Marchis et al., 2002). The level of activity we observe at Amirani is a factor of a 2 lower than the 2001 activity, and there is no major time-variability in our period of observation. As in the NIMS dataset, we find that the position of thermal emission changes between observations, possibly due to multiple active hot spots that we are unable to resolve. However, while Davies et al.

(2014) note mainly north-south differences in hot spot locations, we detect emission varying longitudinally only at the southern end of the flow field (see Figure 5.6P) near these authors' position 5, where only low-level activity was observed by NIMS. These position changes are consistent with the description of Amirani as a network of lava flows fed by lava tubes that extend for hundreds of kilometers, where thermal emission is observed where lava breaks out at the end of or along the lava tube system (Keszthelyi et al. 2001; Davies et al. 2014).

5.4.6 Loki Patera

We detected activity at **Loki Patera** [12°N , 310°W] every time the geometry was favorable, a total of 46 times during our campaign. This site is often the brightest hot spot on Io's disk, and has exhibited regular brightening episodes for decades; a model of Loki Patera as an overturning lava lake (Rathbun et al., 2002) has provided a good fit to past observations (Rathbun et al., 2006; Matson et al., 2006). We detected three brightening episodes in 2013-2015, which are analyzed in the context of the Matson et al. (2006) "magma sea" model in a companion paper (de Kleer and de Pater, 2016b).

5.5 Discussion

5.5.1 Comparison with past activity

The majority of the hot spots where we detected activity have been previously detected by spacecraft, indicating that sites typically stay active (or episodically resurge) for decades or longer. We detected activity at five sites that were not detected during the *Galileo* mission: PV170, Pfu1063, Paive Patera, East Girru, and Chalybes Regio. Activity at most of these sites was detected three or less times during our program, and three were detected only at Ms-band ($4.7\ \mu\text{m}$). East Girru was first detected by *New Horizons* (Spencer et al., 2007), and exhibited high time variability during these observations (Rathbun et al. 2014). We detected activity here three times in December 2013, when it exhibited moderate L'-band intensities. Table 5.1 compares the locations where we detected emission with past detections by the *Galileo* (or ground-based support) and *New Horizons* missions, and whether any plume has been seen in the past.

Table 5.1: Hot Spot Activity Summary

ID	Candidate Surface Feature	P,PV,Pf ^a	Approx. Lat ^b [°N]	Approx. Lon ^b [°W]	$F_{3.8,max}$ [GW/μm/sr]	N _{det} [#]	Detected during <i>Galileo</i> era? ^c	Detected by <i>New Horizons</i> ? ^d	past plume activity? ^e
A	Uta Patera	PV183	-34.4±0.9	22.8±2.1	5.1	21	Keck	-	no
B	Kanehekili Fluctus	Pfu1730	-16.8±1.2	33.8±1.9	1.5	7	NIMS, SSI	LEISA, LORRI	yes
C	Janus Patera	Pfu1723	-4.3±0.6	38.3±1.8	10.7	32	NIMS, SSI	LEISA	no
D	Pfu374	Pfu374	-24.6±0.8	49.2±1.9	<1	3	-	-	no
E	Masubi Fluctus	PfD1737	-42.3±0.6	55.1±1.5	2.8	5	NIMS, SSI	LEISA	yes
F	Chalybes Regio	-	55.7±2.0	68.3±4.5	9.8	22	HST? ^f	-	no
G	Zal Patera	P182	38.3±1.5	74.4±2.8	4.6	19	NIMS, SSI	LEISA, LORRI	yes
H	Tawhaki Patera	P229	3.2±0.7	75.8±1.3	4.5	11	NIMS, SSI	LEISA	no
I	Aluna Patera	P192	41.7±1.3	89.9±1.6	<1	2	SSI, NIMS 131E	-	no
J	Gish Bar Patera	P178	15.2±0.6	89.0±1.5	7.3	13	NIMS, SSI	-	no
K	P207	P207	-36.5±1.2	91.1±0.8	5.0	1	Keck	-	no
L	Shango Patera	P179	33.2±0.9	96.9±2.9	<1	3	NIMS	-	no
M	Sigurd Patera	P219	-4.9±1.0	98.3±2.1	5.9	8	NIMS	-	no
N	Itzamna Patera	P221	-14.4±0.6	98.9±0.9	2.6	4	NIMS	-	no
O	P197	P197	-46.5±1.7	107.3±2.1	11.6	11	NIMS I32G	-	no
P	Amirani	Fd2021	20.9±1.0	113.7±2.8	4.1	12	NIMS, SSI, Keck	LEISA, LORRI	yes
Q	Dusura Patera	P161	36.2±0.8	121.6±1.3	8.1	3	NIMS	-	no
R	Malik Patera	P120	-33.0±1.2	129.4±1.8	6.9	8	NIMS	LEISA	no
S	Thor	-	40.4±1.2	135.0±1.6	<1	2	NIMS	LEISA	yes
T	P123	P123	-41.6±0.6	139.8±3.2	4.5	3	NIMS I32H/1	-	no
U	Tupan Patera	P97	-17.8±0.5	140.1±2.8	1.6	3	NIMS	LEISA	no
V	Surya Patera	P55	21.3±0.5	149.3±0.9	3.5	4	NIMS	-	yes
W	Prometheus	P86	-1.0±0.7	153.6±2.0	5.3	13	NIMS, SSI	LEISA	yes
X	Culann (NW)	Fd1891	-16.2±0.8	162.3±3.3	2.1	5	NIMS, SSI	LEISA	yes
Y	Sethlaus/Gabija Paterae	P134/P136	-50.0±0.8	198.2±1.2	32.6	6	NIMS	LEISA, LORRI	no
Z	Isum Patera	P170	31.9±0.4	209.2±0.5	<1	1	NIMS, SSI, PPR	LEISA, LORRI	no
AA	Marduk Fluctus	P32	-23.9±1.3	210.7±3.4	9.1	29	NIMS, SSI, PPR	LEISA, LORRI	yes
AB	Kurdalagon Patera	P142	-48.8±1.4	221.3±2.8	68.1	11	NIMS, PPR	LEISA, LORRI	yes
AC	Susanoo/Mulungu Paterae	P2/P1	18.8±1.6	221.9±2.4	3.7	8	NIMS, SSI, PPR	LORRI	no
AD	201308C	-	29.0±1.0	229.8±2.5	>500	11	NIMS I32A?	-	no
AE	East Girru	-	21.4±0.8	233.5±1.2	5.3	3	-	LEISA, LORRI	no
AF	Pyerun Patera	PV26	-57.7±1.9	237.1±2.3	<1	1	Voyager IRIS	-	no
AG	Pillan Patera	P147	-11.5±0.4	245.4±1.5	7.5	7	NIMS, SSI, PPR	LORRI	yes
AH	Chors Patera	-	64.8±1.2	246.7±3.7	56.7	5	PPR	-	no
AI	Pele	PV30	-18.1±1.0	255.0±2.5	6.9	10	NIMS, SSI, PPR	LEISA, LORRI	yes
AJ	Mithra Patera	PV39	-58.1±0.9	266.2±2.4	54.5	4	SSI, PPR	-	no
AK	PV59	PV59	-38.4±1.5	290.0±2.4	17.5	8	NIMS, PPR	LEISA	no
AL	N Lerna Regio	-	-57.3±1.2	288.8±5.3	7.1	8	PPR at 62S 292W	LEISA, LORRI	yes
AM	Amaterasu Patera	PV78	39.4±0.8	304.3±1.1	43.1	1	NIMS, PPR	-	yes
AN	Rarog Patera	PV73	-38.7±2.0	306.0±2.6	325	14	PPR	-	no
AO	Heno Patera	PV85	-56.0±1.3	307.2±1.8	270	7	PPR	LEISA	no ^g
AP	Loki Patera	PV81	12.0±1.0	308.2±4.2	136	46	NIMS, SSI, PPR	LEISA	yes

AQ	Tol-Ava Patera	PV106	0.7±0.7	326.2±1.2	8.3	4	PPR	LORRI	no
AR	Fuchi Patera	PV122	28.3±1.1	328.7±1.1	1.0	1	SSI, PPR	-	no
AS	PV170	PV170	-47.8±1.6	327.9±1.8	11.6	3	-	-	no
AT	Surt	PV131	44.3±1.3	334.0±2.3	< 1	2	HST, Keck	LEISA	yes
AU	Pfu1063	Pfu1063	40.5±1.7	355.2±2.4	2.3	3	-	-	no
AV	Paive Patera	PV171	-42.1±1.5	359.6±1.6	< 1	1	Voyager	-	no

^aWhen available, the listed patera designations (P/PV) are from the Radebaugh (2005) analysis of *Galileo* observations. Otherwise, patera floor unit (Pf) designations are given; the identifiers correspond to the object ID numbers in the IoGeoUnits_Smooth layer of the ArcGIS database from the Williams et al. (2011a, 2011b) mapping project.

^bLatitudes and longitudes are for the average location calculated for each hot spot, given in Table A.2.

^cLopes et al., 2004; 2007; Veeder et al., 2015

^dSpencer et al., 2007; Rathbun et al., 2014; Tsang et al., 2014

^eGeissler et al., 2004; Lopes et al. 2007; Spencer et al., 2007

^fHST NICMOS at 60±15N, 60±15W, detected by J. Spencer and R. Howell

^gWhile plumes have not been observed at Loki Patera, they have been seen at Loki, a linear feature a few degrees to the northeast of Loki Patera.

Of the new hot spots, only Chalybes Regio was detected consistently throughout the period of observation. Activity here was not detected by *Galileo* or *New Horizons*, though an HST NICMOS detection during the *Galileo* mission with errorbars of $\pm 15^\circ$ in latitude and longitude (Lopes et al., 2007) is consistent with its location. Apart from this, the first documented activity at this location was in 2010 Keck observations (de Pater et al., 2014b). There are no apparent features indicative of recent volcanic activity in spacecraft images, though the region is full of undivided and bright flows (Williams et al., 2011a; 2011b), indicating activity in this area in the distant past. In addition, there was no evidence for surface changes in this region in *New Horizons* images from 2007 (Spencer et al., 2007). It appears that this is a new active hot spot, or an older volcanic center becoming active again after a long interval of inactivity. A future detection of new flows or deposits in this region by spacecraft or high-resolution visible imaging would substantiate this possibility.

The LEISA instrument (1.25-2.5 μm) detected 37 active hot spots during the *New Horizons* fly-by of the Jupiter system in 2007 (Tsang et al. 2014); 90% of these were active during the *Galileo* era, indicating that most hot spots are active on decadal timescales. Of the 37 hot spots detected during the *New Horizons* fly-by, we detected activity at only 25 (67%) of them. If activity at the remaining sites continued through 2015, their emission was below our detectability threshold.

While the same hot spots appear to stay active on Io for decades, the relative intensities at different locations varies greatly. Veeder et al. (2015) identify the least powerful hot spot measurable from *Galileo* data as P197, and the most powerful eruption during the same years as Surt (measured from the ground by Keck; Marchis et al., 2002). While we detected thermal emission from both sites during our program, P197 stayed active at a moderate level of activity for over a year, while Surt was barely detected twice, and only at 4.7 μm . We also detected no activity at Tvashtar Paterae, which has exhibited bright outbursts in the past (Howell et al., 2001; Milazzo et al., 2005), and was the most powerful event observed in 2006-2007, detected from the ground and by *New Horizons* (Laver et al., 2007; Spencer et al., 2007; Rathbun et al., 2014). Other sites that have exhibited past bright eruptions include Kanehekili Fluctus and Pillan Patera (detected from the ground: Marchis et al., 2002; de Pater et al., 2014; de Pater et al., 2016a, and by *Galileo*: Keszthelyi et al., 2001; Davies et al., 2001), which were all at or below our detection threshold in 2013-2015, until the eruption at Pillan Patera in Feb 2015 (de Pater et al., 2016a). It appears that the sites that host the most powerful eruptions also exhibit the greatest time variability, often remaining below the detection threshold for long periods of time before brightening abruptly. In contrast, sites such as Marduk Fluctus and Janus Patera have held steady at low to moderate brightness for decades without exhibiting such brightening events. This difference can be understood in terms of the longer period of repose necessary to recharge a system after a major eruption with a large volume discharged, before another eruption is possible (Davies 2007).

5.5.2 Eruption classification

In our dataset, we find a clear distinction between two observational classes of hot spots: those that exhibit brief activity involving a pattern of sudden appearance and decay, and

Table 5.2: Classification of Hot Spots

Persistent Activity	Sudden Brightening Events			Both
	Outbursts	Mini-Outbursts ^a	Other	
Marduk Fluctus	Rarog Patera	Sethlaus/Gabija Paterae	Sigurd Patera	Loki Patera
Uta Patera	Heno Patera	Kurdalagon Patera	East Girru	P197
Janus Patera	201308C	Chors Patera	PV59	
Chalybes Regio		Mithra Patera	Malik Patera	
Zal Patera		Pillan Patera	Dusura Patera	
Tawhaki Patera		Amaterasu Patera	PV170	
Gish Bar Patera			Tol-Ava Patera	
Amirani				
Prometheus				
Pele				

^aSee Section 5.5.6.

those that exhibit long-lived activity with low time variability and moderate intensities. The timelines of the hot spots in each class are compared in Figure 5.9. We define and characterize these two eruptions classes as follows:

1. *Hot spots exhibiting sudden brightening events:* These hot spots are typically below the detectability threshold until a sudden increase in brightness, which is followed by a steady decay typically over a timescale of ~ 1 month. The peak L'-band brightness are 5-10 GW/ $\mu\text{m}/\text{sr}$ or higher, and may even exceed 500 GW/ $\mu\text{m}/\text{sr}$. Every single detection of an L'-band intensity over 15 GW/ $\mu\text{m}/\text{sr}$ in our dataset is associated with such a brightening event. The 16 hot spots included in this category are listed in Table 5.2.

2. *Persistent hot spots:* Hot spots in this category were consistently active for >1 year (and usually for the entire duration of the program), and were detected whenever the geometry was favorable during their period of activity. They exhibit low time-variability, typically remaining within a factor of a few in brightness. They also maintain a low to moderate L'-band brightness; no detection of a consistently-detected hot spot exceeds 15 GW/ $\mu\text{m}/\text{sr}$. This category includes the 10 hot spots listed in Table 5.2.

Loki Patera and P197 exhibit eruption events despite being persistently active, and we consider them in both categories. An additional 20+ hot spots were detected too few times to confidently classify them into either category. While bright eruptions preferentially occur at high latitudes and on the trailing hemisphere, we see long-lived eruptions of moderate brightness located preferentially at equatorial latitudes and on the leading hemisphere. This phenomenon is analyzed in de Kleer and de Pater (2016a).

The distinction between hot spots characterized by persistent (months to years) or sporadic (short-lived events) activity was also present in the *Galileo* dataset, as discussed in Lopes-Gautier et al. (1999). While these authors find hot spots to be evenly distributed on the surface, they also find persistent hot spots located preferentially at equatorial latitudes.

We identify 10 persistent hot spots, while 22 were identified in *Galileo* NIMS data (Lopes-Gautier et al., 1999). We note that our definition requires persistent hot spots to be *consistently* detected, while these authors only require detections over a >1 year period. If we

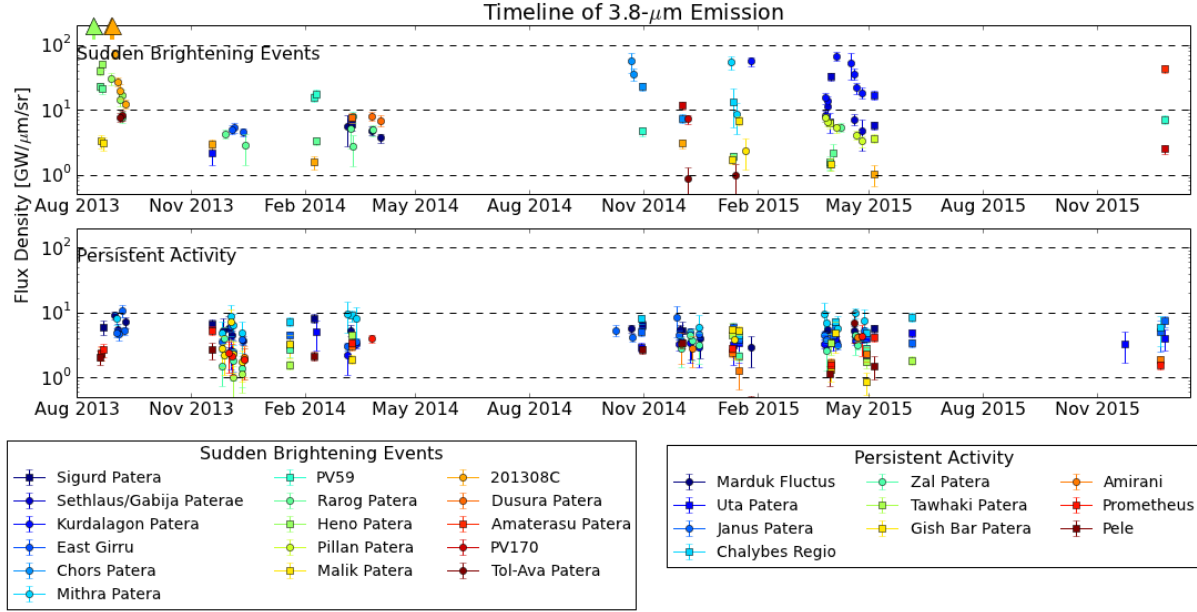


Figure 5.9: Comparison of thermal emission timelines for the two classes of hot spots defined in Section 5.5.2. The two classes are clearly distinguished by eye in terms of the peak brightness obtained, and the duration of activity. The two hot spots that fall into both categories (P197 and Loki Patera) are omitted.

adopt the latter definition, we find that of the 22 long-lived spots identified in the NIMS data, 16 of them were also active for >1 year in our dataset. In addition, of the 15 bright, sporadic hot spots identified in our dataset, only three were active for 1 year or more during the *Galileo* mission.

This consistency over decadal timescales supports the hypothesis that eruption characteristics represent physically-distinct eruption styles (Davies et al. 2010; Veeder et al. 2012). Davies et al. (2010) present a method to distinguish between different eruption styles based on their thermal signatures, in particular the time-evolution of their 2-to-5- μm radiant flux densities, based on a comparison with thermal signatures of volcanism on Earth. We do not typically detect thermal emission at 2 μm and in general cannot interpret our observations using this metric. However, the temporal variability and peak brightnesses can be used to broadly associate persistent hot spots with insulated flow fields or lava lakes, and hot spots with brightening events as lava fountains, open sheet flows, or break-outs in lava flow fields (Davies et al. 2010).

5.5.3 Searching for periodicity in volcanic activity level

Io's volcanic activity is powered by periodic tidal forcing from Jupiter, and we might therefore expect to see periodic variations in Io's activity level with its orbit, or on longer timescales associated with secondary factors such as the orbits of Europa and Ganymede, or

possible obliquity tides such as has been hypothesized for Europa's plumes (Rhoden et al., 2015). However, we note that the periodic forcing is modulated by many geological factors, and will not necessarily lead to periodic volcanic activity.

We search for periodic behavior in the level of volcanic activity on Io, parameterized by the total volcanic L'-band emission on each date of observation. We employ a generalized Lomb-Scargle analysis (Scargle 1982; Zechmeister and Kürster, 2009), which is designed for frequency analysis of unequally-spaced time-series data. The generalized Lomb-Scargle periodogram is shown in Figure 5.10 including the 50% and 90% significance thresholds. We do not find significant periodicity at Io's orbital period or any multiples thereof. The cluster of low-significance peaks in this vicinity may be due in part to the fact that bright eruptions may last for many days, and observations separated by an interval near Io's period will catch the same eruption.

The strongest signal we detect is at a period of 14.937 days. Figure 5.10 shows the data phased to this period, and demonstrates that the periodicity is due almost exclusively to observations during the Earth-approaching phase of Io's orbit. It is difficult to distinguish trends in volcanic activity with orbital phase from trends with longitude, since (from Earth) the same longitudes are always observed at the same orbital phase. However, observations at times far from either opposition sample both leading and trailing hemispheres simultaneously, and can help distinguish between these two scenarios. If we consider only hot spots in the leading hemisphere of Io, the noted periodicity is not present, while when we consider only observations in the leading phase of Io's orbit (as is shown in Figure 5.10) it is apparent. If this trend is real, it is therefore more correlated with orbital phase than with the longitudes of hot spots.

We consider this signal tentative; additional observations will be needed to confirm its validity, and in particular observations which trace Io's total volcanic heat flow rather than intensity at a single wavelength.

5.5.4 How long do eruptions last?

Constraints on typical eruption durations are crucial for constraining the contribution of an individual hot spot to Io's total heat flow, and for determining the physical mechanisms at play. Of the hot spots where we detected thermal activity, a quarter of them stayed active for a year or more, at moderate intensity and with only moderate time variability (within a factor of a few). Another third exhibited discrete eruption phases, where the emission either appeared or increased rapidly, followed by a monotonic decline in intensity. In nearly all cases, this decline occurred over a matter of days to weeks; we find that with the exception of the outburst eruptions, most events have declined to half their peak detected level after 10-30 days. The three outbursts we detected decreased in intensity by a factor of 10 in a matter of days, probably marking the transition from lava fountaining to effusive flows (de Kleer et al., 2014; de Pater et al., 2016a). Figure 5.11 compares the timelines for appearance and decay of all the bright discrete eruption events detected. The rate of decay appears somewhat correlated with the peak intensity. However, this may be an artifact arising from the fact that we generally do not capture the actual peak eruption intensity.

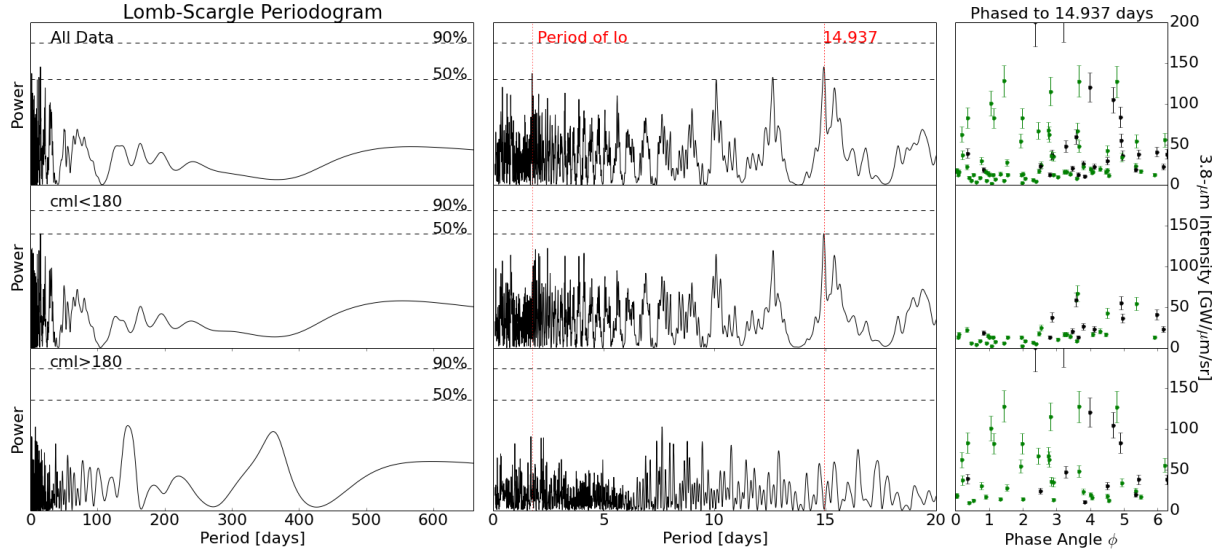


Figure 5.10: Generalized Lomb-Scargle periodogram for total volcanic L'-band emission as a function of date, separated into all data (top), and data with central meridian longitude (cml) above or below 180° , indicative of orbital phase. The middle panels show a zoom-in of the periods between 0-20 days, and the right panels show the data phased to 14.937 days, the strongest signal in the periodogram. The dashed lines indicate confidence levels, based on bootstrap resampling.

Of the remaining events, several were detected only a few times in a period of 1-3 months, and the rest were either too near the detection threshold or detected too few times to draw conclusions about their durations.

5.5.5 Power output of different eruption classes

The total time-averaged power of a given hot spot is dictated by both the power emitted when active, and the duration of activity. In most cases, the duration of activity is a better predictor of total power than the peak power emitted. While a low-power hot spot may generate only 100 GW compared to the peak outburst powers of 50+ TW, the time-averaged power of a smaller, continuously-active hot spot will still dominate over that of the outburst. Indeed, Veeder et al. (2012) estimate that although outbursts are the most powerful class of eruptions on Io, they contribute less than 4% of the total heat flow from Io's surface because they are both infrequent and short-lived. We can only constrain the power output for $\sim 30\%$ of our detections, and therefore cannot quantify the distribution of volcanic heat flow in our observations with precision. However, we make a rough estimation based on the measurements where we do constrain power. We take an average power output of 200 GW for moderate, long-lived hot spots, and an average power of 1 TW over a 15-day period for eruption events. Using these numbers, a moderate long-lived hot spot will contribute $\sim 5\times$ as much to Io's total heat flow as a violent but short eruption. Although we detect 50% more

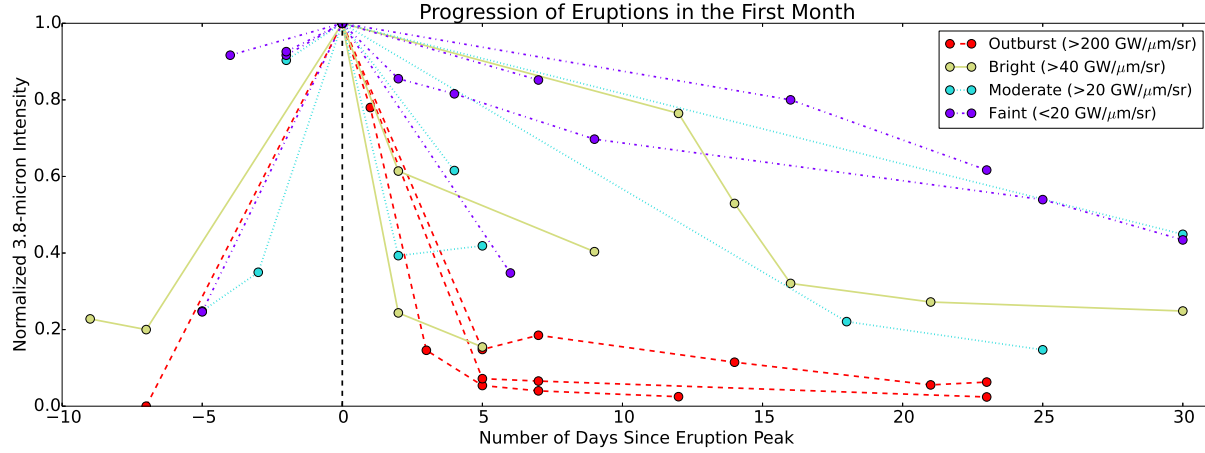


Figure 5.11: Comparison of eruption timelines for all hot spots that exhibited “eruption phases”, defined as a sudden brightening followed by a steady decay. The timelines demonstrate the evolution of emission at a wavelength of $3.8 \mu\text{m}$.

hot spots exhibiting eruption events than persistent hot spots, we estimate based on these numbers that long-lived hot spots dominated Io’s volcanic heat flow during 2013-2015.

5.5.6 Frequency and Timing of Large Eruptions

Due to the very low number of outburst events ever detected on Io, it has been difficult to estimate the frequency of their occurrence and to characterize their properties. An outburst is defined empirically as an event which doubles Io’s total $5\text{-}\mu\text{m}$ intensity (Blaney et al., 1995; Spencer and Schneider, 1996). Based on 55 nights of observation, Veeder et al. (1994) estimated that outbursts occur 4% of the time. The occurrence of three outburst events in a two-week period in August 2013 suggested that such events may be more common than this, and led de Pater et al. (2014) to update the estimate to 10% for the chance of detecting an outburst on a given night, based on 75 nights of observation. However, following these three outburst events in August 2013, no others were detected during the remaining 90+ nights of our observing period, although it is possible that some of the eruptions we detected which were bright but not of outburst scale may have been outburst events that we did not detect until they had passed the brightest phase of the eruption.

We identify a second class of bright “mini-outburst” eruptions, whose peak $3.8\text{-}\mu\text{m}$ emission is a factor of ~ 5 too low to qualify as outburst eruptions, but whose eruption characteristics resemble those of outbursts. These characteristics include a sudden appearance of emission, rapid decay, high peak brightness, and high short-wavelength emission (when measured). We identify five such eruptions in our dataset, all of which appeared abruptly, exhibited rapid time-variability, and reached peak $3.8\text{-}\mu\text{m}$ intensities of $30\text{-}80 \text{ GW}/\mu\text{m}/\text{sr}$: Kurdalagon Patera, Chors Patera, Mithra Patera, Sethlaus/Gabija Paterae, Amaterasu Patera. In the case of Kurdalagon Patera, we also detect high thermal emission at $2.3 \mu\text{m}$.

These “mini-outbursts” may be caused by a similar physical mechanism as outburst eruptions operating on a smaller scale, i.e. lava fountains and open channel flows (Davies et al. 2010). Eruptions in this “mini-outburst” class have been seen before, for example at Tung Yo Patera and Sui Jen Patera in 2004; South of Babbar Patera in 2005 (de Pater et al. 2016b); and Kanehekili Fluctus in 2010 (de Pater et al. 2014b). All four of these eruptions had peak $3.8\text{-}\mu\text{m}$ intensities in the same range as those of our dataset.

The occurrence of three outburst eruptions within a two week period, followed by a lack of detections in the subsequent two years, indicates that either the outburst frequency estimate needs to be lowered again and the three events detected in August were a rare coincidence, or that outbursts are correlated in time. There is some precedent for outburst events occurring closely-spaced in time. In 1996, two outbursts were detected just over a month from one another, at 16 and 35°W (Stansberry et al., 1997). Two outbursts were also detected within 3 days of one another in February 2001, at Amirani and Surt (at 118 and 340°W), following only two months after an outburst at Tvashtar in December 2000 (at 120°W) (Marchis et al., 2002; Milazzo et al., 2005).

A similar effect is seen within the “mini-outburst” class. The eruptions at Kurdalagon Patera and Sethlaus/Gabija Paterae in Apr/May 2015 began abruptly within a few days of one another; these sites are separated by ~ 500 km. Nearby sites erupting within days of one another were also seen in the eruptions at Tung Yo Patera and Sui Jen Patera on 28 and 30 May 2004 (de Pater et al., 2016b). The phenomenon of volcanic eruptions occurring in pairs within a two-day period and up to a separation of 200 km has been observed on Earth (Linde and Sacks, 1998; Manga and Brodsky, 2006; Williams 1995), although the mechanisms are not well understood. The correlation disappears at a separation greater than 200 km, suggesting either a regional seismic trigger for both eruptions, or the triggering of one volcano by the other due to eruption-generated earthquakes (Manga and Brodsky, 2006). Triggering of eruptions by earthquakes has been documented up to distances of 1000 km or more (Hill et al. 1993). Such a mechanism could operate over longer distances on Io if eruptions generate more intense shaking, or seismic waves propagate longer distances, on Io than on Earth. However, a localized phenomenon such as a seismic trigger is difficult to invoke over the longer distances that separate some of the past outburst eruption pairs. It is clear that we still do not have a good understanding of the frequency and triggering mechanisms for these high-energy events.

5.5.7 Potential impact on Jupiter system: Connection to the EXCEED Mission

Our observations overlap with observations of the Jupiter system by the ISAS/JAXA EXCEED Mission on board the SPRINT-A Earth-orbiting satellite (Ueno et al., 2011; Murakami et al., 2012), which also began in 2013. One of the goals of this mission is to observe the Io-Jupiter plasma system in the Extreme-UV for multiple continuous months, to investigate plasma torus phenomena including the timescales and causes of variability in the torus brightness. Because Io’s volcanically-produced atmosphere is the source of plasma torus con-

stituents, a timeline of Io's simultaneous volcanic activity is crucial for understanding the processes that bring particles and gas from Io into the plasma torus. Io's massive volcanic plumes inject gas and material into Io's primary atmosphere that may lead to a spike in the supply of neutral and ionized material to the sodium cloud and plasma torus.

The connection between variability in Io's volcanic activity and the plasma torus brightness is complicated by the fact that Io hosts many different styles of volcanic activity, only some of which have been seen to produce plumes (e.g. Geissler et al., 2008). The intensity of an eruption alone is insufficient to predict whether a plume is present, nor is the scale of thermal emission necessarily correlated with plume emission. In addition, plumes themselves vary greatly in magnitude and in gas-to-particle ratio (McEwen and Soderblom, 1983; Johnson et al., 1995), and spacecraft observations of plumes via scattered sunlight are sensitive only to the dusty component (Geissler and Goldstein, 2004). We can nevertheless gain some insight into which active sites are most likely to host plumes based on where plumes have been observed in the past. Of the sites where we observed thermal activity, the following were seen to host plume activity by *Galileo*, based either on direct observation or new surface deposits: Kanehekili Fluctus, Masubi Fluctus, West Zal Patera, Amirani, Thor, Prometheus, Culann Patera, Marduk Fluctus, Pillan Patera, Pele, and Surt (Geissler et al., 2004; Geissler and MacMillan 2008). *New Horizons* additionally detected plume activity at N. Lerna and Kurdalagon Patera (Spencer et al., 2007). Of the sites listed, only Marduk Fluctus, Pillan Patera, and Kurdalagon Patera hosted moderate to bright thermal activity during our program. We note that past plume activity cannot be ruled out by a lack of *Galileo* detection, as a lack of dusty material can make a plume invisible even if it hosts significant gas emission (Johnson et al., 1995).

In early 2015, a brightening in the sodium cloud was detected from D-line emission (Yoneda et al., 2015). The event began in mid-January and peaked just past mid-March, after which the sodium cloud brightness decreased to below its pre-brightening level by April. An accompanying response was seen in the plasma torus, with an increase in S^+ emission intensity followed by an increase in S^{2+} and S^{3+} emission in January-February 2015, followed by a decay to baseline levels by mid-May (Tsuchiya et al., 2015). A second, smaller brightening of the sodium cloud was seen in April-May.

Two bright eruptions took place during this time period: at Kurdalagon Patera and Pillan Patera. Kurdalagon Patera became detectable in the NIR between January 15 and 26, and reached peak intensity twice, at the end of January and again at the beginning of April, before diminishing during April and May (see Section 5.4.3). The eruption at Pillan Patera was detected on Feb 18⁶ (de Pater et al., 2016a) and had diminished substantially by the following month. Both sites have hosted plume activity in the past.

The timing of the eruption at Kurdalagon Patera is more consistent with the onset of the sodium cloud brightening, and the second smaller brightening accompanying the second eruption at Kurdalagon strengthens this case. While the two eruptions at Kurdalagon Patera were of similar intensity and temperature, the two sodium cloud brightenings were vastly different in magnitude. However, the gas emission from volcanoes on Earth varies greatly

⁶Detected at the IRTF by R. Howell

even within the course of a single eruption (Gerlach and McGee, 1994; Sutton and Elias, 2014), and it is possible that the first eruption at Kurdalagon Patera was accompanied by a large outgassing of volatiles, while the second was not.

We emphasize that the link between thermal emission, plume activity, and the plasma torus brightness depends heavily on many complex processes that are poorly understood, and that longitude-time coverage of Io is always incomplete. The association between these two eruptions and the sodium cloud brightening is therefore speculative, but represents a plausible scenario based on the abrupt onset of bright activity at these sites where plumes have been active in the past, coincident with the brightening of the neutral cloud and plasma torus.

5.6 Conclusions

We imaged Io in the near-infrared with adaptive optics on 100 nights from August 2013 through December 2015 at the Keck and Gemini N telescopes. This dataset represents the most complete coverage of activity at individual hot spots over a multi-year period to date. Our main conclusions are as follows:

1. **Volcanic Activity Timeline:** We present the positions and intensities of over 400 detections of 48 hot spots, and a timeline of global activity on Io. When observations were made at two or more wavelengths (30% of detections), we present the estimated temperatures and powers. Io's global level of volcanic activity varies widely in time. There was widespread bright activity on Io in Aug-Sep 2013 and from Oct 2014 through the spring of 2015. However, no bright hot spots were detected from Nov 2013-May 2014 despite good coverage during much this time. A search for periodicities in the timeline of total volcanic L'-band emission finds only a tentative signal at 14.937 days, due primarily to observations during the Earth-approaching phase of Io's orbit. In particular, we do not find a strong periodicity associated with Io's orbital period or any multiple thereof.
2. **Detection Limits:** We perform an extensive analysis of the detection limits and retrieval uncertainties for hot spots detected with Keck/NIRC2 L' and Ms filters, and Gemini N/NIRI L' filter. Based on this analysis, we establish upper limits on hot spot non-detections and quantify the accuracy of intensity and position retrievals as a function of flux density and emission angle. These are incorporated into our own results, and can be used by others in future observation planning and analysis.
3. **Eruption Classifications:** We classify the detected hot spots into two observationally-distinct categories: (1) Hot spots exhibiting eruption events, which are highly time-variable and reach a peak L'-band intensity of 5-10 GW/ $\mu\text{m}/\text{sr}$ or more, and often greater than 50 GW/ $\mu\text{m}/\text{sr}$; (2) Persistent hot spots, which are consistently detected for one year or more, exhibit low time variability, and never exceed an L'-band intensity of 15 GW/ $\mu\text{m}/\text{sr}$. Of the 48 hot spots we detected, 16 exhibited bright eruptions,

10 were persistently active, and 2 exhibited characteristics of both categories. The remaining hot spots were too faint or detected too few times to classify. A comparison with persistent hot spots identified in the NIMS dataset (Lopes-Gautier et al., 1999) indicates that eruption characteristics often stay constant for a decade or more. Of the hot spots that exhibited bright eruptions, the activity typically began abruptly, increasing from undetectable to peak brightness in a matter of days to weeks. The timescale for decay is of the order of 10-30 days, with more rapid decay for outburst eruptions. We find that persistent hot spots dominate over bright eruption events in terms of contribution to Io's total heat flow.

4. **Comparison to Past Activity:** Of the 48 hot spots detected, all but five were seen during the *Voyager* or *Galileo* missions (by spacecraft or ground-based support). Of these five, most exhibited only small-scale activity, and may be associated with nearby paterae on the surface. The exceptions are East Girru, which was first detected in 2007 by *New Horizons*, and was active briefly with moderate intensity in 2013; and Chalybes Regio, which was consistently active throughout our observations, and was first detected in 2010 (de Pater et al., 2014b). Neither of these sources is near a volcanic surface feature, and both may represent locations of new volcanic activity since the *Galileo* mission. Future observations of new surface flows or deposits could confirm this possibility.
5. **Outburst Eruptions:** After the three outburst eruptions in August 2013 (de Kleer et al. 2014; de Pater et al. 2014a), we detected no other eruptions of outburst scale, despite observing on 90 more nights over the subsequent two years. However, we identify five “mini-outburst” eruptions, which exhibit the temporal characteristics of outburst eruptions but whose intensity is a factor of ~ 5 too low ($3.8\text{-}\mu\text{m}$ intensities of $30\text{-}80\text{ GW}/\mu\text{m}/\text{sr}$). These eruptions may be outburst events caught after their peak brightness, or eruptions generated by a similar physical mechanism operating on a smaller scale. The clustering of the three outburst eruptions into a two-week time period, and the occurrence of two of the mini-outbursts within a few days of one another, is intriguing. Some previous detections of large eruptions have also included multiple events in a short time period, although the total number of outburst events observed to date is too small to draw definitive conclusions.
6. **Eruption at Kurdalagon Patera:** We detected bright eruptions at Kurdalagon Patera on Jan 26 and April 5 of 2015, with measured temperatures of $\sim 1200\text{ K}$. Kurdalagon was not detected prior to this date, in particular 11 days earlier on Jan 15 when the viewing geometry was favorable. Between the two eruptions, activity dropped to a moderate level.
7. **Implications for the Jovian system:** Our observations covered a period of time when the Sprint-A/EXCEED Mission was observing the Io plasma torus, and ground-based support observations were monitoring the sodium cloud. Near the end of January 2015, a brightening of the sodium cloud and plasma torus was observed (Yoneda et

al., 2015; Tsuchiya et al., 2015). This timing coincides with the sudden brightening of Kurdalagon Patera, and suggests the possibility that the brightenings may have been caused by an influx of neutral material from a plume at Kurdalagon Patera. This possibility is supported by a past detection of plume activity at Kurdalagon by *New Horizons* (Spencer et al., 2007). In addition, a second sodium cloud brightening of a much smaller scale occurred simultaneously with the second eruption at Kurdalagon Patera in April 2015.

These data demonstrate the continued value of frequent, ground-based observations of Io in the near-infrared. Such observations can be very brief (<30 minutes/night) and have high scientific benefit. Between spacecraft and ground-based observations, the database of Io observations is becoming sufficiently large to begin to look at statistical properties such as periodic behaviors and the correlation of eruption properties with latitude and longitude, which are important clues for understanding the tidal forcing and heat dissipation that power Io's volcanic activity. Consistent high-cadence observations over long time baselines are needed to gain additional information on the timeline of activity, typical eruption duration and variability, and outburst frequency. As demonstrated here, good time coverage of Io's volcanic activity is particularly valuable during missions such as EXCEED and the upcoming *Juno* arrival, when the data can be tied to other components of the Jovian system.

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Chapter 6

Spatial Distribution of Io's Volcanic Activity from Near-IR Adaptive Optics Observations on 100 Nights in 2013-2015

The extreme and time-variable volcanic activity on Jupiter's moon Io is the result of periodic tidal forcing. The spatial distribution of Io's surface heat flux provides an important constraint on models for tidal heat dissipation, yielding information on interior properties and on the depth at which the tidal heat is primarily dissipated. We analyze the spatial distribution of 48 hot spots based on more than 400 total hot spot detections in adaptive optics images taken on 100 nights in 2013-2015 (data presented in de Kleer and de Pater, 2016). We present full surface maps of Io at multiple near-infrared wavelengths for three epochs during this time period, and show that the longitudinal distribution of hot spots has not changed significantly since the *Galileo* mission.

We find that hot spots that are persistently active at moderate intensities tend to occur at different latitudes/longitudes than those that exhibit sudden brightening events characterized by high peak intensities and subsequent decay phases. While persistent hot spots are located primarily between $\pm 30^\circ\text{N}$, hot spots exhibiting bright eruption events occur primarily between 40° – 65° in both the northern and southern hemispheres. In addition, while persistent hot spots occur preferentially on the leading hemisphere, all bright eruptions were detected on the trailing hemisphere, despite the comparable longitudinal coverage of our observations to both hemispheres. A subset of the bright hot spots which are not intense enough to qualify as outburst eruptions resemble outbursts in terms of temporal evolution and spatial distribution, and may be outbursts whose peak emission went unobserved, or else scaled-down versions of the same phenomenon. A statistical analysis finds that large eruptions are more spatially clustered and occur at higher latitudes than 95% of simulated datasets that assume that eruptions occur at random and independent locations.

The preferential occurrence of bright, violent eruptions at higher latitudes supports the idea that a deeper magma source supplies these events, as has been previously hypothesized.

The monotonic eastward progression of bright eruptions at southern latitudes from 300° to 200° W also suggests a possible eruption triggering mechanism operating across distances of ~ 500 km. A comparison to tidal heating models finds a good correspondence between recent models incorporating a partially-fluid interior (Tyler et al., 2015) and hot spots in the leading hemisphere as well as persistent hot spots. However, hot spots on the trailing hemisphere and bright eruptions do not match these models well, corresponding better to standard deep-mantle heating models (Segatz et al., 1988), although this match is still imperfect.

6.1 Introduction

An understanding of the interior properties and geophysics of rocky bodies in the Solar System is crucial for providing a framework in which to interpret observations of extrasolar planets. In cases of tidally-heated bodies with subsurface oceans such as Europa and Enceladus, models for how and where tidal heat is dissipated in planetary interiors are needed to answer questions about the presence and history of liquid water, which affects their long-term habitability. Such models would also help predict whether extrasolar planets might have volcanism, global magma layers, or even liquid water. However, a major challenge to understanding planetary interiors is the sparsity of information that can be obtained remotely, particularly without in situ gravity and magnetometer measurements.

Io represents a unique case where an interior process (tidal heating) manifests on the surface in a clearly detectable way, as extreme volcanic activity. This moon therefore provides a unique testbed for interior processes, tidal heat dissipation in particular. The distribution of heat flow on a planet's surface puts an important constraint on models of tidal heat dissipation, and in particular on how deep within the interior the heat is dissipated. Models show that if the heat is primarily dissipated in the deep mantle, Io's surface heat flux should be highest at the poles, and should be higher on the leading/trailing hemispheres (longitudes of 90° and 270° W) than on the sub- and anti-jovian hemispheres (longitudes of 0° and 180° W). In contrast, if the heat is primarily dissipated in a fluid asthenosphere, surface heat flux should be very low at the poles, reaching maxima around the sub- and anti-jovian points at $\pm 30^\circ$ latitude, with secondary maxima at the equatorial leading and trailing points (Segatz et al., 1988; Ross et al., 1990). Io's true heat dissipation is likely a combination of these idealized scenarios, potentially with lateral convective flows that smooth out the surface heat flux pattern (Hamilton et al., 2013; Tyler et al., 2015; Davies et al., 2015).

Much recent progress has been made in characterizing the distribution of volcanic heat flow on Io, and on developing realistic tidal heating models that can be tested against observations. Previous work has assumed that the volcanic heat flow distribution on the surface can be used as a tracer of the distribution of internal heat flow. We follow this assumption, while noting that the connection between interior heating and its surface expression as volcanism has not been checked, and these properties may correlate imperfectly.

Early results from the *Galileo* mission found that there is a lower concentration of volcanic centers at high latitudes (Carr et al. 1998; Schenk et al. 2001), but that high latitude paterae

are larger, suggesting a different eruption character (Radebaugh et al., 2001). Schenk et al. (2001) and Radebaugh et al. (2001) also noted a bimodal distribution of volcanic centers that peaks near 330°W and 150°W . Lopes et al. (2004) analyzed 166 volcanic centers observed by *Galileo* NIMS (78 at the highest resolution), and confirm that the distribution of active centers also has a peak at 150°W . In a series of recent papers, Veeder et al. (2009; 2011; 2012; 2015) identified additional faint emission sources in the NIMS dataset and characterized the thermal emission from ~ 250 total volcanic centers observed by *Galileo*. A heat flow map based on this analysis is presented in Davies et al. (2015), and indicates a non-uniform distribution of heat flow which is not a good match to any of the tidal heating model end-members. These authors note a lack of close correlation between density of volcanic centers and local heat flow. The clustering of hot spots and paterae on Io, as identified from the first global geologic map of Io (Williams et al., 2011) as well as from space- and ground-based observations, shows more uniformity and less randomness in equatorial regions compared to the poles. This suggests that volcanic centers are independently formed at high latitudes but that magma scavenging occurs in the near-equatorial region (Hamilton et al., 2013), consistent with a shallow magma source near the equator and a deeper source for eruptions at high latitudes.

All of the above authors identify an eastward offset of $30\text{--}60^\circ$ in the concentration of volcanic activity from the locations predicted by heating models. In addition, the longitudes of the maxima based on active volcanism fall $\sim 30^\circ$ eastwards of the maxima based on paterae (Hamilton et al., 2013). In the first model to incorporate the fluid effects of a partially-molten interior layer, Tyler et al. (2015) demonstrate that the longitudinal offset can be explained by including the tidal response of a fluid layer such as the “magma ocean” implied by constraints derived from the *Galileo* magnetometer data (Khurana et al., 2011). They propose that high-latitude eruptions may be driven by deep-mantle heating, while equatorial volcanoes may have a shallow magma source. Such a scenario would imply hotter, more violent polar volcanoes occurring at random locations, while equatorial volcanoes may be cooler, less violent, and distributed more evenly due to competition for shallow magma reservoirs (Hamilton et al., 2013).

In a companion paper (de Kleer and de Pater, 2016), we present a new dataset of ground-based adaptive optics images of Io in the near-infrared, including 409 detections of activity from at least 48 distinct hot spots over a period from Aug 2013 through Dec 2015. The high cadence of our observations samples both transient and long-lived eruptions, and the number of detections is large enough to provide a statistical sample for an analysis of the spatial distribution of active centers. While the time-variability of hot spot emission is discussed in de Kleer and de Pater (2016), this article focuses on the spatial distribution of the detected hot spots. In Section 6.2 we summarize our observations. The spatial distribution of volcanic activity is presented in Section 6.3, including near-infrared surface maps for multiple epochs and wavelengths. Section 6.4 presents a statistical analysis of the distribution of large eruptions, and Section 6.5 discusses the implications of our results, including a comparison with patera and hot spot distributions determined by past work and an investigation of correlations between eruption characteristics and hot spot locations. Our main conclusions are summarized in Section 6.6.

6.2 Observations and Data Processing

The analysis in this paper is based on near-infrared (1-5 μm) images of Io obtained on 100 nights between August 2013 and December 2015 with adaptive optics at the Gemini N and Keck telescopes. The observations, data reduction, and analysis methods are described in a companion paper (de Kleer and de Pater, 2016), and the hot spot positions and intensities are listed in Table B.4 of that article. The reader is also referred to that paper for a detailed study of the uncertainties on the retrieved hot spot properties.

6.2.1 Projection and Surface Maps

The Keck data are projected with an equirectangular projection onto a grid of constant latitude and longitude intervals. Before projection, the images are deconvolved using the stellar point spread function (PSF) for each night of observation using the AIDA routine (Hom et al., 2007), in order to sharpen the images and enhance contrast. All images are corrected for limb darkening according to a Minnaert law:

$$I = I_0 \mu_0^k \mu^{k-1}, \quad (6.1)$$

where μ_0 is the cosine of the angle of incident sunlight, μ is the cosine of the emission angle¹, and k is an empirically-determined value between zero and one. The best correction is typically found for values of k between 0.65 and 0.75, in agreement with Laver and de Pater (2008) and de Pater et al. (2014b). The effect of the limb-darkening correction at Kc-band is demonstrated in Figure 6.1 before and after projection onto the rectangular grid.

The projected images within each of three observing epochs are stitched together to produce global maps in each filter. At longitudes which were observed on multiple nights, the map is the median-average of all available observations. Each observation is scaled so that the over-lapping regions on all nights match as well as possible, using the highest-quality image as a photometric reference. After applying the flux-calibration procedures described in de Kleer and de Pater (2016), we typically need to scale the projected images by a few percent at most.

6.3 Results

6.3.1 Multi-Wavelength Surface Maps

Maps of Io's surface at near-infrared wavelengths provide an informative visualization of the distribution, magnitude, and temperature of activity on Io. We present surface maps for three distinct periods in Figure 6.2, in five near-infrared filters (K-cont, L', Br- α , Br- α -cont, Ms; wavelengths of 2.27, 3.78, 3.99, 4.05, and 4.67 μm), based on Keck observations. For the last time period, we present additional maps in narrowband filters at 3.06 and 3.29 μm . At 2.27 μm , the intensity is almost entirely due to reflected sunlight, and the maps show

¹Ephemeris from JPL HORIZONS System: ssd.jpl.nasa.gov/horizons.cgi

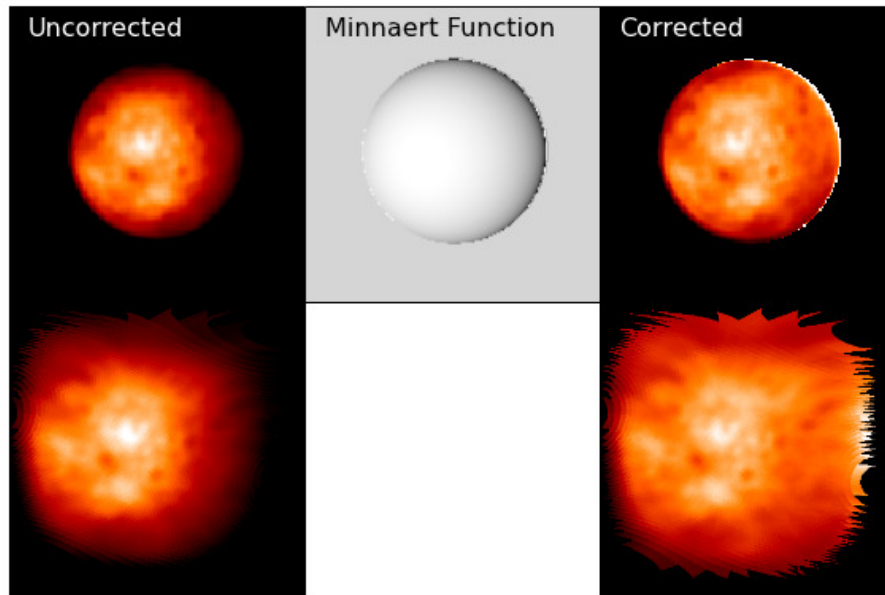


Figure 6.1: Demonstration of limb darkening correction: Keck Kc-band data from Oct 30, 2014, before and after limb-darkening correction by a Minnaert law with $k = 0.67$. The top row shows the images before and after the correction, and bottom row shows the same two images after projection onto a regular latitude-longitude grid.

the near-infrared albedo distribution. At longer wavelengths, thermal emission from active volcanic regions is an increasingly significant component of the emission. At intermediate wavelengths ($\sim 3 \mu\text{m}$), the thermal emission and albedo distribution can both be seen, and the location of emission within large dark paterae such as Loki Patera and Pele is immediately apparent.

Io's surface is covered in SO_2 frost, which has a broad absorption band centered near $4 \mu\text{m}$. The filter at $4.05 \mu\text{m}$ (Br- α) falls within this absorption band, while the filter at $3.99 \mu\text{m}$ (Br- α -cont) lies just outside it and can be considered the nearby continuum. As can be seen in Figure 6.2, the absorption of incident sunlight within this band increases the contrast of hot spots to the surface, particularly in regions of greater SO_2 frost, i.e. the brighter regions at other wavelengths.

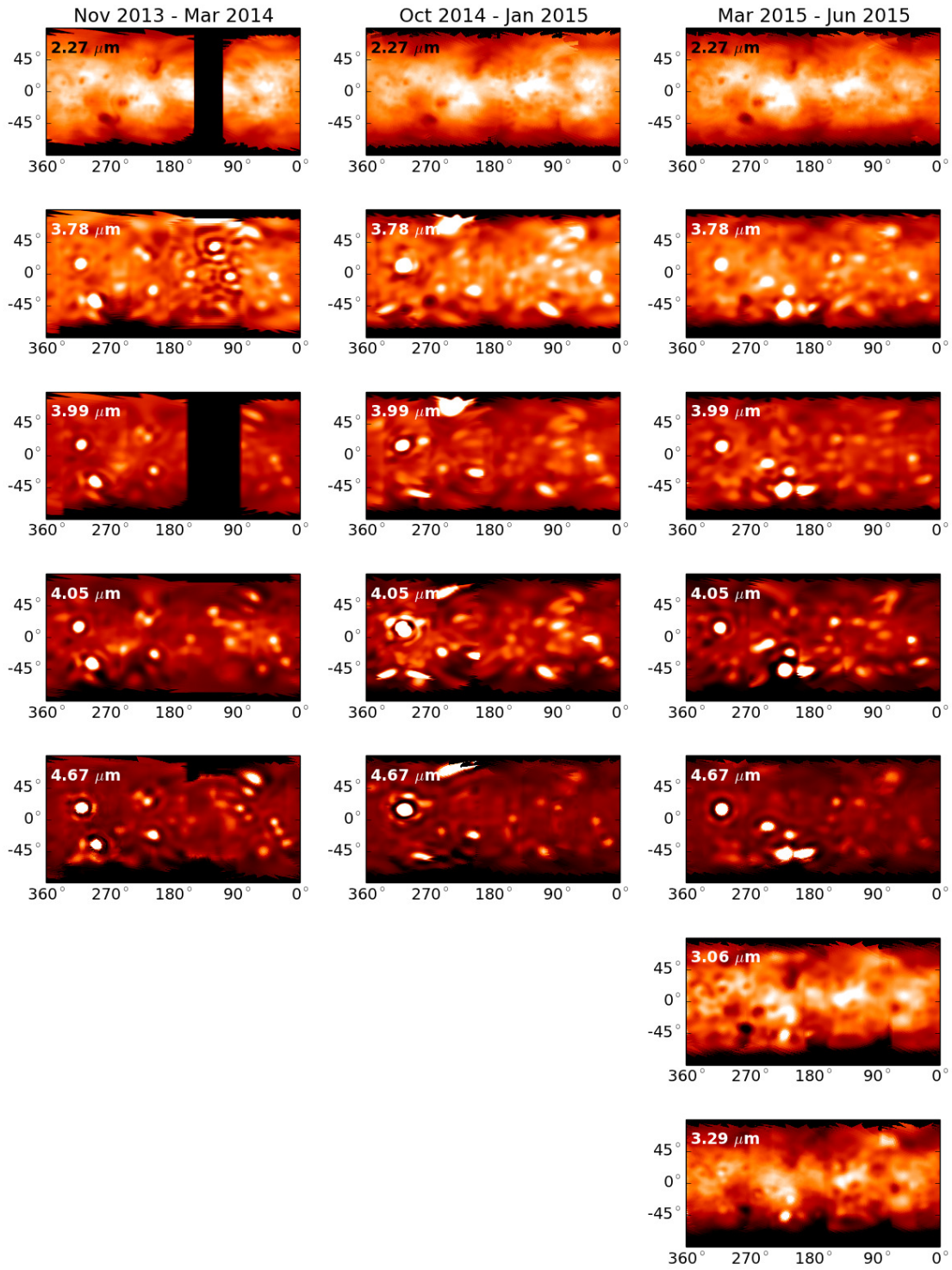


Figure 6.2: Surface maps of Io at multiple near-infrared wavelengths. Each map is made up of several separate observations with the Keck telescope, projected onto a rectangular grid and stitched together. Latitude and longitude are labeled in $^{\circ}\text{N}$ and $^{\circ}\text{W}$.

6.3.2 Spatial Distribution of Volcanic Activity

The high spatial resolution of our observations allows us to constrain the location of hot spots on Io's surface to within a few degrees or better in latitude and longitude. We present the position of each hot spot detection on Figure 6.3, where each shaded circle represents a single detection, and the size of the circle indicates the magnitude of the $3.8\text{-}\mu\text{m}$ intensity. An animation is also included in the Supplementary Material which steps through time plotting each of the detections shown in Figure 6.3 at its time of occurrence. In Section 6.5.1 we analyze this distribution in light of observational biases to make an estimate of the true longitudinal distribution of volcanic activity on Io in 2013-2015, which we compare with previous distributions and with the predictions of tidal heat dissipation models.

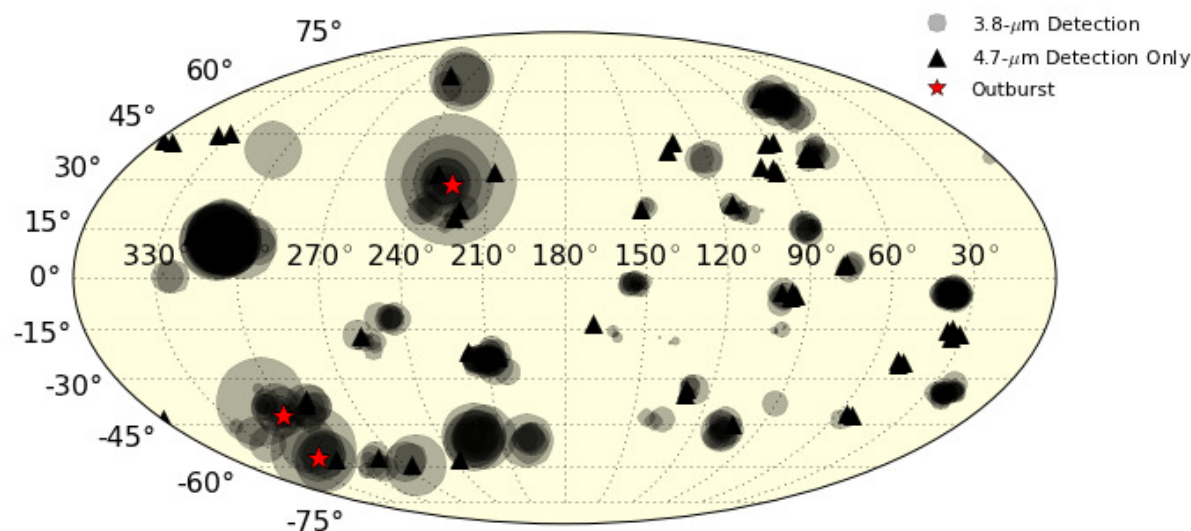


Figure 6.3: All hot spot detections from August 2013 through December 2015, shown with a Mollweide equal-area projection. Each circle represents a $3.8\text{-}\mu\text{m}$ hot spot detection; the size of the circle corresponds logarithmically to the $3.8\text{-}\mu\text{m}$ intensity, and darker regions are where a hot spot was detected multiple times. Hot spot detections at $4.7\text{ }\mu\text{m}$ correspond to lower-temperature events. The timing of each detection shown here can be seen visually in the animation included in the Supplementary Material.

6.4 Spatial Clustering of Large Eruptions

The most striking feature of Figure 6.3 is the asymmetric distribution of the locations of the largest eruptions, which are detected exclusively between ~ 200 and $\sim 300^\circ\text{W}$, and often at mid to high latitudes. We test the significance of this apparent clustering of eruptions by seeking a quantitative answer to the question: what is the probability that the locations of large eruptions are random, given the observations?

Table 6.1: Brightest eruptions detected with Gemini N/Keck in 2013-2015

Site	Latitude ^a [°N]	Longitude ^a [°W]	Date ^b	Peak 3.8- μ m Intensity [GW/ μ m/sr]
201308C ^c	29.0 $\pm$ 1.0	229.8 $\pm$ 2.5	08-29-13	>500
Rarog Patera ^c	-38.7 $\pm$ 2.0	306.0 $\pm$ 2.6	08-15-13	320 $\pm$ 80
Heno Patera ^c	-56.0 $\pm$ 1.3	307.2 $\pm$ 1.8	08-15-13	270 $\pm$ 70
Loki Patera ^c	12.0 $\pm$ 1.0	308.2 $\pm$ 4.2	08-22-13	136 $\pm$ 20
Kurdalagon Patera	-48.8 $\pm$ 1.4	221.3 $\pm$ 2.8	01-26-15	68 $\pm$ 11
Chors Patera	64.8 $\pm$ 1.2	246.7 $\pm$ 3.7	10-22-14	57 $\pm$ 19
Mithra Patera	-58.1 $\pm$ 0.9	266.2 $\pm$ 2.4	01-10-15	55 $\pm$ 12
Amaterasu Patera	39.4 $\pm$ 0.8	304.3 $\pm$ 1.1	12-25-15	43 $\pm$ 6
Sethlaus/Gabija Paterae	-50.0 $\pm$ 0.8	192 $\pm$ 1.2	04-01-15	32.6 $\pm$ 4.9
PV59	-38.4 $\pm$ 1.5	290.0 $\pm$ 2.4	02-10-14	17.6 $\pm$ 2.6
P170	-47.8 $\pm$ 1.6	327.9 $\pm$ 1.8	12-02-14	11.7 $\pm$ 1.7
P197	-46.9 $\pm$ 0.7	107.3 $\pm$ 0.7	01-11-15	11.7 $\pm$ 1.8

^a Latitude and Longitude are the median of all observations from 2013-2015, from de Kleer and de Pater (2016).

^b Date of peak 3.8- μ m intensity.

^c 201308C outburst intensity from de Kleer et al. (2014); Rarog and Heno Paterae outbursts and Loki Patera on 08-22-13 from de Pater et al. (2014).

We restrict this analysis to sites that hosted large eruptions, which we define as a peak L'-band intensity exceeding 30 GW/ μ m/sr. We include both Loki Patera and outburst eruptions in this classification; the nine hot spots meeting this intensity cut-off are given in Table 6.1. The three brightest detections which did not meet this cut-off are also listed, and are used to test the robustness of our analysis to intensity cut-off. We note that this cut-off ensures that our dataset is complete; our detection limit analysis indicates that we detect all eruptions above this flux level, at both telescopes, and at all disk locations (de Kleer and de Pater, 2016). All detections in Table 6.1 share the distinguishing feature of rapid brightening events followed by a decay over a timescale of days to weeks (or months in the case of Loki Patera), implying that these events constitute a physically-distinct class.

We test the null hypothesis that large eruptions occur in random locations as follows. We create a sample of 100,000 simulated datasets, each of which contains nine eruptions at random and independent locations on Io's surface, matching the number of bright detected hot spots in our dataset. The eruptions are each placed in a box of size 5°x5°, where the probability of an eruption occurring in a given box is weighted by the surface area contained in that box, and by the fraction of our observations that were sensitive to its longitude. The former weighting factor corrects for the fact that a 5°x5° region at high latitudes contains a much smaller area than one near the equator. The map of eruption probabilities, corrected for longitudinal coverage of our observations, is shown in Figure 6.4.

We then define two metrics to evaluate the spatial distribution of eruptions:

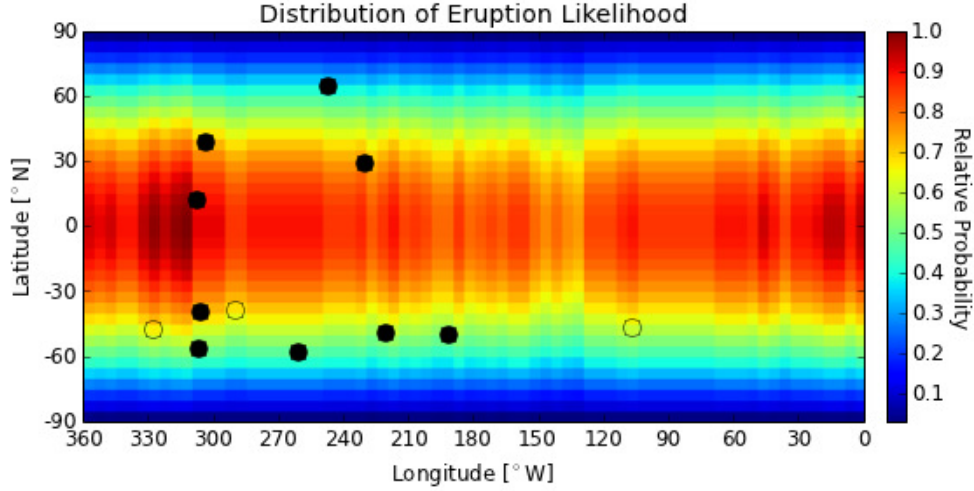


Figure 6.4: Map of the likelihood of our program detecting a bright eruption in a given latitude-location box, if eruptions are randomly distributed. Map is based on the frequency of observation of each longitude assuming we are sensitive to bright eruptions at all emission angles, and on the surface area in a given latitude-longitude bin. Red regions have a higher eruption likelihood, and blue regions a lower likelihood. Circles indicate observed eruptions: filled circles are the observed large eruptions ($3.8\text{-}\mu\text{m}$ flux $> 30 \text{ GW}/\mu\text{m}/\text{sr}$) used in the analysis, and open circles are the locations of the three brightest hot spot detections that fall below this cut-off, included to demonstrate that the observed clustering and high-latitude locations are not the result of the chosen intensity cut-off.

(1) The mean pairwise spacing (in distance on the surface) between eruptions, describing how clustered the set of eruptions is; and

(2) The mean absolute latitude of eruptions, describing whether large eruptions are weighted towards specific latitude ranges. The expected mean absolute latitude for randomly-spaced eruptions is the area-weighted mean of the absolute latitude φ :

$$\bar{\varphi} = \frac{\int_0^{\pi/2} \varphi \cos(\varphi) d\varphi}{\int_0^{\pi/2} \cos(\varphi) d\varphi} = \frac{\pi}{2} - 1 \approx 32.7^\circ, \quad (6.2)$$

where the cosine term describes the area covered by a fixed latitude interval as a function of φ .

Figure 6.5 shows the distribution of these metrics in our simulated data compared to the observations. We find that our dataset has a smaller mean eruption separation than 97% of the simulated datasets, and a higher mean latitude than 94% of the simulations. While the mean latitude of the set of large eruptions in a typical simulation is $30\text{--}35^\circ$, the mean value from our observations is 44° . In contrast, the average latitude of all the sites where we detected activity is 31.5° , which is very close to the expected mean latitude in the case of randomly-distributed eruptions. We note that this number is not corrected for observational

biases, and the detection of faint activity at high latitudes is challenging; this correction would shift the mean latitude of all eruptions towards higher latitudes, though it does not affect our analysis of bright eruptions.

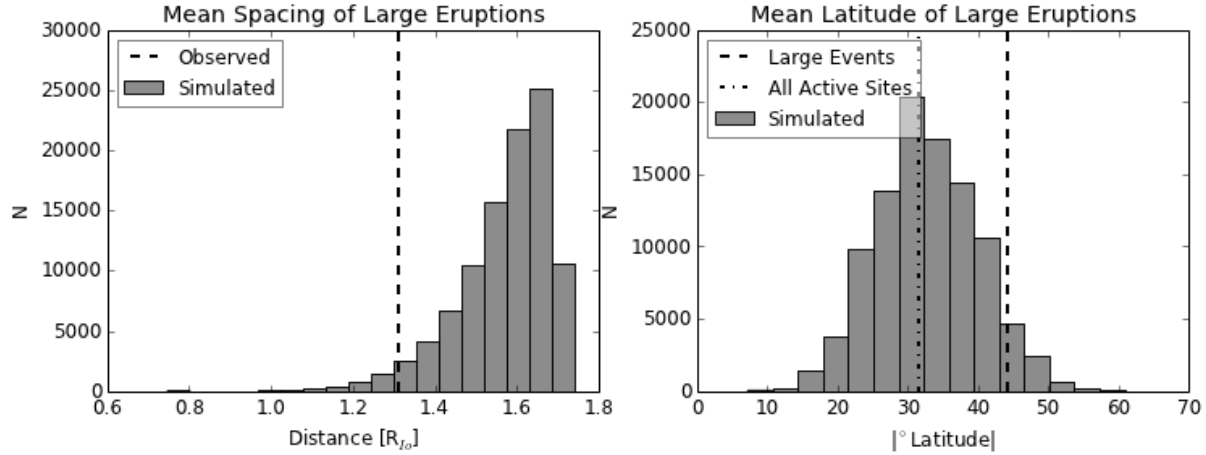


Figure 6.5: Comparison of two hot spot distribution metrics for simulated vs. observed data. Unless otherwise noted, both simulated and observed values are for hot spots where high-intensity ($>30 \text{ GW}/\mu\text{m}/\text{sr}$) activity was detected, corresponding to the nine sites listed in Table 6.1. The comparison indicates that bright hot spots in our dataset are highly clustered and at high latitudes compared to simulations which assume random and independent eruption locations.

To test the robustness of this result, we re-perform the analysis including the three brightest hot spots which fall short of our intensity cut-off (shown as open circles in Figure 6.4). Including these sites increases the clustering significance from 97% to 99%, and the high-latitude significance from 94% to 97%. We therefore find our conclusions robust to the level of flux density cut-off.

In conclusion, our comparison to observational-bias-corrected simulated datasets indicates that large eruptions occur closer to one another and at higher latitudes in our dataset than in $\sim 95\%$ of simulations generated under the assumption of random eruption location, and the likelihood that our observations were drawn from a population where large eruptions occur randomly and independently is $<5\%$.

6.4.1 Temporal Clustering of Large Eruptions

The timeline of volcanic activity on Io presented in de Kleer and de Pater (2016) also shows an apparent correlation of large eruptions in time. That is, there is an apparent dichotomy in the timeline, where there are either multiple bright eruptions ongoing and none at all; it is less common to have only a single ongoing bright eruption. We perform a similar analysis to the above to analyze the significance of the temporal correlation. Simulated datasets in the temporal case consist of an array of dates with a 0 or 1 assigned to each

date between the first and last day of the program (660 days), representing whether a large eruption occurs. Each dataset is then masked by the dates we actually observed, which selects out only the eruptions we would have detected with our program.

The selected simulated datasets are then evaluated for clustering by dividing them into windows of 10-60 days, and determining how many windows contained new eruptions. In a highly-clustered dataset, all the eruptions would fall in just a few of the windows, while an evenly-distributed dataset might find at most 1-2 eruptions per window. For a given window size, we repeat this procedure with the start date shifted by different numbers of days, to ensure that we are not biased by the exact dates at which the boundaries between successive windows fall.

We find some indication of temporal clustering, but are unable to draw any definitive conclusions. While most choices for window size find that the observed data is more clustered than 80-99% of the simulated datasets, some choices of window sizes find the clustering significance as low as 55%. In addition, the results are highly sensitive to changing the window size by a few days, shifting the start date, or removing single data points. We therefore conclude that our eruption number is too small to draw conclusions about the temporal correlation of eruptions by this analysis technique.

6.5 Discussion

6.5.1 Spatial Distribution of volcanic activity

During the time period of observation, we find that Io's volcanic activity is non-uniform, exhibiting substantial asymmetries between the leading (0-180°W) and trailing (180-360°W) hemispheres, and high vs. low latitudes (see Figure 6.3). In de Kleer and de Pater (2016), we classify the detected hot spots into two observationally-distinct classes: (1) hot spots with sudden brightening events and high time variability; and (2) persistent hot spots, consistently active for >1 year and never exceeding 15 GW/ $\mu\text{m}^2/\text{sr}$ in L' intensity. Figure 6.6 shows the distribution of volcanic activity, color-coded to indicate which category each eruption belongs to. In addition to the preponderance of bright eruption events in the trailing hemisphere and at mid-to-high latitudes, we find that the majority of persistent hot spots are located in the leading hemisphere and at low latitudes. While detections of lower-intensity hot spots are somewhat biased towards lower latitudes where geometric foreshortening diminishes their intensities by a smaller amount, the hot spots classified as persistent were all of sufficient intensity to be detected at higher latitudes as well. If our analysis did miss persistent hot spots at high latitudes due to observational biases, these hot spots would have been of a lower typical intensity than those at more equatorial latitudes.

The correlation between persistent hot spots occurring at lower latitudes and short-lived, violent eruptions at high latitudes has been discussed by many previous authors (e.g. Lopes-Gautier et al., 1999; Geissler, 2004). In addition, it has been noted that paterae at high latitudes are less numerous and larger (Schenk et al., 2001; Radebaugh et al., 2001). The high cadence of our observations, which allows us to constrain eruption durations to within

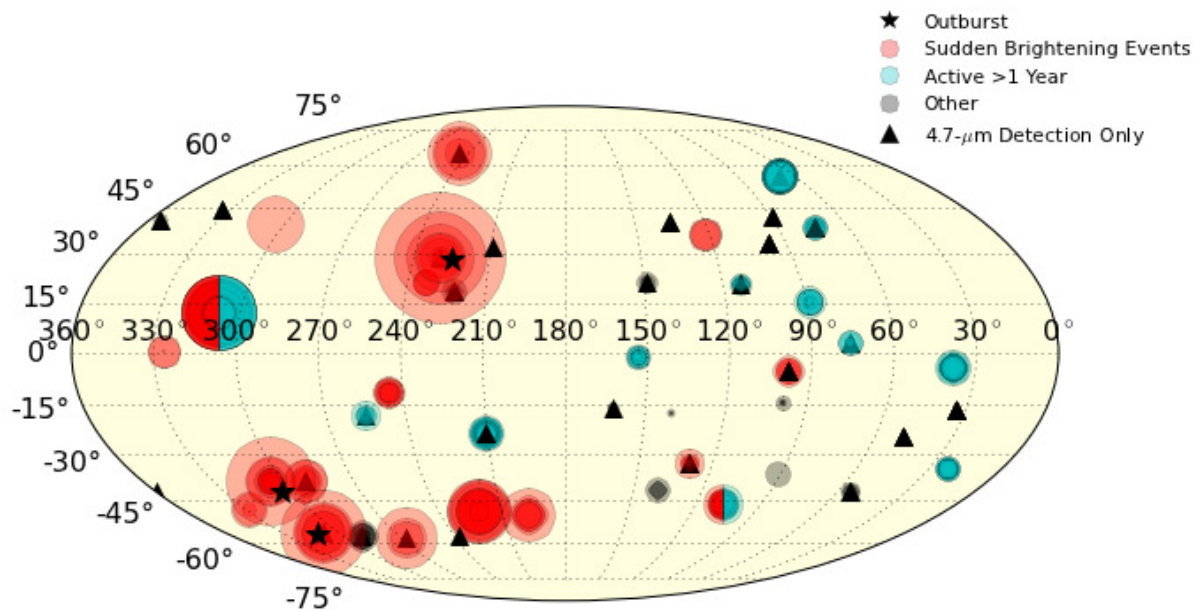


Figure 6.6: All hot spot detections in 2013-2015. Figure follows Figure 6.3, except that all detections attributed to the same hot spot have been over-plotted at their median location. Red and cyan coloring indicate eruption classification; points that share both colors exhibit characteristics of both categories, and gray points were detected too few times to classify.

weeks or months, has permitted quantitative definitions for these two categories, and a confirmation of this previously-identified correlation.

Of the 48 hot spots detected, only one is located definitively polewards of 60° (Chors Patera), while five others are located on or within a few degrees of 60° (Pyerun Patera, Mithra Patera, Chalybes Regio, N Lerna Regio, and Heno Patera). We did not detect any event higher in latitude than 65° in either hemisphere. If eruptions are randomly distributed on Io's surface, we would expect to see $\sim 9\%$ of eruptions at higher latitudes than 65° based on surface area coverage alone, i.e. ~ 4 eruptions in our dataset. The lack of detections at these latitudes is due in part to observational biases which prevent detection of faint activity at these latitudes; however, as demonstrated by Figure 6.7, we still have good sensitivity to eruptions of moderate brightness up to $\pm 75^\circ$.

6.5.2 Comparison to Galileo-era distribution & patera distribution

Previous analyses of the spatial distribution of volcanism on Io have focused on the distribution of paterae (Carr et al., 1998; Schenk et al., 2001; Radebaugh et al., 2001; Hamilton et al., 2013); of active volcanism detected primarily by *Galileo* (Lopes-Gautier et al. 1999; Lopes et al. 2004); and of the heat flow as estimated from *Galileo* observations

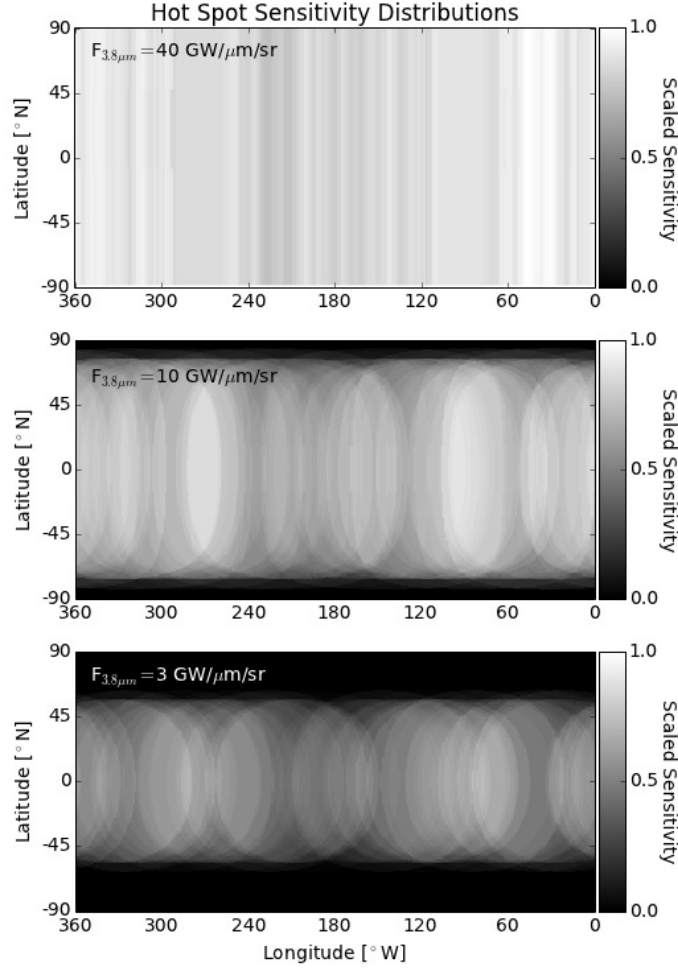


Figure 6.7: Maps of the relative sensitivity of our dataset to hot spots of different L'-band intensities, based on the Ionian longitudes sampled by our observations, and the detectability regimes described in de Kleer and de Pater (2016). All three plots follow the same scale.

(Veeder et al. 2012, 2015; Davies et al., 2015). We compare the longitudinal distribution of hot spots we detected with the distributions from previous work.

Like previous authors, we find an eastward offset in peak number density of hot spots of 30-60° from the sub- and anti-jovian points. Our distribution is similar in overall character to the longitudinal distribution of heat flow inferred from *Galileo* observations (Veeder et al., 2015). We note that this is not entirely expected, since we are comparing number of hot spots with total heat flow, and it has been previously noted that these properties are not closely correlated (Davies et al., 2015). However, since we are more likely to detect hot spots that are brighter and active for longer periods of time, we will preferentially detect the hot spots that contribute the most to Io's total heat flow, so that our distribution should indeed roughly mirror the distribution of total heat flow. In contrast, the distribution of paterae

(e.g. Hamilton et al. 2013) does not contain information on the magnitude of heat flow from each location, and would not necessarily be expected to match the heat flow distribution. While the majority of the volcanic thermal emission measured from *Galileo* does come from paterae, at certain longitudes (e.g. 150°W – 240°W) a fair proportion of thermal emission comes from lava flow fields (Veeder et al. 2012; Figure 10).

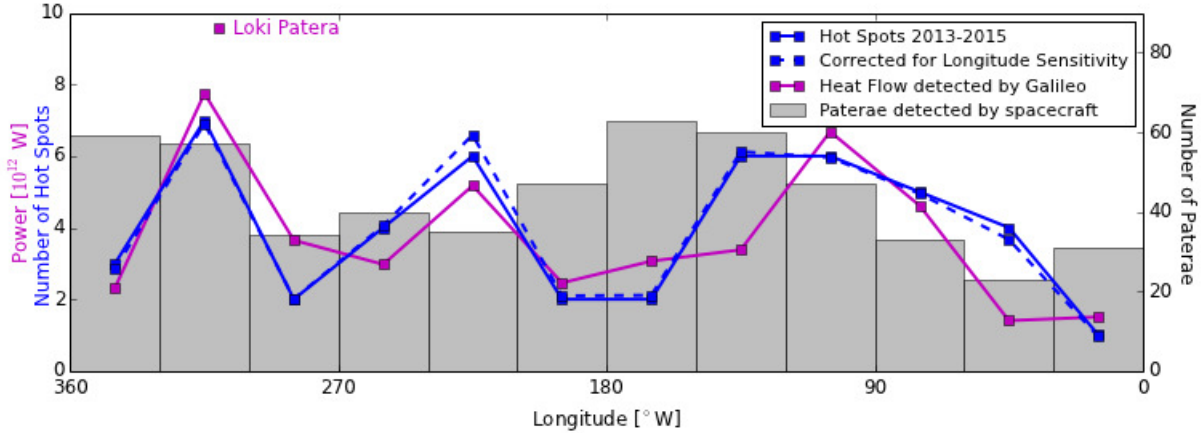


Figure 6.8: Number of hot spots detected per 30° longitude bin in 2013–2015, compared to distribution of heat flow detected by *Galileo*, and paterae. *Galileo* results are from Veeder et al. (2015) Fig. 11 (thermal emission), and exclude outburst eruptions. The total power of Loki Patera is shown separately, and would bring the total emission in its longitude bin to nearly 18 TW if included. Paterae numbers are from Hamilton et al. (2013) Fig. 3 for 529 bright, dark, and undivided patera floor units. The y-axis scale on the left side serves for both hot spot number in 2013–2015 and *Galileo* total power measurements. The mismatch between the 2013–2015 hot spot numbers and the *Galileo* power measurements (blue and purple lines) from 120°W to 150°W may be due to the particularly high concentration of low-intensity hot spots in this region.

The uniformity of our observations and roughly equivalent sensitivity to both the leading and trailing hemispheres allow us to confirm some previously-tentative conclusions. Veeder et al. (2012, 2015) and Davies et al. (2015) find that the region from 90°W to 180°W and 45°S to 45°N contains the greatest number of thermal sources, but note that this result may be biased by the high spatial resolution of *Galileo* observations of this region. Our dataset, which is in fact less sensitive to these longitudes than other regions, also finds a high concentration of thermal sources in this region, confirming the previous conclusion. This trend can be seen in the map in Figure 6.3. We note that it is less apparent in Figure 6.8 because this figure combines all latitudes, while the high hot spot concentration is focused at low to mid latitudes; in addition, the hot spots in this region are generally faint and contribute only minorly to the heat flow.

6.5.3 Comparison to Tidal Heating Models

Previous studies have found greater heat flow from equatorial regions than polar regions, which was taken as evidence of an asthenospheric heating mechanism. Although we find that intense and rapidly-varying eruptions occur primarily at mid to high latitudes, we estimate that the persistent hot spots of moderate intensity dominated Io's total heat flow during 2013-2015 (de Kleer and de Pater 2016), consistent with previous findings. However, solid-body asthenospheric heating models predict heat flow maxima at 90°W and 270°W , while observations find these maxima offset.

In Figure 6.9, we compare the locations of detected hot spots with the predictions of tidal heating models for the cases of deep mantle heating and combination heating with a partial fluid layer, from Hamilton et al. (2013; based on model by Segatz et al., 1988) and Tyler et al. (2015) respectively. We find that hot spots in the leading hemisphere (longitude $< 180^\circ$), and in particular the hot spots with persistent activity, fit well with the Tyler et al. (2015) model shown. The distribution matches less well in the trailing hemisphere, where nearly all large eruptions fall at locations of low predicted heat flow, and no hot spots at all were detected in the region of maximum predicted heat flow. In contrast, the large eruptions do correlate well with the distribution expected for deep mantle heating (Figure 6.9a), although no eruptions were detected at the highest latitudes, which are the most probable in the pure deep-mantle heating case.

The distribution of dark-floored paterae observed by *Galileo* follow a similar hemispheric asymmetry, where the locations of such paterae match the combination model for longitudes $< 180^\circ\text{W}$, while the region of maximum predicted heat flow is nearly lacking in dark paterae for longitudes $> 180^\circ\text{W}$ (Veeder et al., 2012; Tyler et al., 2015).

6.5.4 Bright Southern-Latitude Eruptions: Implications

We find that nearly all bright eruptions during 2013-2015 occurred at latitudes between 40°S and 65°S , and demonstrate in Section 6.4 that such an occurrence is unlikely at the 95% level if such eruptions occur randomly, even considering the small number of bright eruptions observed. In the previous section, we discussed the latitudinal distribution in terms of tidal heating models, where violent high-latitude eruptions are predicted by deep-mantle heating scenarios.

An additional consideration is the possibility that the bright eruptions in the southern hemisphere were triggered by earlier eruptions. Following the eruptions at Heno and Rarog Paterae in August 2013, the southern-latitude eruptions occurred in a monotonic eastward progression over the two years of observation; this can be seen clearly in the animation included in the Supplementary Material. This steady progression, combined with the low probability of this collection of eruptions occurring coincidentally, suggests the possibility of a physical link between the events. Bright eruptions on Io have occurred closely spaced in time in the past, as discussed in de Kleer and de Pater (2016).

There is evidence that some eruptions on Earth are triggered by large earthquakes up to a thousand km or more away (Linde and Sacks, 1998; Manga and Brodsky, 2006), or by

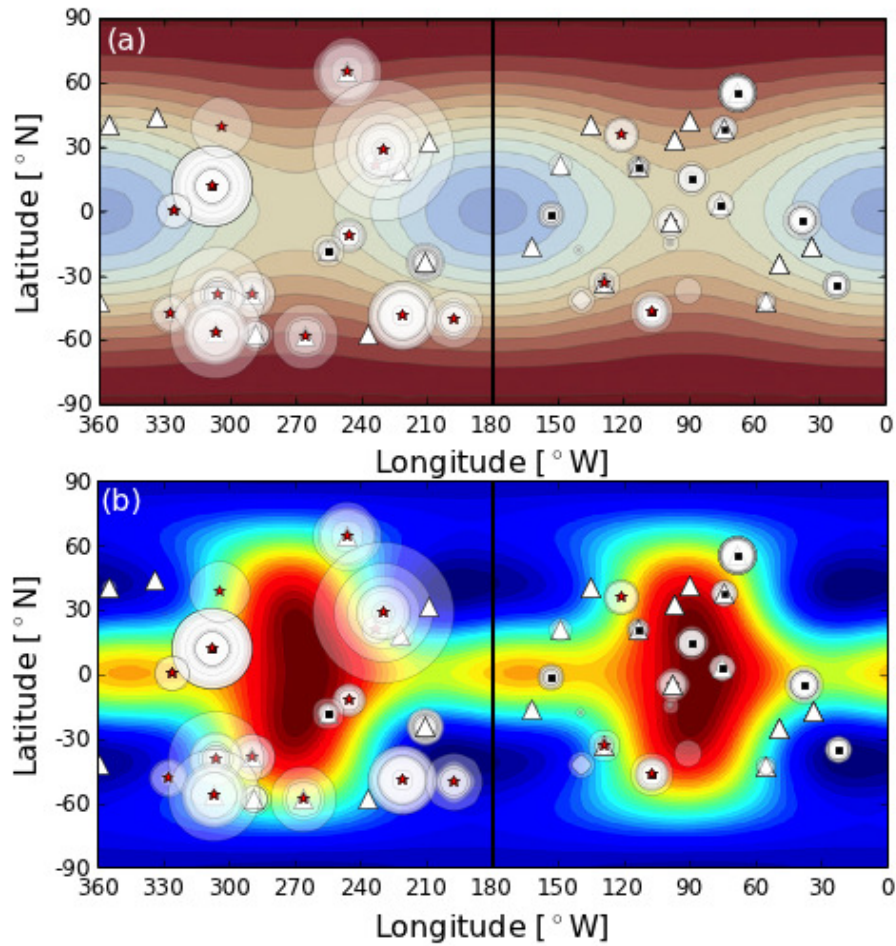


Figure 6.9: Locations of hot spot detections over-plotted on tidal heating model end-members in the case of (a) deep-mantle heating, base image from Hamilton et al. (2013) based on model by Segatz et al. (1988); and (b) combination heating with a partially-fluid interior, base image from Tyler et al. (2015). In both cases, red indicates regions of high heat flow, and blue regions of low heat flow. Black squares indicate persistent hot spots, and red stars indicate hot spots that exhibited bright eruption events. Low-intensity hot spots at longitudes $< 180^\circ\text{W}$ fit well with model (b), while bright hot eruptions at longitudes $> 180^\circ\text{W}$ do not fit with this model, and instead fit better with a deep-mantle heating model (a), despite the lack of detection of any very high latitude eruptions.

other volcanic eruptions up to 200 km distant. The triggered eruptions can be delayed from the triggering event by as much as several months (Schminke 2004; Bautista et al., 1996). Some authors have argued that eruptions can be triggered at a distance of 10^3 km with a time lag of years in the case of viscoelastic relaxation of stresses as the triggering mechanisms (Hill et al., 2002; Marzocchi et al., 2004). Eruptions can be triggered due to external factors such as seismicity, or by internal factors such as large-scale magma movement (Manga and

Brodsky, 2006). Although these conclusions are considered tentative and are based primarily on temporal correlations, it is intriguing that the same sort of correlation is seen in this string of southern volcanoes on Io, which are each separated from the next by ~ 500 km. If such an association could be confirmed by future observations of temporally-correlated eruptions, the distances and timescales over which such triggering occurs would yield new insight into the triggering mechanisms and magma supply for Io's eruptions.

Regardless of whether the eruptions around $45\text{--}60^\circ\text{S}$ were mutually triggered, their occurrence requires a large magma supply and violent eruption events to push through the lithosphere, consistent with a deep mantle magma source for these events.

6.6 Conclusions

We present an analysis of the spatial distribution of volcanic activity on Io based on 409 detections of 48 hot spots in 2013-2015; this analysis follows on a companion paper (de Kleer and de Pater 2016) which presents the data and timelines of thermal emission variability. In addition, we present here near-infrared maps of Io in numerous filters, during three separate epochs of observation. Based on our analysis, we conclude the following:

1. **Clustering of large eruptions:** We detected 9 hot spots that reached an L'-band brightness above $30 \text{ GW}/\mu\text{m}/\text{sr}$. These events occur exclusively on the trailing hemisphere, and primarily at latitudes of $40\text{--}65^\circ$. In a statistical analysis based on simulated data corrected for observational biases, we find that bright eruptions in our dataset are more clustered and occur at higher latitudes than in $\sim 95\%$ of simulations which assume that eruptions occur at random locations. The eruptions between 45 and 60°S occurred in an eastward progression over the two years of observation, and we suggest the possibility that the earlier eruptions triggered the subsequent ones, perhaps beginning with the outbursts at Rarog and Heno Paterae in August 2013. However, we note that the most powerful eruption we detected (201308C) does not appear to have any nearby major events.
2. **Hemispheric asymmetries:** The character of the volcanism observed during our program differs substantially between Io's leading and trailing hemispheres. All bright eruptions occurred on the trailing hemisphere, primarily between $40\text{--}65^\circ \text{ N and S}$, while the leading hemisphere predominantly hosts faint, persistent hot spots that tend to be located between $\pm 30^\circ\text{N}$. In de Kleer and de Pater (2016), we identify a class of "mini-outbursts", bright hot spots which exhibit temporal characteristics of outbursts but are a factor of ~ 5 less bright. In this analysis, we see that outbursts and "mini-outbursts" also follow similar spatial distributions, supporting the possibility that these smaller events are either outbursts captured a few days after their peak, or smaller-scale versions of the same type of eruption.
3. **Comparison to past activity:** The longitudinal distribution of hot spot numbers observed in 2013-2015 is a close match to the longitudinal distribution of heat flow as

observed by *Galileo* (Veeder et al., 2012). In particular, our data indicate that the peak in hot spot number is shifted eastward by 30-60° from the sub- and anti-jovian points, in agreement with past findings. This match confirms that two years of ground-based observations of Io are indeed sufficient to recover some of the general properties of Io's heat flow distribution, and that this distribution does not vary significantly over decadal timescales.

4. **Implications for tidal heating:** The spatial distribution of hot spots detected in our dataset does not match the distributions predicted by solid-body asthenospheric or deep-mantle heating. While the hot spots on the leading hemisphere, and persistent hot spots everywhere on Io, match the predictions of recent models incorporating a partial fluid interior (Tyler et al., 2015), this model is a poor match to the distribution of eruptions on the trailing hemisphere, and of bright eruptions in particular. It may be that future developments in tidal heating models will improve this discrepancy. However, the distribution may also reflect inhomogeneities in the degree of mantle convection or lithospheric thickness, as was recently suggested by Davies et al. (2015).

While these observations give new insight into the distribution of thermal activity on Io, many of the unresolved questions could be addressed by future ground-based observations or by a dedicated Io mission. If the string of southern eruptions are indeed physically interconnected, future observations in the months following outburst eruptions may reveal similar connections. This dataset also reveals that bright eruptions which still fall well short of outburst intensity (i.e. 3.8- μm intensities of 30-80 GW/ $\mu\text{m}/\text{sr}$, compared with >150 GW/ $\mu\text{m}/\text{sr}$ for outburst eruptions) are more similar to outbursts than to persistent hot spots in terms of temporal characteristics and spatial distribution. These may be a viable avenue for studying high-energy eruptions on Io, and they occur much more frequently than outbursts. Future detections of new hot spots in previously-inactive regions could also point to evolution in the location of magma supply to the surface, or the opening of new heat pipes through the lithosphere.

This dataset demonstrates the value of high-cadence ground-based observations of Io. Frequent, high-resolution images provide a statistically significant database of hot spot detections. A continued campaign of this nature would improve constraints on the spatial distribution of activity, as well as revealing any variability in the locations of eruptions of different classes. In addition, the possibility of eruption triggering is intriguing, but requires consistent observation to assert that large eruptions occur near other large eruptions a meaningful fraction of the time. Ideally, future programs of this nature will observe at multiple near-infrared wavelengths spanning 2-5 μm , so that the distribution of eruption powers and temperatures can also be investigated.

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Chapter 7

Io's Loki Patera: Modeling of Three Brightening Events in 2013-2016

Loki Patera is one of the most dramatically time-variable volcanic features on Io, exhibiting episodic brightening events every 1-3 years that may produce over 15% of Io's global heat flow. We observed three such brightening events with adaptive optics imaging at the Keck and Gemini N telescopes over the course of 70 nights of observation in 2013-2016. The high cadence and multi-wavelength nature of the observations provides constraints on models for activity at Loki Patera. The Matson et al. (2006) model for Loki Patera as an overturning basaltic magma sea is adapted to fit the observations of all three events. In particular, we adjust the details of the overturn progression, and modify the lava thermal properties to include dependencies on temperature and porosity, to improve the fit to the data. The preferred models find overturn front propagation velocities of 1.2-1.7 km/day, corresponding to resurfacing rates of 1500-2200 m²/s. The time intervals of 440-540 days between successive events are roughly consistent with the 540-day period calculated by Rathbun et al. (2002) for events prior to 2001. The best coverage was obtained for the 2016 brightening; model fits to this event require a lava bulk thermal conductivity of 0.55-0.75 W/m/K, with the best fit obtained for a value of ~ 0.7 W/m/K and an average porosity that decreases during cooling. For all three events, the overturn front appears to propagate around the patera in the clockwise direction, opposite to what has been inferred for past brightening events. There is evidence that the overturn may be more complex than a single propagating wave, perhaps involving multiple simultaneous resurfacing waves as well as portions of the patera that are active even after the nominal brightening phase has ended. The measured intensities are anomalously low when Loki Patera is viewed at high emission angles, suggestive of topographic shadowing due to a raised area or the edge of the depression in which the magma sea resides.

7.1 Introduction

One of the most distinctive and well-studied volcanic features on Io, Loki Patera is a large low-albedo region approximately 2.15×10^4 km² in area and roughly annular in shape. Its size and consistently-present activity during the 37 years since its discovery by *Voyager* (Smith et al., 1979) make it an ideal observational target for studying volcanic processes on Io. Its immense heat flow constitutes 10-15% of the total time-averaged heat flow from Io (Veeder et al., 1994; Spencer et al., 2000); understanding how Io’s heat is released globally therefore requires an understanding of this unusual volcanic feature.

After its discovery by *Voyager* (Smith et al., 1979), Loki Patera was observed in detail by *Galileo* (e.g. Lopes-Gautier et al., 1999; Spencer et al. 2000; Turtle et al. 2004) and from the ground via occultations by Jupiter (e.g. Spencer et al., 1990). With adaptive optics on large near-infrared telescopes, the emission from individual volcanoes on Io can be distinguished (Marchis et al., 2005), Loki Patera’s 1-5 μ m intensity can be measured, and the location of the primary source of emission within the patera can be constrained (de Pater et al., 2014b; 2017). Recently, the Large Binocular Telescope Interferometer (LBTI) resolved emission from Loki Patera for the first time from the ground with near-infrared Fizeau imaging, detecting emission from two distinct locations within the southern part of the patera (Conrad et al., 2015).

Shortly after its discovery, Loki Patera was noted to brighten every 1-3 years, involving a rapid increase of intensity followed by months of high activity before fading (Howell and Sinton, 1989; Spencer et al., 1994). Based on *Galileo* photopolarimeter-radiometer (PPR) observations during the I24 and I27 flybys, Spencer et al. (2000) suggested that the hottest area within Loki Patera could represent a flow front or lava lake overturn front, and early brightening models treated Loki Patera as a spreading lava flow (Carr 1986; Davies 1996; Howell et al., 2001). From a synthesis of 3.5-4.0 μ m measurements of eight distinct brightening events between 1987 and 2002, Rathbun et al. (2002) derived a periodicity of 540 days for the brightenings and proposed a model in which Loki Patera is an active lava lake with a resurfacing wave that propagates across the surface (though they could not rule out resurfacing by lava flows). In this model, overturn is triggered when the solid crust that forms on the surface of the lake becomes denser than the underlying magma; the time it takes for this to occur may vary between brightenings based on variable magma properties such as volatile content. This model was adapted to interpret *Galileo* high-resolution observations (Davies, 2003) and expanded by Rathbun and Spencer (2006) to explain an apparent “turning off” of the activity after 2001. Matson et al. (2006) built on these models, adding an analysis of the volatile content of the magma to develop a self-consistent and physically-motivated model of Loki Patera as an overturning magma sea. After 2001, no major activity was detected at Loki Patera until 2009, after which five additional brightening events were seen (de Pater et al. 2011; 2017).

We observed the three events that took place between 2013 and 2016 with near-infrared (2-5 μ m) adaptive optics imaging at the Keck and Gemini N telescopes on 70 nights during this period. The high-cadence and multi-wavelength nature of these observations yields unprecedented constraints on models for volcanism at Loki Patera, and are used here to

refine the Matson et al. (2006) magma sea model. Section 7.2 describes the observations. In Section 7.3, the original magma sea model is summarized, and our modifications to the model are discussed in detail. An analysis of the fits for a variety of model choices is presented in Section 7.4, and the implications of these results are discussed in Section 7.5. Section 7.5.3 focuses on evidence for a topographic feature blocking emission at high viewing angles. The conclusions are summarized in Section 7.6.

7.2 Observations

Observations of Loki Patera in the near-infrared were made with adaptive optics at the Keck and Gemini N telescopes between August 2013 and June 2016, on 17 and 53 nights for the two telescopes respectively. The Keck observations use the NIRC2 imager with a platescale of 9.94 ± 0.03 mas/pixel (de Pater et al., 2006), or 30-45 km on Io's surface at disk center depending on the Earth-Io distance. Data are obtained in a range of filters from H-cont ($1.6 \mu\text{m}$) out to Ms ($4.7 \mu\text{m}$). At Gemini N the NIRI instrument is used to image Io in the L-prime and K-cont filters (3.78 and $2.27 \mu\text{m}$ respectively) at a platescale of $0.022''/\text{pixel}$. Emission from Loki Patera is typically only seen at wavelengths longer than $3 \mu\text{m}$. Emission at shorter wavelengths is detected primarily during the peak of brightening episodes.

These observations were obtained as part of an high-cadence, high-spatial-resolution Io imaging campaign (de Kleer et al., 2014; de Kleer and de Pater, 2016). This article focuses exclusively on an analysis of the observations of Loki Patera; the observing and data reduction procedures, including the extraction of intensities and positions, are described in de Kleer and de Pater (2016) where the results of the full program are presented, and in de Pater et al. (2017). The details of all observations, as well as the measured intensities and positions, are summarized in Table 7.1.

Table 7.1: Observations and Measured Intensities

UT Date	Telescope ^a	CML ^b	Latitude [°N]	Longitude [°W]	θ^c	$F_{2.3\mu\text{m}}^d$ [GW/ $\mu\text{m}/\text{sr}$]	$F_{3.8\mu\text{m}}^d$ [GW/ $\mu\text{m}/\text{sr}$]	$F_{4.7\mu\text{m}}^d$ [GW/ $\mu\text{m}/\text{sr}$]
08-15-13 ^e	Keck	338°	10.8±1.2	308.8±1.2	29°	7.7±1.4	60±10	
08-20-13	Keck	275°	12.0±0.7	307.9±0.7	33°	13.0±3.3	133±27	200±33
08-22-13	Keck	320°	11.0±0.7	307.8±0.7	13°	7.5±1.3	136±20	205±34
08-29-13	Gemini N	305°	11.4±1.4	307.2±1.5	11°		126±19	
09-03-13	Gemini N	241°	10.9±1.5	308.5±4.8	67°		50±14	
09-05-13	Gemini N	285°	11.3±1.4	307.4±1.7	24°		73±11	
09-07-13	Gemini N	334°	12.0±1.4	307.1±1.7	29°		84±13	
09-09-13	Gemini N	24°	10.3±1.5	310±5	74°		37±19	
09-10-13	Gemini N	226°	12.1±1.5	295±5	69°		14.8±4.6	
11-18-13	Keck	221°	14.3±0.5	309.5±3.7	83°			28±10
11-27-13	Gemini N	257°	11.9±1.5	307.0±2.6	50°		12.0±1.8	
11-29-13	Gemini N	307°	12.5±1.1	306.6±1.1	12°		12.6±1.9	
12-06-13	Gemini N	273°	12.0±1.1	307.5±1.5	36°		10.5±1.6	
12-15-13	Gemini N	320°	12.5±1.1	307.3±1.2	18°		11.2±1.7	
01-20-14	Keck	34°	12.3±0.7	312.6±2.9	75°			17.4±3.8
02-08-14	Keck	274°	10.1±1.0	310.6±0.5	38°		8.5±1.3	24.7±3.8
02-10-14	Keck	318°	10.9±0.6	310.1±0.3	13°		11.1±1.7	31.8±4.8
03-10-14	Gemini N	257°	12.2±1.3	314.0±2.7	57°		6.4±3.2	
03-12-14	Gemini N	302°	12.0±1.2	311.3±1.3	14°		7.7±1.1	

03-28-14	Gemini N	337°	13.1±1.3	309.6±1.6	30°	7.6±1.1	
10-03-14	Gemini N	307°	12.2±1.5	306.9±1.5	12°	127±19	
10-10-14	Gemini N	290°	11.7±1.5	306.7±1.6	19°	128±19	
10-24-14	Gemini N	258°	10.8±1.4	304.8±2.4	47°	66±10	
10-30-14	Keck	39°	11.1±0.6	310.0±4.9	86°	40±28	43±25
10-31-14	Keck	241°	11.2±1.0	302.1±1.0	63°	78±12	155±23
11-25-14	Gemini N	284°	10.7±1.3	307.0±1.5	25°	55±8	
11-27-14	Gemini N	334°	11.1±1.3	305.7±1.6	30°	54±8	
11-29-14	Gemini N	22°	9.4±1.2	299±8	83°	59±31	
11-30-14	Gemini N	228°	9.8±1.3	293.1±3.8	65°	10.5±2.5	
12-02-14	Keck	275°	9.7±1.4	305.2±0.7	32°	47±7	122±18
12-06-14	Gemini N	329°	11.8±1.2	306.1±1.4	25°	29.0±4.3	
12-09-14	Gemini N	249°	10.7±1.3	303.4±2.7	54°	24.1±3.8	
12-16-14	Gemini N	247°	11.2±1.2	305.1±2.8	58°	14.0±2.9	
12-18-14	Gemini N	293°	12.0±1.2	306.5±1.3	17°	24.0±3.6	
01-10-15	Gemini N	296°	12.9±1.1	307.2±1.2	17°	12.4±1.9	
01-12-15	Keck	338°	11.8±0.8	306.7±1.6	35°	23.2±3.5	66±10
01-14-15	Gemini N	327°	12.4±1.1	307.5±1.3	23°	18.7±2.8	
01-26-15	Gemini N	249°	11.7±1.2	307.6±2.8	58°	7.7±3.9	
03-29-15	Gemini N	244°	12.8±1.2	311.7±4.2	68°	11±5	
03-31-15	Keck	291°	12.3±0.8	311.8±0.6	23°	9.8±1.5	29.8±4.5
04-02-15	Keck	339°	12.9±0.9	310.4±0.4	30°	9.3±1.4	28.3±4.2
04-04-15	Keck	25°	12.9±0.9	310.4±0.4	65°		15.4±2.3
04-05-15	Gemini N	250°	12.0±1.2	307.1±2.7	57°	6.0±3.0	
04-09-15	Gemini N	322°	12.4±1.2	311.8±1.3	16°	8.7±1.3	
11-23-15	Keck	327°	12.0±0.6	307.5±1.5	22°	2.9±0.4	13.4±2.0
12-25-15	Keck	328°	14.9±0.7	305.7±1.2	27°	38±6	85±13
01-22-16	Keck	277°	13.6±0.4	305.7±0.6	33°	147±22	205±30
02-09-16	Gemini N	323°	13.3±1.2	305.3±1.3	22°	94±12	
02-16-16	Gemini N	299°	12.8±1.2	306.4±1.2	14°	72±12	
02-18-16	Gemini N	18°	13.4±1.3	307.1±4.0	71°	60±20	
02-21-16	Gemini N	257°	12.1±1.2	302.7±1.9	46°	43±8	
02-23-16	Gemini N	296°	11.5±1.2	305.6±1.2	14°	63±12	
03-12-16	Gemini N	336°	12.6±1.2	307.9±1.4	31°	75±14	
03-14-16	Gemini N	27°	10.6±1.3	313.9±4.3	74°	31±13	
05-02-16	Gemini N	250°	13.2±1.3	307.7±2.9	57°	16.4±3.4	
05-04-16	Gemini N	299°	14.1±1.3	314.2±1.4	20°	25.9±4.9	
05-09-16	Gemini N	238°	12.0±1.5	313±8	75°	14±8	
05-11-16	Gemini N	281°	14.1±1.3	309.1±1.7	31°	17.8±3.4	
05-13-16	Gemini N	343°	12.3±1.3	308.6±1.7	36°	20.1±3.8	
05-18-16	Gemini N	264°	13.0±1.4	312.3±2.4	49°	19.7±3.8	
05-20-16	Gemini N	314°	12.8±1.3	311.4±1.3	13°	21.9±4.1	
05-25-16	Gemini N	261°	12.5±1.4	311.1±2.5	50°	15.9±3.1	
05-27-16	Gemini N	299°	13.7±1.4	311.4±1.5	18°	20.7±3.9	
06-01-16	Gemini N	234°	11.7±1.2	314.1±5.1	80°	12±8	
06-03-16	Gemini N	281°	14.2±1.4	308.8±1.8	30°	13.9±2.6	
06-05-16	Gemini N	329°	12.5±1.4	311.5±1.5	21°	15.3±2.9	
06-10-16	Gemini N	264°	14.2±1.4	306.4±2.3	44°	8.5±1.6	
06-12-16	Gemini N	314°	11.1±1.4	310.7±1.4	11°	14.0±2.6	
06-17-16	Gemini N	249°	13.1±1.5	308.9±3.7	60°	11.3±2.5	
06-19-16	Gemini N	297°	13.6±1.5	310.8±1.6	19°	12.1±2.3	

^a Further information on the Keck observations is given in de Pater et al. (2017), which includes locations and intensities at additional wavelengths.

^b Central Meridian Longitude from JPL Horizons: <http://ssd.jpl.nasa.gov/horizons.cgi>.

^c Emission angle for Loki Patera.

^d Intensities are taken from de Pater et al. (2014a) for 08-15-13 through 08-20-13; from de Kleer et al. (2014) for 08-29-13 through 09-10-13; and from de Kleer and de Pater (2016a) for 11-18-13 through 12-25-15.

^e Intensities on this date are poorly constrained (see de Pater et al. 2014a for details), and are shown here for completeness but are not included in the plots or analysis.

7.3 Overturning magma sea model

The time evolution of Loki Patera’s near-infrared intensity during and after brightening events places important constraints on the nature of its volcanic activity. This analysis uses a model based on the Matson et al. (2006) model of Loki Patera as an overturning magma sea of basaltic composition, to which modifications are made to improve the fit to the data. In addition, the thermal properties of the lava are adapted to include dependencies on temperature and porosity according to models for volcanism on Earth (Keszthelyi and Delinger, 1996; Patrick et al., 2004). The analysis treats Loki Patera as an overturning magma sea; alternate mechanisms such as resurfacing by lava flows have not been ruled out, although previous authors have found the foundering crust mechanism to match the observed properties better (Rathbun et al., 2002; Matson et al., 2006). Alternative models for activity at this volcanic site are discussed in Section 7.5.4.

The model consists of (1) a thermochemical cooling model for basalt (Section 7.3.1); (2) a model for the overturn, including geometry of the lake and propagation of the overturn front (Section 7.3.2); and (3) a model for the thermal properties of the lava, as a function of temperature and porosity when relevant (Section 7.3.3). Two variants of the lava thermal properties are used in the analysis: the fixed properties used by Matson et al. (2006; *Standard Model*), and a *Modified Model* in which thermal properties depend on temperature and porosity. In the Matson et al. (2006) model, the average porosity of the crust decreases as the crust thickens, and overturn is triggered when this system becomes gravitationally unstable. We implicitly assume this mechanism for overturn triggering, although our data do not provide new insight into the triggering mechanism and we thus do not directly treat this aspect of the model.

7.3.1 Basaltic Cooling Model

The magma sea model treats Loki Patera as a semi-infinite lava reservoir of basaltic composition. It calculates the crust thickness and surface temperature as a function of time, including the effect of latent heat released as the crust solidifies, according to the method described by Turcotte and Schubert (1982), which was used by Head and Wilson (1986) to model Venusian lavas, and applied to Io by Davies (1996).

The model is formulated on the assumptions that the magma remains continuously molten beneath a surface crust layer, and that the magma is deep enough that boundary conditions at the bottom of the lake do not affect the observed emission. As an area of crust founders, a section of hot magma becomes newly exposed to the environment. As this new magma cools, a new crust forms and thickens on the surface. Magma in contact with the base of the crust solidifies onto the crust, releasing latent heat that is then conducted through the crust layer and released in the form of radiation. The radiative intensity is given by the Stefan-Boltzmann law:

$$F_{rad} = \sigma \epsilon (T_{surf}^4 - T_{env}^4) \text{ [W/m}^2\text{]} \quad (7.1)$$

where T_{env} is taken as zero for Io, ϵ is the thermal emissivity, and σ is the Stefan-Boltzmann constant. The latent heat released at the crust-magma boundary is (Turcotte and Schubert,

1982)

$$Q = \rho L \frac{dC}{dt} \text{ [W/m}^2\text{]} \quad (7.2)$$

where ρ is the density (kg/m³), L is the latent heat (J/kg), and C is the thickness of the crust in meters. This heat is conducted upward according to Fourier's Law:

$$F_{cond} = k \left(\frac{\delta T}{\delta z} \right)_{z=C} \quad (7.3)$$

where z is the vertical coordinate, increasing with depth from a value of $z = 0$ at the surface, and k is the thermal conductivity of the lava composing the crust in units of W/m/K.

Using Equations 7.2 and 7.3, and given a surface temperature T_{surf} , the proportionality constant λ_1 between the thickness of the crust and the thermal diffusion lengthscale is solved for (Turcotte and Schubert, 1982):

$$\lambda_1 = \frac{C(t)}{2\sqrt{\kappa t}}, \quad (7.4)$$

assuming a thermal diffusivity κ .

This then yields the crust thickness as a function of time. The energy radiated into space is equal to the heat conducted from the crust-magma interface to the surface, given by (Turcotte and Schubert, 1982)

$$F_{rad} = F_{cond,z=0} = k \left(\frac{\delta T}{\delta z} \right)_{z=0} = k \frac{T_{z=C} - T_{z=0}}{\sqrt{\pi \kappa t} \operatorname{erf}(\lambda_1)}, \quad (7.5)$$

which is the standard solution to the 1D diffusion equation evaluated at the surface boundary, adjusted by the value of the error function evaluated at λ_1 . The release of latent heat slows the rate of cooling and of crust thickening compared to a case where no phase change occurs. The precise method of solution is described in detail by previous authors (e.g. Turcotte and Schubert, 1982; Head and Wilson, 1986).

Figure 7.1 shows the temperature, 3.8- μm intensity, and crust thickness as a function of time for basaltic and ultramafic models with fixed thermal properties, as well as a basaltic composition model modified as described in Section 7.3.3.

7.3.2 Overturn Model

The shape of Loki Patera is approximated as an ellipse with a total overturning area of 21,500 km² and dimensions (semi-major and semi-minor axes) of 196 $\times$ 140 km. This emitting area matches the area of the dark patera floor as seen in spacecraft images (Veeder et al. 2011), but the shape is simplified from the irregular annular shape of the real patera. Such a simplification is reasonable given the other uncertainties in geometry and physics. While the assumed geometry affects the retrieved propagation velocity, the areal overturn rate is not highly sensitive to this geometry and is constrained directly (see Section 7.4.2).

In the model, an overturn front propagates at a fixed velocity along the long axis of the ellipse until the entire area has been resurfaced, following the Matson et al. (2006) model,

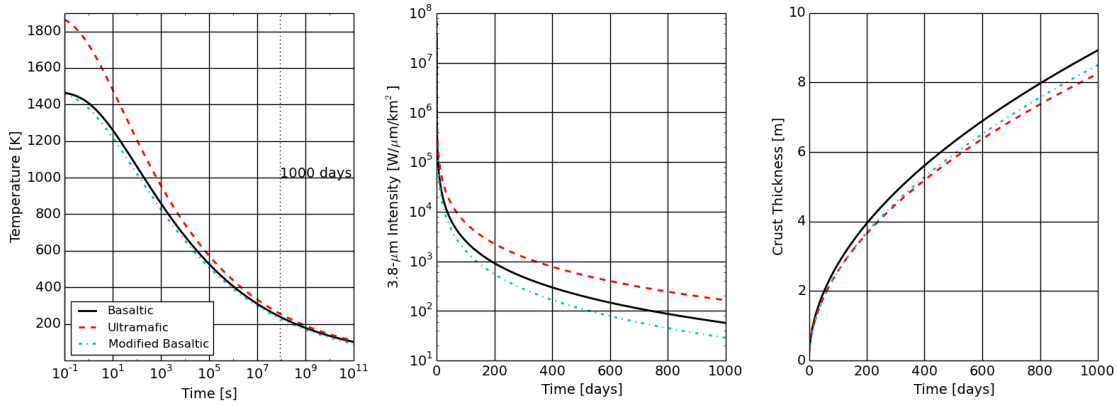


Figure 7.1: Time-evolution of lava crust properties for different thermal models: Basaltic and Modified Basaltic models use the *Standard* and *Modified* thermal properties given in Table 7.2, and the Ultramafic model uses the thermal properties given for this magma composition by Davies et al. (2005).

which is based on the periodically-overturning lava lake model introduced by Rathbun et al. (2002). The ellipse is divided into surface area segments defined so that one segment is overturned every time interval Δt , and the segment areas are calculated from the ellipse geometry as described in Figure B1 of Matson et al. (2006). The thermal emission timeline produced by the model includes a spike as each segment founders (most prominent at short wavelengths), followed by a decay. One feature of modeling the overturn as a series of foundering segments is therefore that the measured emission varies greatly depending on the time interval between the last segment foundering and the data being taken. We choose to always evaluate the model a fixed amount of time τ after the most recent segment has overturned. Different combinations of choices for the parameters Δt and τ are tested in the model fits, including a continuous overturn model which assumes that the overturn front moves continuously at a constant velocity. The spread in best-fit models produced using these parameters gives a sense for the uncertainties in the model fits due to uncertainties in the exact details of the overturn progression.

The default overturn has a propagation velocity of 1 km/day and a total cycle duration of 540 days, consistent with observations of brightening cycles prior to 2001 (Matson et al. 2006; Rathbun et al., 2002; Davies 2003). However, the cycle duration and overturn velocity depend sensitively on the magma properties and thus may vary between brightenings (Rathbun and Spencer 2006). The default values do not provide a good fit to the observations presented here, and the overturn velocity v and cycle duration N_{cyc} are left as free parameters in the model fits, allowing different velocities and durations for each brightening event.

The temperature of each surface area unit at each time-step is calculated from the cooling model (Section 7.3.1). The emission from the lake is then calculated using Planck's Law for

blackbody radiation:

$$F_{\lambda}(t) = \sum_{i=1}^n \frac{c_1 A_i \epsilon}{\lambda^5} \frac{1}{e^{c_2/\lambda T_i(t)} - 1} \text{ [W}/\mu\text{m}] \quad (7.6)$$

and the total wavelength-integrated thermal power is

$$F(t) = \sum_{i=1}^n \sigma A_i \epsilon T_i(t)^4 \text{ [W]} \quad (7.7)$$

where $c_1 = 2hc^2/\pi = 3.7413 \times 10^8 \text{ W}/\mu\text{m}^4/\text{m}^2$ and $c_2 = hc/k_B = 1.4388 \text{ }\mu\text{m-K}$. A_i is the area of the i th surface element in units of m^2 , ϵ is the emissivity, and the wavelength λ is expressed in μm . Flux densities can be expressed per steradian by dividing by a factor of π .

Analysis of high-resolution *Galileo* NIMS images of the southern half of Loki Patera suggested the presence of hot cracks through the crust (Davies 2003). Matson et al. (2006) did not include cracks in their thermal model, determining that the total crack fraction was too small to be significant. Cracks or other localized high-temperature activity would preferentially affect shorter wavelength data. Although the models presented here are fit only to the 3-5 μm data, the presence of such features could account for some of the emission at 2- μm wavelengths seen in the figures.

7.3.3 Thermal Properties

The Matson et al. (2006) model fixes the thermal properties of basalt at specific parameters based on those estimated by Davies (1996) for Ionian lavas. These authors note that the available data did not warrant a more complex model. However, the thermal properties of lavas on Earth are observed to depend strongly on properties including temperature and porosity; Patrick et al. (2004) give a concise summary of decades of analytical and experimental work on thermal properties of lava flows on Earth. The *Standard* thermal model used by Matson et al. (2006) is tested alongside a *Modified* thermal model based on the recommendations of Patrick et al. (2004) and the model of Keszthelyi and Delinger (1996). This section describes the thermal property parameterizations used in the *Modified* model, which are summarized alongside the fixed properties from the *Standard* Model (Davies, 1996; Matson et al., 2006) in Table 7.2.

7.3.3.1 Density

The overturn scenario is based on the premise that the crust forms at a low enough density to be initially buoyant, but increases in density over time until it becomes gravitationally unstable and founders (Rathbun et al., 2002; Rathbun and Spencer, 2006). A basic requirement of the model is therefore that the bulk density of the crust increase over time. Although this density change is predominantly due to the evolving porosity profile in the crust (Matson et al. 2006), the temperature-dependent density of basalt is also included in the *Modified* model. This dependency is incorporated via the formula for the density of vesicular basalt given by Keszthelyi and Delinger (1996) based on data presented by Touloukian

Table 7.2: Basalt Thermal Properties

Property	Symbol	Standard	Modified
Latent heat of crystallization [J/kg]	C_L	4×10^5	4×10^5
Specific heat [J/kg/K]	c_p	1500	1500 for $T > 1000$ K; $1600 - \frac{10^5}{T}$ for $T < 1000$ K
Liquidus Temperature [K]	T_{liq}	1475	1475
Lava solid density [kg/m ³]	ρ_{sol}	2800	2800
Lava liquid density [kg/m ³]	ρ_{liq}	2600	2600
Crust density [kg/m ³]	ρ_{crust}	ρ_{sol}	$\frac{\rho_{sol}}{1 + \beta(T - 1450)}$
Lava thermal conductivity [W/m/K]	k_{bas}	0.9	1.1
Gas thermal conductivity [W/m/K]	k_{gas}	—	$(c_p + \frac{5R}{4m_{gas}})\mu$
Crust thermal conductivity [W/m/K]	k_{bulk}	k_{bas}	$k_{bas} \times \frac{[2(1-\phi)k_{bas} + (1+2\phi)k_{gas}]}{[(2+\phi)k_{bas} + (1-\phi)k_{gas}]}$
Emissivity	ϵ	0.9	0.9
Thermal diffusivity [m ² /s]	κ	$\frac{k}{\rho_{crust}c_p}$	$\frac{k}{\rho_{crust}c_p}$
Crust porosity	ϕ	—	$\phi = 30\% \times \frac{T}{T_{liq}} + 20\%$
Coefficient of thermal expansion [K ⁻¹]	β	—	1.5×10^{-5}

et al. (1989):

$$\rho_{bas} = \frac{\rho_{sol}}{1 + \beta(T - 1450)} \quad (7.8)$$

where ρ_{sol} is the density of solid basalt given in Table 7.2, and β is the coefficient of volumetric thermal expansion for vesicular basalt (1.5×10^{-5} K⁻¹; Keszthelyi and Delinger, 1996). This parameterization gives a density that increases by ~ 50 kg/m³ as the crust cools from the liquidus temperature down to 250 K. The effect on the model of including this temperature-dependence is minor; the term is included primarily for completeness in the treatment of the increase in crust density with time.

7.3.3.2 Porosity

The porosity of the crust affects its thermal conductivity and its bulk density, impacting its cooling rate and thermal emission as well as triggering overturn initiation when the bottom of the crust layer becomes dense enough to create a gravitational instability (Matson et al. 2006). Measurements of the Hawaiian Alae lava lake (Peck et al., 1966) revealed surface porosities of 40%, decreasing almost exponentially to around 10% at depth. This is consistent with the work of Leone and Wilson (2001), who used the dynamics of plumes on Io to infer a volatile mass fraction of $\sim 30\%$, as well as with the calculation by Matson et al. (2006) for Loki Patera considering SO₂ content and pressure. Matson et al. (2006) developed a model for the evolving porosity profile of Loki Patera as a function of crust thickness; the porosity reaches a maximum of 50% porosity at the surface decreasing with depth to a minimum of 5-10% at the base of the crust, assuming a crust thicknesses in the 5-10 meter range. Their model provides a physical mechanism for understanding why and when the crust becomes

unstable and overturn is triggered. However, the porosity is not incorporated into the Matson et al. (2006) thermal model, and is therefore not included in the *Standard* model used here.

The primary outcome of including porosity in the thermal model is to decrease the bulk thermal conductivity of the crust. Although incorporation of the time- and depth-dependent porosity into the thermal model is beyond the scope of this paper, the *Modified* model includes a simple parameterization describing the decreasing average porosity of the crust with time. The description is based on the Matson et al. (2006) model, in which the average porosity of the crust decreases from 50% for a thin crust to $\sim 20\%$ around the time that overturn is triggered. Due to other uncertainties in the thermal model, the model-fitting is not sensitive to the exact shape of this decrease, and a linear profile is used in the *Modified* models:

$$\phi = 30\% \times \frac{T}{T_{liq}} + 20\%, \quad (7.9)$$

which achieves the required value for both high and low temperatures.

7.3.3.3 Thermal conductivity

Typical basalts have thermal conductivities in the range of 0.9-4.0 W/m/K (Davies 2007). Peck (1978) recorded thermal conductivities of 0.1-1.8 W/m/K in the porous crust of the Hawaiian Alae lava lake, noting changes with vesicularity and temperature. By comparing model cooling curves with cooling data from the crust of a Hawaiian pahoehoe flow (Flynn and Mougini-Mark, 1992), Davies (1996) note a favorable correspondence for a value of $k = 1$ W/m/K, although the data also compare favorably with models using values of k from slightly below 1 up to nearly 3 W/m/K. The value chosen for models of Ionian basalts has often been on the low end of this range, between 0.6 and 0.9 W/m/K (Davies 1996; Matson et al., 2006; Davies 2007).

Studies of basalts on Earth disagree about whether the thermal conductivity increases with temperature (e.g. Birch and Clark, 1940; Robertson, 1988) or decreases as temperature increases (e.g. Murase and McBirney, 1973; Dunn et al., 1983). Patrick et al. (2004) discuss the evidence for each case, noting a strong consistency in the results of the latter group. The high density of observations during the cooling phases of the Loki Patera brightenings in 2013 and 2014 place constraints on the shape of the cooling curve. Models with a thermal conductivity that increases with temperature are unable to match the shape of this curve. Models with a thermal conductivity that increases as the lava cools are able to fit the observations, but give no significant improvement in fit over models with a constant thermal conductivity. The *Modified* thermal model therefore assumes a basalt thermal conductivity without temperature dependency. However, the *bulk* thermal conductivity of the crust does increase during cooling due to the temperature-dependence of the lava porosity. Values for the basalt thermal conductivity between 0.9 and 1.2 W/m/K (corresponding to bulk thermal conductivities of 0.55-0.75) are explored in the fits; values outside of this range predict too little or too much emission to match the observations, assuming a fixed overturn area of $2.15 \times 10^4 \text{ km}^2$.

The porosity ϕ of basalt also has a significant effect on the bulk thermal conductivity k_{bulk} . The model follows Rathbun et al. (2002) and Keszthelyi and Delinger (1996) in using the porosity dependence of Maxwell (1891), which calculates the bulk thermal conductivity k_{bulk} in terms of the thermal conductivity of the lava k and of the gas k_{gas} , taken here to be SO_2 :

$$k_{bulk} = k \frac{2(1 - \phi)k + (1 + 2\phi)k_{gas}}{(2 + \phi)k + (1 - \phi)k_{gas}}. \quad (7.10)$$

The thermal conductivity of a gas is given by (Bird et al., 1960):

$$k_{gas} = (c_p + \frac{5}{4} \frac{R}{m_{gas}}) \mu \quad (7.11)$$

where R is the gas constant, m_{gas} is the molar mass, and μ is the dynamic viscosity, given by Sutherland's formula (Sutherland 1893)

$$\mu = \lambda \frac{T^{3/2}}{T + C} \quad (7.12)$$

where λ and C are constants of the gas, which are $1.7684 \mu\text{Pa}\cdot\text{s}/\text{K}^{1/2}$ and 416 K respectively, for SO_2 gas. The net result of including vesicles in the treatment of the thermal conductivity is a reduction in the bulk crust conductivity of 30-40%. The thermal conductivity of the gas within the vesicles themselves contributes <5% to the bulk conductivity.

7.3.3.4 Specific heat capacity

A formula approximating the change in the specific heat capacity of lava with temperature is presented in Keszthelyi (1994) based on laboratory data in Touloukian et al. (1989). This formula assumes a maximum (high-temperature) specific heat of 1100 J/kg/K . For the *Modified* thermal model, this formula is adjusted to match the maximum specific heat to the value of 1500 J/kg/K used by previous authors for Io (Davies, 1996; Matson et al., 2006):

$$c_p = 1500 \text{ J/kg/K for } T > 1000 \text{ K} \quad (7.13)$$

$$c_p = 1600 - \frac{10^5}{T} \text{ J/kg/K for } T < 1000 \text{ K} \quad (7.14)$$

7.3.4 Fits and Model Comparison Metrics

The model fits employ the Python **emcee** implementation (Foreman-Mackey et al., 2013) of an affine-invariant ensemble Markov chain Monte Carlo (MCMC) method (Goodman and Weare, 2010), which has been used in the past for planetary science applications (e.g. de Kleer et al., 2015).

Discriminating between models requires careful treatment of the degree of model complexity. Although the determination of best-fit parameters for a given model relies on χ^2

minimization, χ^2 is not a meaningful metric for comparison between non-linear models because the number of degrees of freedom is not in general well-defined (Andrae et al. 2010). Although χ^2 values for model fits are given in the results section, these are intended to give a rough sense of the fit quality and should not be used for quantitative comparison between models.

Instead, two model-comparison metrics are employed to distinguish between models: the Deviance Information Criterion (*DIC*) and the Kolmogorov-Smirnov Test (KS-test) *p*-value. The *DIC* combines a standard term for goodness-of-fit with a penalty term for model complexity, and considers the full posterior distribution of each parameter, allowing comparison of the models themselves rather than their single best-fit manifestations (Spiegelhalter et al. 2002). Smaller values correspond to better fits; values are reported in the form of ΔDIC , the difference between the value for a given model compared with that of the best model (lowest *DIC* value). This metric is explained in more detail in de Kleer et al. (2015), and is particularly convenient because it is simple to calculate from the output of MCMC simulations.

The KS-test (Kolmogorov 1933; Smirnov 1948) is reported because it gives insight into whether the deviations from the model are random or systematic; systematic deviations indicate an incorrect model, even if the χ^2 value is small. The KS-test checks the likelihood that a given dataset (in this case, the residuals from the model fits) is consistent with a given distribution (here, the Gaussian distribution). Residuals consistent with a Gaussian distribution indicate a correct model; an incorrect model can be identified by a skewed distribution, by too much power in the wings, or by a very peaked noise distribution indicative of a model that overfits the data. If the *p*-value is less than one minus the chosen significance level, the hypothesis that the residuals are drawn from a Gaussian distribution can be rejected.

7.4 Analysis and Results

The original magma sea model (Matson et al. 2006) provides a good fit to the first two overturns, provided the following three parameters are allowed to vary: the propagation velocity of overturn front, the interval between the start of successive overturns, and the background intensity level. Fits using this model are shown in Figure 7.2. The background intensity parameter is an additive scalar value that is fixed over time per brightening event, representing activity in the patera that is independent of the overturn, such as the active southwest margin observed by *Galileo* (Spencer et al. 2000; Davies 2003; Howell & Lopes 2007). Although the best-fit values for this parameter are low relative to Loki Patera’s total emission ($<5 \text{ GW}/\mu\text{m}/\text{sr}$), the parameter is required to fit the data during the quiescent phase without invoking high thermal conductivities that fit the data poorly at earlier times. The third overturn is not well fit by the standard overturn model; in particular, the short duration of the bright period cannot be matched by the model without drastically overpredicting the thermal emission. A forward model with an overturn velocity of 2 km/day (at the upper end of the velocities determined in the past for Loki Patera) is shown in Figure

7.2. Although the K-band ($2.3\text{-}\mu\text{m}$) data and models are shown in the figures, in all cases the model-fitting is based on only the L- and M-band (3.8- and $4.7\text{-}\mu\text{m}$) data. The short wavelength data are omitted from the fits because they are very sensitive to features such as localized irregularities in the overturn propagation or the presence of cracks in the crust (Davies 2007), which are not included in the model.

Table 7.3: Best-fit Model Parameters: Third Brightening

<i>Thermal</i>	Model			Parameters				Fit Quality ^a		
	k_{bas}	k_{bulk}	N_{phase}	$frac$	$frac_{cover}$	v	$\bar{A}$	χ^2	p	ΔDIC
	[W/m/K]					[km/day]	[m ² /s]			
Std	0.9	0.9	2	0.58 ± 0.05	0.63 ± 0.05	1.11 ± 0.17	1410	18.9	0.53	0.0
Mod	0.9	0.57	2	0.59 ± 0.05	1	1.70 ± 0.21	2150	20.3	<0.01	3.8
Mod	1.0	0.63	2	0.57 ± 0.04	1	1.69 ± 0.18	2150	20.1	0.04	1.6
Mod	1.1	0.69	2	0.56 ± 0.04	1	1.74 ± 0.18	2220	23.0	0.19	1.2
Mod	1.2	0.75	2	0.56 ± 0.04	1	1.88 ± 0.23	2390	28.7	0.35	7.5

^aSee Section 7.3.4 for interpretation of the metrics. In general, better models have lower χ^2 and ΔDIC values, while p -values below 0.02 rule out models at the 98% level. Note that χ^2 is not a meaningful metric for comparison between models. In addition, χ^2 and ΔDIC values cannot be used to compare directly between different overturn events.

Table 7.4: Best-fit Model Parameters: First Two Brightenings

Model ^a			Parameters					Fit Quality ^b					
Thermal Model	Geo	ΔT [days]	τ [days]	v_0 [km/day]	v_1 [km/day]	$\overline{A_0}$ [m ² /s]	$\overline{A_1}$ [m ² /s]	χ^2_1	χ^2_2	p_1	p_2	ΔDIC_1	ΔDIC_2
Std	Ellip	1.0	0.5	1.25±0.14	1.31±0.13	1600	1660	12.3	21.8	0.87	0.14	1.3	1.0
Std	Ellip	1.0	1.0	1.42±0.16	1.52±0.18	1800	1910	14.6	22.1	0.95	0.27	2.8	0.0
Std	Ellip	0.1	0.05	1.19±0.13	1.22±0.12	1520	1560	11.2	23.1	0.61	0.05	0.0	2.2
Std	Ellip	0.1	0.1	1.22±0.14	1.26±0.13	1560	1600	11.8	22.4	0.59	0.04	0.9	1.6
Std	Ellip	<i>Continuous</i>		1.19±0.13	1.20±0.13	1520	1540	10.7	25.0	0.40	0.02	0.1	1.9
Std	Rect	1.0	0.5	1.33±0.14	1.50±0.16	1680	1910	10.5	22.2	0.61	0.08	0.5	0.0
Mod	Ellip	1.0	0.5	1.65±0.19	2.16±0.40	2110	2760	13.3	37.8	0.84	<0.01	2.9	13.8

^a All models have a fixed total patera surface area of 2.15×10^4 km².

^b See Section 7.3.4 for interpretation of the metrics. In general, better models have lower χ^2 and ΔDIC values, while p -values below 0.02 rule out models at the 98% level. Note that χ^2 is not a meaningful metric for comparison between models. In addition, χ^2 and ΔDIC values cannot be used to compare directly between different overturn events.

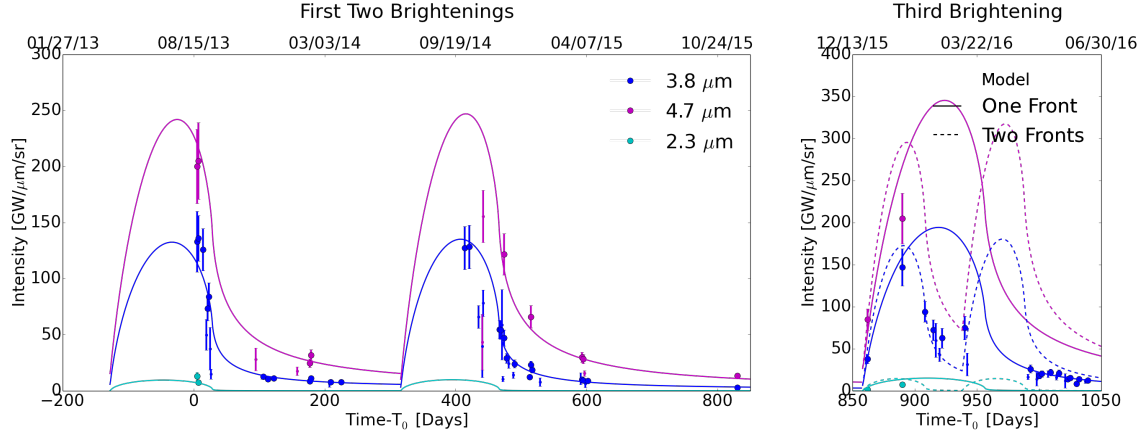


Figure 7.2: Timelines of the three brightening events with the original Matson et al. (2006) overturning magma sea model. For the first two events, the model is fit to the data with the velocity of overturn, interval between successive overturns, and background intensity level as free parameters in the fits. For the third overturn, the model does not provide a good fit to the data, and models are shown demonstrating the resurfacing of the patera in both one and two phases with an overturn velocity of 2 km/day (not fit to the data). Circles are observations with $\mu > 0.7$ and were used in the fit; points are limb-viewing observations with $\mu < 0.7$ which were not used in the fits. Note the difference in y-axis scale between the two panels.

A rise in intensity during the nominal cooling phase suggests that the third brightening was more complex than a single, fixed-velocity overturn. The data lack the time-resolution to determine the specific details of the overturn progression, and two simple alternatives are therefore modeled: a two-phase overturn, and an overturn that resurfaces only a fraction of the patera. In the two-phase model, the fraction of the patera that is overturned in the first phase is left as a free parameter in the fits ($frac$ in Table 7.3), and the model requires the entire patera to overturn. Allowing a two-phase resurfacing event improves the model fit somewhat, but still predicts higher intensities than seen in the data (see Figure 7.2). If the percentage of the patera overturned during the brightening is left as a free parameter ($frac_{over}$), model fits find that only $\sim 60\%$ of the patera is resurfaced. This model is compared with models for which the entire patera overturns in Figure 7.3 and Table 7.3, and provides a comparably good fit to the model with *Modified* thermal properties in which the entire patera is resurfaced.

An alternate resolution to the poor model fit to the third brightening is that the thermal properties may be incorrect. The thermal properties used for past modeling of Io's lava flows (Matson et al. 2006; Davies 2007) were adopted as typical values for basaltic composition, but were not well-constrained by past data. The following sections discuss the results of varying the thermal parameters as described in Section 7.3.3 and of varying the patera geometry and the continuity of overturn. Models assuming a single overturn fail to fit the data regardless of input parameters, and all fits therefore assume a two-phase overturn, which is adopted as

the simplest parameterization of a complex overturn progression.

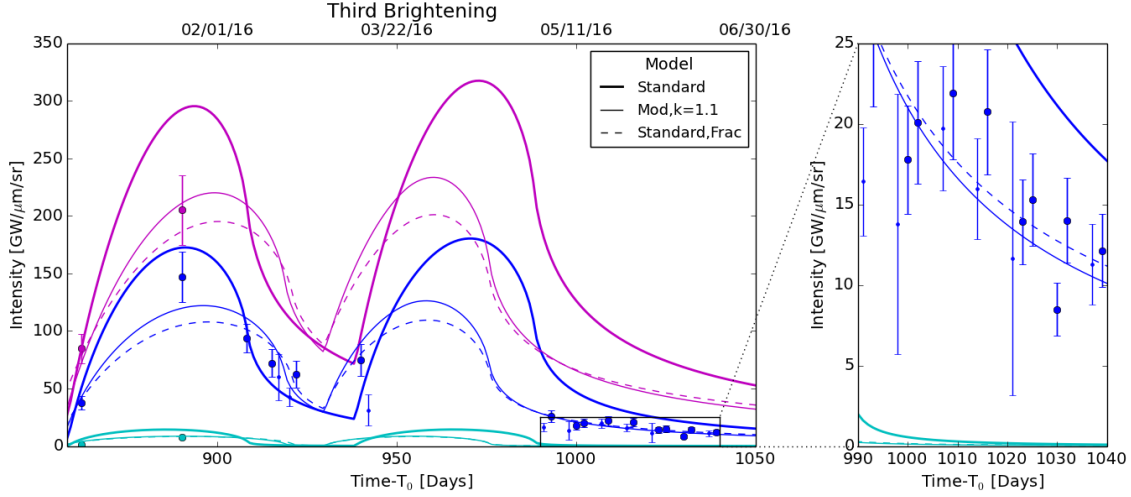


Figure 7.3: Model for the third brightening event using *Standard* thermal properties and a best-fit resurfacing fraction of 0.63, compared with models in which the entire patera is resurfaced. The *Standard* model is a forward model with a velocity of 2 km/day, while the other two models are fit to the data. The magenta, blue, and cyan points correspond to M-, L-, and K-band data, as in the other figures, and the rightmost panel is a close-up view of the boxed region indicated on the main panel.

7.4.1 Thermal Properties

The modifications made to the original magma sea model (Matson et al. 2006) include the porosity, specific heat capacity, density, and thermal conductivity (see Section 7.3.3). Of these properties, the porosity ϕ and the thermal conductivity k of the lava have the greatest impact on the quality of fit (though the porosity impacts the model primarily through its effect on the bulk thermal conductivity). In general, models with lower thermal conductivities predict shorter bright phases given the observations, since higher overturn front velocities are required to match the peak intensities observed. The durations of the first two overturns are unconstrained by the observations, and models with a range of thermal properties fit the data well. In contrast, the duration of the third brightening event is well-constrained, and this event is used to constrain the thermal properties within the framework of the model assumptions.

Figure 7.4 shows best-fit models to the third event for basalt thermal conductivities from $k = 0.9 - 1.2$ W/m/K and other thermal properties fixed at the *Modified* model values. These models all predict more realistic peak intensities than the *Standard* thermal model; the best fits are achieved for $k = 1.0$ and 1.1 W/m/K. However, the $k = 1.0$ W/m/K case does not find a good fit to the first two brightenings, and the residuals from the third brightening are suggestive of systematic deviations; $k = 1.1$ W/m/K is therefore chosen as

the nominal model value. All choices for k find similar values for the fraction of the lake that is overturned for the first versus second phase of the third event, but the overturn velocity is higher for larger values of k . Note that because the *Modified* model incorporates porosity into the calculation of bulk thermal conductivity, a basalt thermal conductivity of 1.1 W/m/K corresponds to a *bulk* thermal conductivity of 0.7 W/m/K (see Table 7.3), which is lower than that used by the *Standard* model.

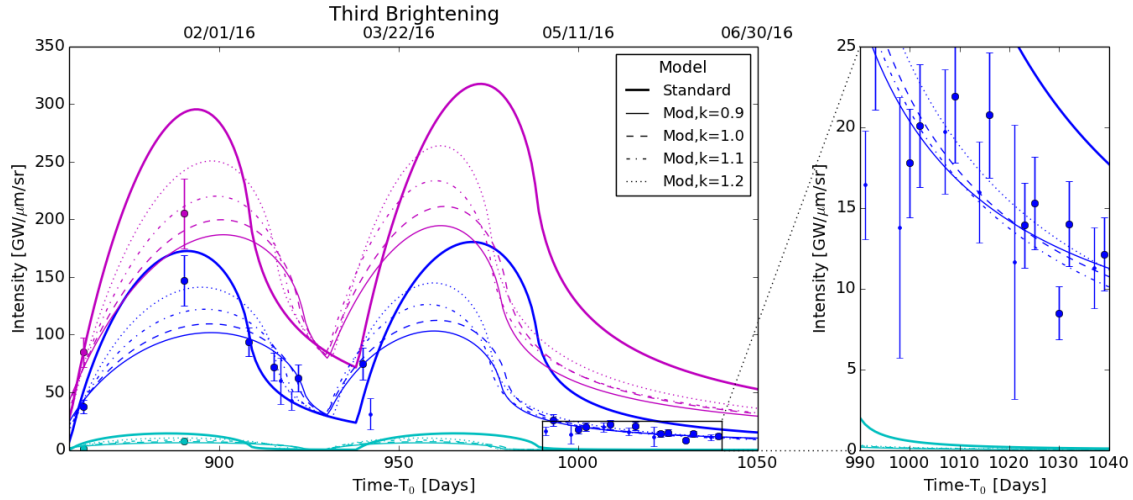


Figure 7.4: Fits to the thermal emission during the third brightening event for models with different thermal properties, assuming a two-phase overturn. All “Mod” models use the *Modified* thermal properties, with the basalt thermal conductivity k_{bas} given in the legend in units of W/m/K. The *Standard* model is a forward model with a velocity of 2 km/day, while the other models are fit to the data. The magenta, blue, and cyan points correspond to M-, L-, and K-band data, as in the other figures, and the rightmost panel is a close-up view of the boxed region indicated on the main panel.

Models with the *Modified* thermal properties, including a bulk thermal conductivity of $k = 1.1$ W/m/K, also provide a reasonable fit to the 2013 brightening event, but are ruled out by both the KS-test and the *DIC* for the 2014 event. However, there are no data from the first part of the 2014 event; this discrepancy could be improved by postulating a more complex or multi-phase overturn, but the lack of data preclude including these complexities in the model. It should be noted that the third brightening is the only event which was observed from beginning to end and whose duration is constrained, and for which the models therefore have the least ambiguity. However, assuming a single-phase overturn, the best fit for the 2013 and 2014 events is still obtained for the *Standard* thermal properties (see Figure 7.5).

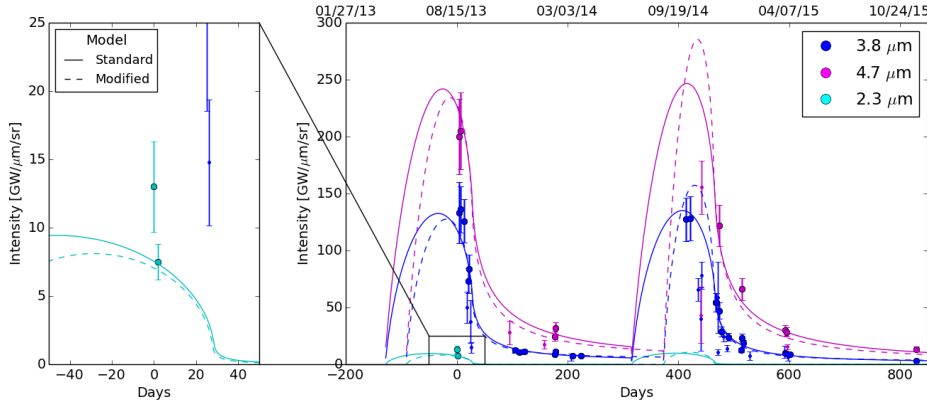


Figure 7.5: Fits to the first two brightening events using models with *Standard* and *Modified* thermal properties. The *Standard* model is as shown in Figure 7.2. The parameter values for the models are given in Table 7.4. The magenta, blue, and cyan points correspond to M-, L-, and K-band data respectively, and the left panel is an enlargement of the indicated region in the right panel.

7.4.2 Geometry

The geometry of the patera as seen in spacecraft images is complex; moreover, the propagation of the overturn front is likely not a smooth, linear process. For a fixed overturn front velocity, the patera geometry determines the area overturned each day, and thus the shape of the thermal timeline. To test the magnitude of influence the adopted geometry has on the model fits, models with both elliptical and rectangular geometries are considered.

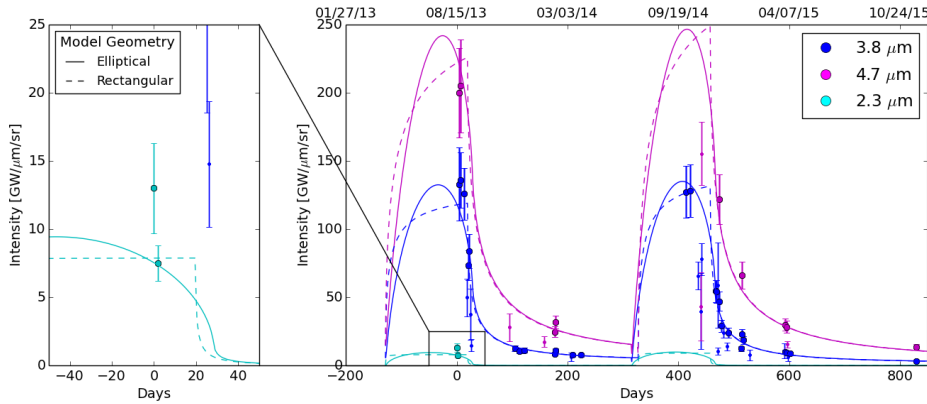


Figure 7.6: Model fits to the 2013 and 2014 overturn events for *Standard* thermal properties and two different patera geometries. Both geometries provide comparable fits to the data. The magenta, blue, and cyan points correspond to M-, L-, and K-band data respectively, and the left panel is an enlargement of the indicated region in the right panel.

The results of these fits are shown in Figure 7.6 and the parameters are given in Table 7.4. The dominant effect of changing the model patera geometry is on the specific shape of the thermal timeline during the peak activity; models for different patera geometries converge rapidly after the active overturn phase has ended. While the elliptical geometry provides a slightly better fit, the values of the quality-of-fit metric for the two geometries are close enough that this improvement is not statistically significant. In addition, the retrieved velocities for both overturns are consistent within uncertainties. The differences between the elliptical and rectangular models are therefore not significant, and can be considered representative of the uncertainties introduced into the fits by using a simplified shape model.

7.4.3 Continuity of Propagation

The foundering and sinking of portions of a lava lake crust is a non-uniform process on Earth (e.g. Wright et al., 1968). The temperature distribution on the floor of the patera determined from *Galileo* observations revealed this to be the case for Loki Patera as well (Davies, 2003; Howell and Lopes 2007). The thermal emission at the time of a given observation is extremely sensitive to the amount of young magma exposed at that moment, and therefore to the size of the most recent foundering portion and how long ago it sank. If only 1% of the lake has foundered within the past half day, the $3.8\text{-}\mu\text{m}$ emission will be $>50\text{ GW}/\mu\text{m}/\text{sr}$, nearly a third of the peak intensity. Figure 7.7 demonstrates that the entire area of Loki Patera at 300 K has a comparable $3.8\text{-}\mu\text{m}$ intensity to a small area of 100 km^2 one day after overturn (i.e. $\sim 0.5\%$ of the lake area at 540 K), or equivalently, to an area of 10 km^2 0.1 days after overturn (i.e. $\sim 0.05\%$ of the lake area at 690 K). Additionally, as can be seen in Figure 7.7, these three scenarios have drastically different ratios of intensity between the observed wavelengths, illustrating the impact of the overturn continuity on the thermal model, and the importance of observations at multiple wavelengths.

The continuity of overturn is parameterized by the two parameters Δt and τ (introduced in Section 7.3.2), which give the time interval between the foundering of successive portions of the crust, and the time between the last raft sinking and a given observation being made. Models using different values for these two parameters are fit to the first two overturns, as is a model for continuous overturn which assumes that the propagation wave moves continuously instead of the foundering occurring in large rafts.

Figure 7.8 demonstrates the best-fit models for cases with $\Delta t = \{0.1, 1.0\}$ days and $\tau = \{0.5, 1.0\} \times \Delta t$, as well as a continuous overturn model; the best-fit parameters for these fits are given in Table 7.4. All models provide a comparably good fit to the data, although models predicting greater short-wavelength emission produce residual distributions for the 2014 event that are somewhat non-Gaussian. The overturn velocities for both events are consistent within uncertainties in all cases. Because the size of the rafts and interval between foundering areas are likely non-uniform, the range of models plotted in Figure 7.8 can be interpreted as giving a qualitative sense for the degree of variability expected due to this non-uniformity.

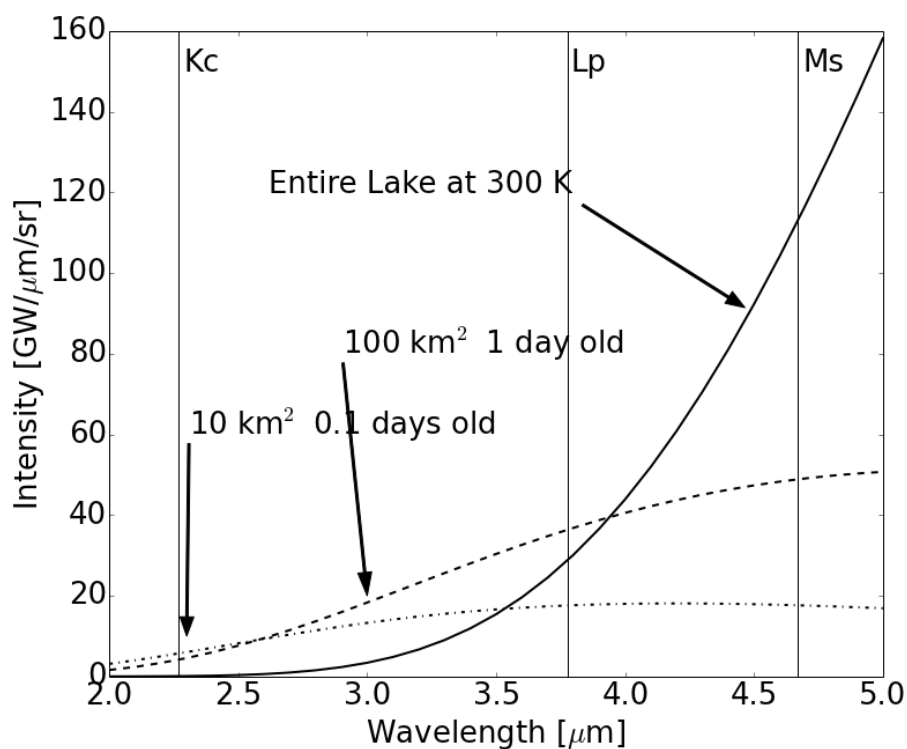


Figure 7.7: The 2-5 μm thermal emission spectra for three areas at different temperatures, comparing the entire lake at a typical quiescent temperature of 300 K with the total emission from small areas of 10 and 100 km^2 at high temperatures corresponding to 0.1 and 1.0 days post-overtun, respectively. A comparison of the three curves demonstrates that a small hot area can produce comparable K- and L-band emission to the entire patera during quiescent times.

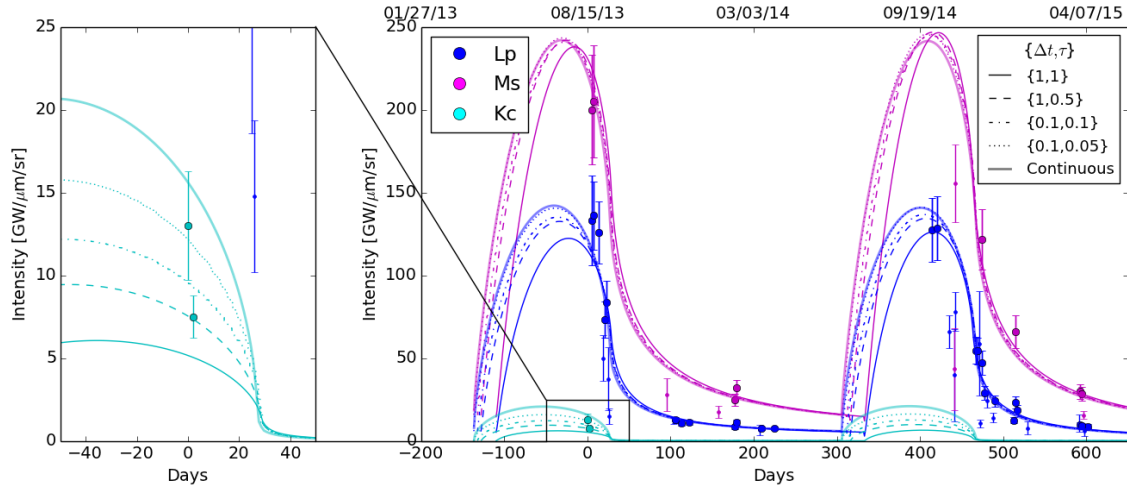


Figure 7.8: Model fits to the 2013 and 2014 brightenings for different values of Δt and τ , the time interval between successive rafts sinking and the time between the last raft sinking and the current observation. A continuous model is also shown, in which the propagation wave moves continuously at a constant velocity. The differences between the models are mainly due to the amount of high-temperature lava exposed at any given time. The magenta, blue, and cyan points correspond to M-, L-, and K-band data respectively, and the left panel is an enlargement of the indicated region in the right panel.

7.5 Discussion

7.5.1 Overturn model

7.5.1.1 2013 and 2014 brightenings

For the brightening events in 2013 and 2014, the Matson et al. (2006) model provides a good fit to the thermal emission timelines at wavelengths of 2.3, 3.8, and 4.7 μm , with a few caveats. The velocity of overturn front propagation, and the time between successive brightenings, must be left as free parameters. While the nominal model includes an overturn front velocity of 1 km/s and an average cycle duration of 540 days, the best-fit models for these brightenings find velocities around 1.3 km/s and cycle durations of 440 and 540 days respectively, with uncertainties of 20 days. In addition, the observed intensity during the quiescent phase is higher than that predicted by the model, and a parameter for the background level of thermal activity beyond the overturn must be included to obtain a close fit at these times. This background emission may represent localized activity such as active margins, or may be due to changes in the lava properties during cooling that are not accurately described by the model.

It is important to note that no data were obtained during the early phases of the events, and the durations of the events are consequently nearly unconstrained. While models with different thermal properties and overturn continuities achieve comparable fit qualities in many cases, they predict very different bright-phase durations. If data from the early part of the events existed, they would provide a clear constraint for distinguishing between these models.

7.5.1.2 2016 brightening

In contrast to the first two events, the duration of the third brightening is closely constrained, and the original Matson et al. (2006) model is not able to fit the data. Postulating that the overturn proceeds in two phases, as suggested by a sharp rise in emission during the cooling phase and consistent with past observations (e.g. Rathbun and Spencer 2006), mitigates the problem somewhat. However, obtaining a good fit to these data requires a mechanism that reduces the emission from the patera during the overturn. Two mechanisms are explored that could produce such an effect: the thermal properties of the lava, and the fraction of the patera that is resurfaced.

Both of these mechanisms introduce potential discrepancies with either past observations or other aspects of the model. If the thermal properties are modified so that the entire patera can be resurfaced during the third event without producing implausibly high emission, the first two events must also be shorter than predicted by the *Standard* model. While the original model produces bright-phase durations of 170-200 days, consistent with the typical ~ 7 -month bright phase observed in the past (Rathbun and Spencer 2006), the modified durations are closer to 100-120 days. In the overturn model, the peak brightness scales inversely with the duration of the event; these events are not significantly brighter than past events, so such short durations contradict this correlation. In addition, the thermal

properties that provide the best fit to the 2016 brightening do not provide a good fit to the 2014 brightening, and predict an overturn front propagation velocity twice that of the other models. These discrepancies may be mitigated by assuming more complex, multi-phase overturns, but such models are not warranted by the data, which lack coverage during the early phase of the 2013 and 2014 brightenings.

An alternative solution, which supposes that only a fraction of the patera is resurfaced during the third event, resolves these discrepancies but requires a mechanism that halts the overturn when only a fraction of the patera has been resurfaced. Neither mechanism is therefore completely satisfactory, although both provide a good fit to the data. The future application of these models to brightening events prior to 2013 may discriminate between possibilities.

7.5.1.3 Constraints from past brightenings

Under the assumption that the entire patera is resurfaced each cycle, there is a clear anti-correlation between bright-phase duration and peak brightness (faster overturns result in larger areas of high-temperature lava at a given point in time). This correlation can be used for a coarse assessment of the predictions of the different models in the context of previously-observed brightening events.

Prior to 2001, typical peak 3.5- μm brightnesses were in the 80-100 $\text{GW}/\mu\text{m}/\text{sr}$ range with three events surpassing 100 $\text{GW}/\mu\text{m}/\text{sr}$ (Rathbun et al., 2002), and the average bright phase duration was 230 days. The peak 3.8- μm brightness observed in the 2013 and 2014 brightenings was around 130 $\text{GW}/\mu\text{m}/\text{sr}$, while the bright-phase durations were just under 200 days for the *Standard* model and 100-150 days for the *Modified* model. These events are thus somewhat shorter than pre-2001 events, despite having the same peak brightness (note that the intensity at 3.8 μm is $\sim 40\%$ higher than the intensity at 3.5 μm for a 300 K surface). The peak 3.8- μm brightness for the 2016 event was 150 $\text{GW}/\mu\text{m}/\text{sr}$ for an event lasting only ~ 100 days, which breaks the expected correlation unless intensities much higher than those detected were present on days when no data were obtained.

The areal production rates of 1500-1800 m^2/s for the 2013 and 2014 brightenings is somewhat higher than the rates estimated for previous brightenings ($\sim 1000 \text{ m}^2/\text{s}$; Howell et al., 2001; Rathbun and Spencer, 2006). However, the past estimates assumed that the resurfacing was active for nearly the entire duration of the bright phase, while the model used in this analysis predicts that active resurfacing ceases shortly after the peak brightness is attained, which can account for a factor of ~ 2 difference.

7.5.1.4 Total Thermal Emission

Previous authors have estimated that Loki Patera produces 10-15% of Io's total heat flow (Spencer et al., 2000; Matson et al. 2006; Veeder et al. 2011), and the Matson et al. (2006) model yielded a minimum power of 5.7 TW and a maximum of 15.6 TW, excluding cracks and active margins. Models with velocities and cycle durations typical of the 2013 and 2014

brightenings predict a total time-averaged heat flow around 8 TW ($\sim 10\%$ of Io's total heat flow), reaching over twice that at the peak of the brightening phase.

This estimate for Loki Patera's heat flow is dependent on model parameters, and in particular requires emission from an area of $21,500 \text{ km}^2$, the surface area of the low-albedo feature in spacecraft images (Veeder et al. 2011). For dates when observations are made at multiple near-infrared wavelengths, an independent estimate of the total thermal emission can be made by fitting a simple model for Loki Patera as a large area of uniform temperature, leaving both temperature and area as free parameters. The thermal emission calculated in this way is typically about half that predicted by the model. The reason for this is illustrated in Figure 7.9, where it can be seen that the bulk of the emission is coming from wavelengths longer than $5 \text{ }\mu\text{m}$; the single-temperature (1T) fit to the $2\text{--}5 \text{ }\mu\text{m}$ data misses a significant portion of emission from large cool areas that is captured by the more physically-motivated overturn model. On the date shown, data out to $12 \text{ }\mu\text{m}$ were obtained (de Pater et al. 2017), and it is clear that the overturn model captures this longer-wavelength emission well.

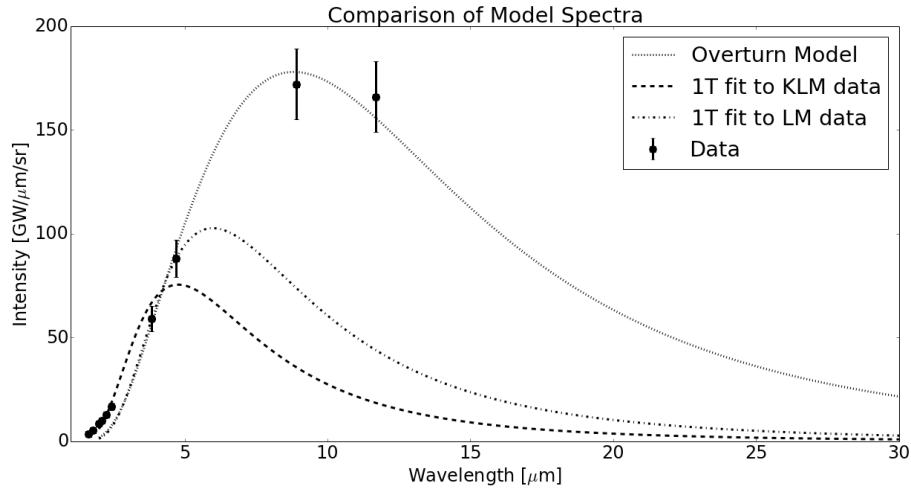


Figure 7.9: Comparison of model spectra for observations on Sep 24, 1999, ~ 24 days after the start of a brightening event, on which data from $1\text{--}12 \text{ }\mu\text{m}$ were obtained (de Pater et al., 2017). The overturn model is calculated for a resurfacing velocity of 1.0 km/day and the 24th day of overturn. The figure illustrates that the total heat flow predicted by the overturn model exceeds that of a single-temperature (1T) fit to the $2\text{--}5 \text{ }\mu\text{m}$ data by a significant amount due to the inclusion of a large low-temperature region in the overturn model whose dominant emission is at longer wavelengths than are probed by near-IR observations. The filters K, L, and M are centered at 2.3 , 3.8 , and $4.7 \text{ }\mu\text{m}$ respectively.

As can be seen from Figure 7.9, simultaneous observations in the near-infrared and at longer infrared wavelengths ($8\text{--}12 \text{ }\mu\text{m}$) provide a valuable validation of the overturn model.

7.5.1.5 Geometry and continuity of overturn

The thermal emission timelines are set by the surface area that is resurfaced each day, which is a function of both the overturn velocity and the patera geometry. Test fits using a rectangular geometry and elliptical geometries with different axis ratios indicate that the model is not particularly sensitive to the adopted geometry. The main difference in the thermal emission timelines produced by these models is the abruptness with which the brightening phase begins and ends, but the degree of difference is generally within the uncertainties of the observations.

Models with different sizes of foundering rafts and intervals between successive rafts sinking also find similar overturn velocities and fit qualities, including the continuous-overturn model, and give a sense for the degree of day-to-day variability that might be present during the overturn event.

7.5.2 Active regions and direction of resurfacing

A comparison of *Voyager 1* and *Voyager 2* images of Loki Patera indicated movement of a high-temperature front from the southwest corner of the patera toward the east, moving at approximately 1 km/day (Pearl and Sinton, 1982; Rathbun et al., 2002). High-resolution *Galileo* images of the southern half of Loki Patera using the PPR instruments in 1999 and 2000 and the SSI instrument in 2001 agreed with this direction and rate of motion (Spencer et al., 2000; Davies, 2003; Howell and Lopes, 2007).

Although the location of the emission within the patera is poorly constrained by ground-based observations, the best-fit locations of emission as a function of overturn phase suggest overall movement of emission in a clockwise direction (see Figure 7.10), consistent with observations made during the peak of the brightening event seen in 2009 (de Pater et al., 2017). However, the initial phase of brightening is typically rapid, and no observations were made during this phase of the 2013 and 2014 brightenings. In the 2016 brightening, the northern origin of the emission early in the brightening phase supports clockwise motion, as do observations from recent years. In 2010, de Pater et al. (2014b) observed Loki Patera five times within a two-month period, detecting an increase in intensity from 30 up to nearly 100 GW/ $\mu\text{m}/\text{sr}$ at 3.8 μm . During this brightening, the source of the emission was centered around 306.5°W 16°N, in the northeast corner of the patera. Both the location and magnitude of emission from the 2010 data are consistent with the model assuming propagation beginning in the north of the patera and propagating in a clockwise direction.

According to the foundering model, resurfacing begins wherever the first portion of crust founders. Although this is most likely the area where the crust is oldest and therefore least stable (Rathbun et al., 2002), localized activity in or near the patera could trigger a different portion to overturn first, reversing the direction of propagation. The observations also suggest that the source of peak emission may move back and forth across the southern portion of the patera within the overall east-to-west trend, or perhaps that the southwest and southeast corners are active outside of the regular overturn. The indications of counter-clockwise movement from spacecraft observations were based on emission only within the

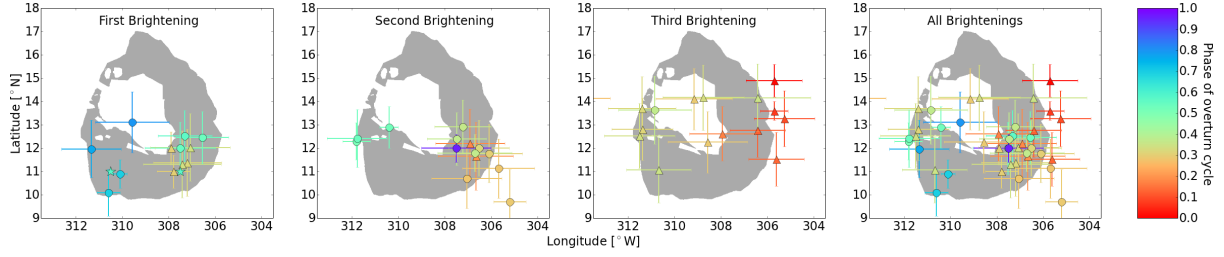


Figure 7.10: The location of the source of peak thermal emission from Loki Patera as a function of cycle phase, given in % of the total number of days in an overturn cycle (~ 450 days). The gray region is the low-albedo patera area as seen by *Voyager* (Veeder et al. 2011). When locations were determined at multiple wavelengths, the mean location is shown. Triangles indicate observations during the nominal overturn phase according to the model, while circles indicate observations taken during the cooling phase. Note that the emission is not resolved in these observations, and positions represent an average or centroid of the emission sources within the patera. Stars give the approximate locations derived by LBT observations that do resolve emission within the patera (Conrad et al., 2015).

southern half of the patera; it is possible that the apparent directionality represented local instead of global propagation, and that the resurfacing has always occurred in a broadly clockwise direction. Based on $2.2\text{-}\mu\text{m}$ ground-based speckle imaging, Macintosh et al. (2003) detected an eastward shift in emission of 100 km over the course of a month, toward the end of a brightening phase. The east-west motion and measured fluxes in the $4\text{-}8\text{ GW}/\mu\text{m}/\text{sr}$ range is very similar to what was observed in 2013-2016 for this portion of the overturn, despite the overall movement in the opposite direction.

There are also indications from other ground-based data that activity at Loki Patera is not as simple as a single overturn front propagating around the patera. Two separate high-temperature emitting regions separated by 100 km were observed during the 1991 Loki Patera brightening (Goguen et al., 1993). Rathbun and Spencer (2006) required a model with a varying propagation velocity within each overturn to match observations of early brightening events. The presence of multiple hot regions with different velocity and timing could produce a similar thermal signature.

In addition, the cumulative evidence from the 2013-2016 brightenings at Loki Patera, as well as past observations, point to sections of the patera that remain active outside of the nominal overturn. In the model fits presented here, a background-intensity parameter is required to fit the observations during the quiescent periods. In the absence of such a parameter, the model predicts much lower intensities during these times than are observed. This effect is also evident in the 1997-2000 brightenings of Loki Patera (Rathbun and Spencer, 2006). While this discrepancy can also be resolved by modifying the thermal properties of the lava to radiate more at low temperatures, such modifications deteriorate the fit during other phases of the brightening cycle.

The recent LBT detection of emission from two distinct regions within the patera during

the nominal cooling phase (Conrad et al. 2015) supports the existence of continuously-active zones in the southwest and southeast corners of the patera. The emission measured by the LBT is also slightly in excess of the model prediction for that date, consistent with short-lived localized activity. An active margin in the southwest is also evident in the *Galileo* high-resolution observations of Loki Patera (Davies 2003). In addition, the bulk of detections in 2013-2016 outside of the nominal overturn phase originate in one of these two margins (see Figure 7.10).

The repeated detection of emission from multiple locations within the southern part of the patera when models predict the crust should be passively cooling suggest that certain areas (e.g. the southeast and southwest corners) may be continually or sporadically active at all times. As the spatial resolution of observations improves, future models of Loki Patera will need to include these additional complexities.

7.5.3 Topography

The flux densities derived from observations when Loki Patera is viewed near the limb of Io are anomalously low compared to other temporally-close observations, indicating that the geometric foreshortening correction is not accurately recovering the flux density at high emission angle. Such an effect could be produced by mechanisms such as nearby topography, cracks through the crust which are blocked at high angles, or non-isotropic emission.

A topographic feature would take the form of either a mountain or raised region next to Loki Patera, or the edge of the patera itself if the magma level is significantly lower than this edge. The fact that the shape of the low-albedo patera region was unchanged between the *Voyager* and *Galileo* encounters in 1979 and 1997 also suggests a topographic confinement (McEwen et al., 1998), and the lack of lava spreading to the west of the patera in spacecraft images indicates a potential barrier in that direction (Spencer et al., 2000). While Loki Patera does not have an Earth analog of a similar size, it shares some characteristics with lava lakes, which on Earth are generally confined in a topographic region such as a caldera, although they may overflow into the surrounding area.

Figure 7.11 demonstrates the fraction by which Loki Patera’s intensity is reduced due to viewing geometry. In the figure, the fractional dimming is plotted in the form $(I_{model} - I_{data})/I_{model}$, the intensity residuals from models with *Standard* thermal properties, $\{\Delta t, \tau\} = \{1.0, 0.5\}$, and a two-phase incomplete overturn for the third brightening. Despite the large uncertainties seen in the figure, the difference in the intensity residuals between high- and low-emission-angle observations is significant. The uncertainty-weighted mean of the obscured fraction of the patera is -0.02 ± 0.02 for low- θ points, while for high- θ points it is 0.32 ± 0.02 . This figure also shows the same parameter as a function of the difference in longitude between Loki Patera and the sub-observer point during each observation, demonstrating that the effect is present when the patera is viewed from both the east and the west, although views of the patera from the west are rare (such observations require a central meridian longitude in the narrow range between $\sim 355^\circ\text{W}$ and $\sim 40^\circ\text{W}$, which occurs primarily when Io is behind Jupiter). Over a time interval much shorter than the period of precession of Io’s periapse (~ 1.5 years), the same sub-observer longitude is seen from Earth at the same orbital phase.

However, the third panel in Figure 7.11 demonstrates that the fractional dimming of Loki Patera is correlated much more strongly with viewing geometry than with orbital phase (as calculated from the time since periapse). The intensities have already been corrected for geometric foreshortening. In the case of high-emission-angle viewing geometries, there are large uncertainties in the best-fit position of the hot spot and hence the emission angle. In these cases, the intensities are corrected to the mean of the intensity using the best-fit location from the data, and the intensity given a position of $12^\circ\text{N } 310^\circ\text{W}$. All data are consistent with both intensities within the uncertainties shown.

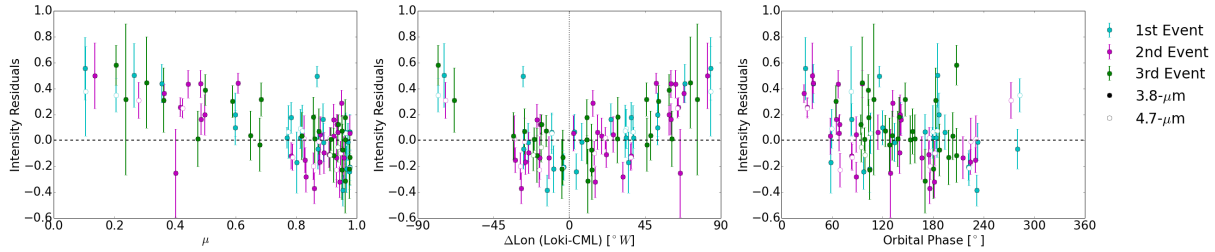


Figure 7.11: The effect of viewing geometry on the measured intensity of Loki Patera. The fractional dimming of Loki Patera is given based on the model residuals $(I_{\text{model}} - I_{\text{data}})/I_{\text{model}}$, as a function of (left) μ , the cosine of the emission angle; (center) the difference in longitude between Loki Patera and the sub-observer point; and (right) Io’s orbital phase at the time of observation. Model intensities are for a model with *Standard* thermal properties and a two-phase, incomplete third overturn. Data are shown for two wavelengths and all three brightening events. As is seen in these figures, the dimming of Loki Patera is more closely correlated with emission angle than with orbital phase, and appears symmetric between eastward and westward viewing angles. Intensities have been corrected for geometric foreshortening.

The fractional dimming of three other persistently-active hot spots from the same dataset (de Kleer and de Pater, 2016) is shown for comparison in Figure 7.12. All three hot spots were stable in intensity between 2013 and 2016, with one exception: Marduk Fluctus was unusually bright in 2016, and the 2016 intensity of Marduk Fluctus is therefore omitted from the figure. The model intensity for each hot spot is defined as the median intensity of that hot spot over the observation period. Marduk Fluctus and Uta Patera show no clear trend with emission angle, while Janus Patera appears brighter when viewed from the west and dimmer when viewed from the east. All three cases differ from Loki Patera, where the dimming effect is purely a function of emission angle and is insensitive to which side the patera is viewed from.

The fractional dimming of Loki Patera is compared to topographic models in Figure 7.13. The top panel considers a uniformly-emitting patera of elliptical geometry, and assumes that the dimming effect is due entirely to the magma level residing a height H below the edge of the patera. In order for such a model to match the data, the level of the magma must fall short of the edge of the patera by $H=10\text{-}20$ km. The model assumes an elliptical lake

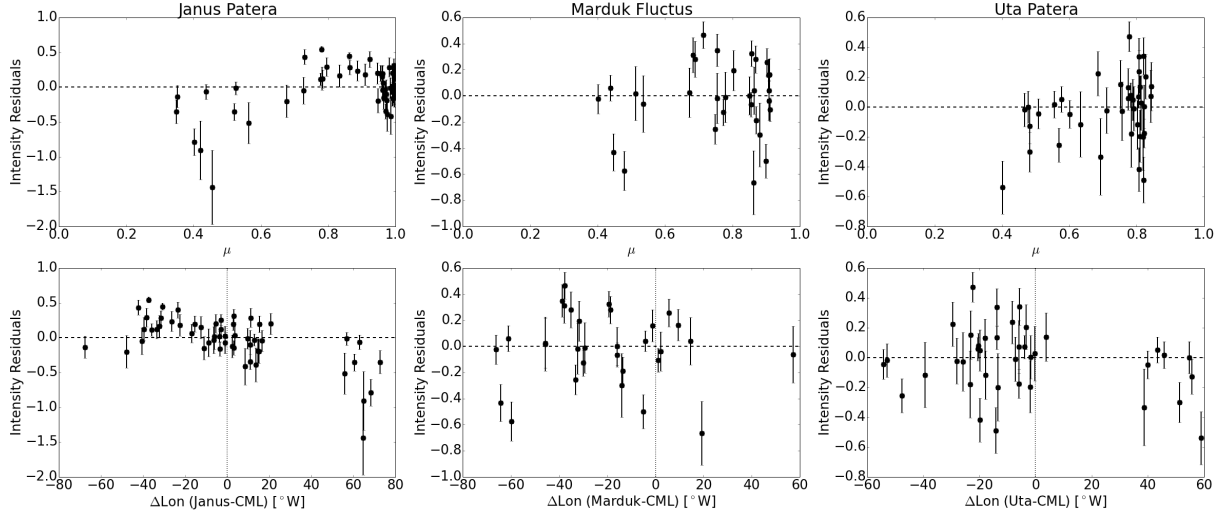


Figure 7.12: The effect of viewing geometry on the measured intensity of Janus Patera, Marduk Fluctus, and Uta Patera. The fractional dimming of all three hot spots is shown as a function of μ , the cosine of the emission angle, and of the longitude difference between the hot spot and the central meridian longitude (CML) of Io. The residuals are calculated as $(I_{model} - I_{data})/I_{model}$, where the model intensity is defined as the median intensity of each hot spot. These three hot spots were chosen because of their relatively stable intensities over the period of observation, 2013-2016 (de Kleer and de Pater, 2016). The correction for geometric foreshortening appears to recover the intrinsic intensity correctly in some cases (Marduk Fluctus, Uta Patera), with definite trends in others (Janus Patera).

geometry without accounting for the island; however, including the island in the calculation reduces the required height by at most a factor of two. In contrast, analysis of *Galileo* images found a maximum value of 100 m for the height of the patera edge above the magma level (Turtle et al. 2004). Although the depth of lava lakes on Earth do change drastically (Tilling, 1987), a change from 100 m to 10 km would require the displacement of over 200,000 km³ of magma, an incredible amount especially considering that the overall activity at Loki Patera has shown no major changes during this time.

An alternate model is shown in the bottom panel of Figure 7.13. In this case, the edge height is fixed at 100 m above the magma level, but 80% of the emission arises from a margin of variable width around the edge of the patera, with the remaining 20% of the emission uniformly emitted from the entire patera. These models can achieve a reasonable match to the data for margin widths of only 200-400 m, while fitting the shape of the data more closely. As the emission angle increases, the observed dimming increases for emission angles above $\sim 50^\circ$, but reaches a maximum patera obscuration of $\sim 50\%$. A uniformly-emitting patera would produce a different effect, whereby the dimming would increase with emission angle until the entire patera was obscured. However, if significant emission arises from a narrow active margin around the edge of the patera, this margin becomes rapidly obscured leading to an apparent step and then leveling-out of the dimming, similar to what is seen in

the data. *Galileo* NIMS observations of Loki Patera at high spatial resolution indicated the highest temperatures along the inner and outer rims of the patera (Howell & Lopes 2007), although the bulk of the 4.8- μm emission was not localized to the edges (Davies, 2003). The lack of berg features in the patera margins may also be evidence that these areas are hotter (Howell et al., 2014). Evidence for the existence of an active margin in localized areas is also discussed in Section 7.5.2.

The model fits find that the amount of background emission produced by a mechanism outside of the overturn itself constitutes only a third of the total emission in quiescent times, and a few percent of the total emission during peak activity. If significant emission is coming from the outer edge of the patera, this must therefore also include emission associated with the overturn itself.

Mechanisms other than topography could also produce a similar effect. Marchis et al. (2001) explored absorption in an overlying SO_2 plume to explain variations in Pele’s intensity with emission angle. An effect like this could also be produced if the majority of emission were coming from cracks through the cooler surface lava. To reproduce the shape of the data in Figure 7.13, such cracks would need to be ~ 3 times as wide as they are deep. A mechanism would be required to continuously generate cracks throughout the overturn cycle, since the hotter areas exposed in the cracks would cool much more rapidly than the cooler lava crust.

If the magma level within the patera is changing over time, it may not be meaningful to compare observations on different days. In addition, the analysis discussed here relies on the models to calculate the intrinsic emission on a given night to compare to the observed emission, and is therefore sensitive to model inaccuracies as well as day-to-day fluctuations in thermal emission during the overturn. Both shortcomings could be circumvented by measuring the intensity of Loki Patera at all emission angles on a single night as the site rotates from limb to disk center. The obscured area could then be calculated in comparison to the intensity at disk center and would not rely on a model, nor would the interpretation be confused by day-to-day variations in thermal emission or magma level. Past programs at Keck (de Pater et al. 2017) and the CFHT and ESO (Marchis et al. 2001) have included observations along these lines, but the interpretation was hindered by poor photometric conditions in the former case, and a lack of complete emission angle coverage within a given night in the latter case.

If the depth of the magma within the patera could be measured in this way on different dates, it could be determined whether the depth is varying in time. Such variability would indicate an active connection between the lake and magma supply, which would provide insight into the mechanisms powering Loki Patera.

Galileo also measured anomalously low intensities at Loki Patera when viewed at high emission angles. Davies et al. (2012) speculated the presence of a topographic barrier based on high-emission-angle observations on June 26, 1997 (orbit C9) compared with observations at low emission angle two days later. These datapoints are shown for comparison in Figure 7.13 along with measurements based on Keck data in 2002 and 2009 (de Pater et al., 2017). This comparison finds no changes in the degree of dimming from 1997 through 2016, indicating that if the topography and magma level are the source of this effect, these properties

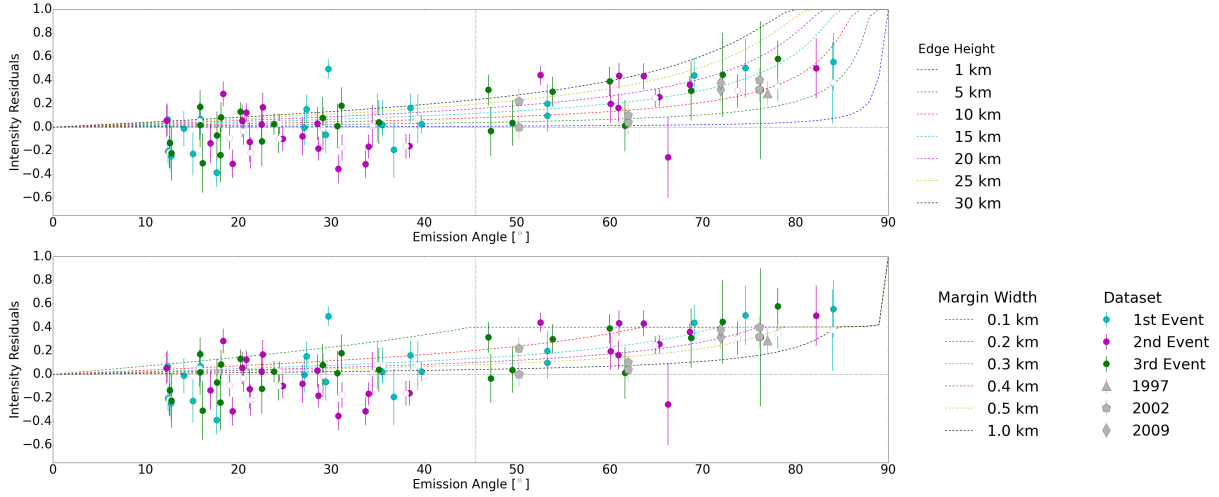


Figure 7.13: The intensity residuals of Loki Patera as a function of emission angle, calculated as $(I_{\text{model}} - I_{\text{data}})/I_{\text{model}}$ from a model with *Standard* thermal properties. (Top) Models of the fractional area of an elliptical patera obstructed by an edge of a given height; (Bottom) models of the fractional area of an elliptical patera obstructed by an edge height of 100 m and an active margin of the specified width that contributes 80% of the total intensity from the patera. Solid and open circles indicate 3.8- and 4.7- μm data respectively. Gray points are past observations: (1) triangle - 1997 *Galileo* observation (Davies et al., 2012); (2) pentagons - 2002 Keck observations (de Pater et al., 2017); (3) diamonds - 2009 Keck observations (de Pater et al., 2017). The dotted vertical line indicates the location of 45.6° ($\mu = 0.7$); only points at lower emission angles are used in the model fits shown in this paper.

are broadly stable on decadal timescales.

Not all past observations align with these findings. An analysis of observations from the 3.6-meter Canadian-France-Hawaii Telescope (CFHT) and European Southern Observatory (ESO) in 1998 and 1999 found that geometric foreshortening perfectly accounted for the change in Loki Patera’s intensity with emission angle (Marchis et al., 2001). However, this result relied on a comparison between data taken on dates separated by months, despite Loki Patera’s high intrinsic variability. If data points are only compared with other observations from the same night, the consistency of the dataset with a geometric foreshortening cosine law is less clear.

7.5.4 Resurfacing Mechanism

The analysis presented here has assumed the overturning-magma-sea mechanism for brightening events at Loki Patera. However, models such as resurfacing by lava flows are not ruled out. Here we discuss a few points related to the different potential scenarios for activity at Loki Patera; a more complete treatment of these scenarios, including their consistency with past observations, can be found in Matson et al. (2006).

The observed rate of cooling requires a mechanism whereby the magma body, whether a flow or a lake, does not cool to the point of solidification between brightenings. Complete solidification would cause a sharp drop in the intensity from the patera when latent heat ceases to be a source of heat flow (Settle 1979); such a drop is not seen in the observations. A 10-m thick lava flow with *Standard* thermal properties would take around a year to solidify completely (Davies et al. 2005), which is close to the amount of cooling time between overturns. The lack of detection of an intensity drop-off during cooling therefore cannot rule out resurfacing by lava flows of 10-m or greater thickness.

Two features of Loki Patera’s activity that are explained by the overturn resurfacing mechanism are the regularity of the brightenings, and the nearly constant resurfacing rate across the southern part of the patera inferred from the smooth temperature distribution seen in *Galileo* observations (Spencer et al. 2000; Davies 2003; Howell and Lopes 2007). However, certain features of the 2013-2016 dataset seem to contradict aspects of the model. The multiple brightening phases required by the 2015-2016 event, as well as a possible reversal in the overturn direction, are inconsistent with a triggering mechanism in which instabilities in the oldest and thickest portion of the crust initiate overturn. A reversal in direction requires an overturn that is initiated at the youngest and hence most stable part of the crust. In addition, the average intensity of the 2015-16 brightening combined with its short duration is consistent with a model where only a portion of the patera is resurfaced. If brightenings are in fact due to an overturning magma sea, such a scenario would require an overturn that halts partway through.

Finally, the presence of two distinct hot spots in the southwest and southeast corners of the patera which are active outside of the nominal overturn phase, and the evidence from this analysis that Loki Patera emits more radiation during quiescent times than predicted by a cooling basaltic surface, suggest continuously-active regions. Although spacecraft detected activity only in the SW margin and not in the SE, earlier Keck data (de Pater et al. 2017) and high-resolution LBT data (Conrad et al. 2015) did see significant emission from the SE part of the patera at relatively quiescent times. If Loki Patera is indeed a magma sea being resurfaced by an overturning crust, the data are now of sufficiently high temporal and spatial resolution that a more complex model is required to match the observations.

7.5.5 Magma composition

Prior to the *Galileo* flybys, sulfur was believed to be the dominant magma composition on Io. Observations with the NIMS and SSI instruments on this spacecraft yielded high temperature measurements, ruling out a sulfuric composition and suggesting a basaltic or possibly ultramafic composition (e.g. McEwen et al., 1998; Lopes-Gautier et al., 2000; Lopes et al., 2004). The analysis presented here assumes a lake of basaltic composition, although other possible compositions have been proposed:

(1) *Sulfuric*: There is strong evidence from *Galileo* and ground-based observations that Loki Patera is not a sulfuric lava lake. The *Galileo* SSI instrument detected Loki Patera at wavelengths short of 1 μm (McEwen et al., 1998) indicative of temperatures >1000 K; two-temperature fits to *Galileo* NIMS observations of Loki Patera found high-temperature

components above 900 K (Davies et al., 2000); and observations of forbidden SO emission indicate vent temperatures near 1500 K (de Pater et al., 2002), too hot for sulfuric magma. Using the Howell (1997) analytic cooling model, Rathbun and Spencer (2006) demonstrate that the calculated brightness assuming a sulfur lake is nearly three orders of magnitude too low to match the observations. The general characteristics of the 2013-2016 brightenings match those of previous years, leading to similar conclusions.

(2) *Ultramafic*: Magmas of ultramafic composition have different thermal properties from standard basalts. The differences that most impact the temperature and therefore thermal emission are in liquidus temperature (1475 vs. 1900 K, for basaltic and ultramafic respectively); latent heat of fusion (4×10^5 vs. 8×10^5 J/kg), and specific heat (1500 vs. 1200 J/kg/K; values from Davies et al., 2005). The observations of the 2013 and 2014 events can be matched similarly well using these thermal properties, but require lower velocities (~ 0.6 km/day) and longer overturns (> 300 days), inconsistent with Loki Patera's typical behavior. The apparently-good fits are likely due to the fact that the start time of these events are unconstrained. Matching the 2016 brightening with an ultramafic model requires resurfacing to cover only a very small fraction of the patera surface. In addition, these fits require a very short dim period which does not give the crust sufficient time to thicken to the point of instability. The ultramafic model predictions are thus less consistent with previous observations and other considerations, and the basaltic model is favored.

7.6 Conclusions

Near-infrared adaptive optics observations of Loki Patera were made at wavelengths of 2.3, 3.8, and 4.7 μm on 70 nights in 2013-2016 (de Kleer and de Pater, 2016). The period of observation covers three brightening events, which are analyzed here in the context of the Matson et al. (2006) model for Loki Patera as an overturning magma sea.

7.6.1 Magma Sea Model

The Matson et al. (2006) model for Loki Patera as an overturning basaltic magma sea provides a good fit to the observations of the 2013 and 2014 brightening events. The best-fit models find overturn propagation velocities of 1.2-1.5 km/day for these events, corresponding to resurfacing rates of 1500-1800 m^2/s . The results are not sensitive to the modeled patera geometry, and do not depend strongly on the continuity of the overturn (large rafts vs. continuous wave). The time-averaged thermal emission predicted by the model is ~ 8 TW with a peak power of 16-22 TW. This is consistent with NIMS observations, from which a minimum emission of 7.6 TW and a maximum of 17 TW were estimated (Davies et al., 2012). The 2016 brightening event appears to be more complex; a second brightening is seen during the nominal cooling phase, and fits to the data require a mechanism to reduce the modeled thermal emission during overturn. Models with modified lava thermal properties and models in which only a fraction of the patera is resurfaced fit these data equally well.

7.6.2 Interval between brightenings

The time intervals between successive brightenings depend on which thermal model is chosen, since observations during the early phases of the 2013 and 2014 brightenings are lacking. Models with *Standard* thermal properties find cycle durations of 440 ± 20 and 540 ± 20 days for the two events respectively, while models with *Modified* thermal properties find durations of 470 ± 20 days for both. For comparison, Loki Patera's periodicity prior to 2001 was best fit with a period of 540 days, although variability in this interval was also present (Rathbun et al. 2002). Both sets of thermal properties predict a crust thickness around 6 meters at the beginning of overturn, although the crust thickness is slightly higher for models with *Standard* thermal properties. Rathbun et al. (2002) estimate that solid crust overlaying magma with 10% bubbles will become gravitationally unstable at a thickness of 6 meters; the model predictions are therefore very consistent with gravitational instability as the mechanism triggering overturn. The future incorporation of the depth-dependent porosity into the thermal conduction would provide a more realistic and internally-consistent overturn model.

7.6.3 Decadal context

While brightening events at Loki Patera were observed consistently from 1987 through 2001 with a period around 540 days, bright activity may have shut off for several years beginning in 2002 (Rathbun and Spencer, 2006). Such a shut-off could be explained by small variations in the magma properties (Rathbun and Spencer, 2006). Brightenings at Loki Patera were again detected beginning in 2009 (de Pater et al., 2017), and brightening events since that time have had very similar characteristics (durations, intensities, and total power) to the pre-2002 activity. The most prominent difference is in the somewhat shorter interval between successive overturns despite similar bright-phase durations and derived propagation velocities.

7.6.4 Direction of Resurfacing

The source locations of the emission from within the patera indicate that resurfacing propagates in a clockwise direction, contrary to previous findings. This may indicate a reversal in propagation direction after 2002 or an overturn that is not well represented by a single, unidirectional wave. Past observations as well as new results presented here provide evidence for multiple overturn fronts and regions that remain continually active outside of the nominal overturn phase.

7.6.5 Topography

The intensity measured from Loki Patera is consistently low when viewed at high emission angle compared to the model as well as to measurements on the surrounding days. This indicates that the correction for geometric foreshortening is not accurately correcting for

different viewing geometries. If this effect is due to a topographic shadowing of a uniformly-emitting patera (by mountains or the edge of the depressed patera), the height of the feature would need to be greater than 10 km, which is inconsistent with *Galileo* observations. Models in which the majority of emission comes from within 500 m of the patera edge are able to match the observation with a magma level only 100 m below the patera edge, but are qualitatively at odds with aspects of the overturn model. If the effect is due to shadowing of cracks which emit the majority of the radiation, the cracks must be ~ 3 times as wide as they are deep to match the observations.

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Chapter 8

Multi-phase volcanic resurfacing at Io's Loki Patera

The jovian moon Io hosts the most powerful persistently-active volcano in the Solar System, Loki Patera (Davies 2007; Lopes and Spencer 2007, which is composed of a 21,500-km² warm patera floor (Veeder et al. 2011) surrounding a mostly-cool central “island” (Lopes-Gautier et al. 2000). The temperature gradient seen across areas of the patera indicates a systematic resurfacing process (Lopes-Gautier et al. 2000, Rathbun et al. 2002, Spencer et al. 2000, Rathbun et al. 2004, Howell and Lopes 2007, Davies 2003), which has been seen to occur typically every one to three years since the 1980's (Rathbun et al. 2002, Veeder et al. 1994). Analysis of past data has indicated that the resurfacing progressed around the patera in a counter-clockwise direction at a rate of 1-2 km/day, and that it is caused either by episodic eruptions that emplace voluminous lava flows or by a cyclically-overturning lava lake contained within the patera (Rathbun et al. 2002, Howell and Lopes 2007, Davies 2003, Howell 1997). However, spacecraft and telescope observations have been unable to map the emission from the entire patera floor at sufficient spatial resolution to establish the physical processes at play. Here we present temperature and lava cooling age maps of the entire patera floor at a spatial sampling of ~ 2 km, derived from ground-based interferometric 4.8- μm imaging of thermal emission from Loki Patera obtained on UT 8 March 2015 as the limb of Europa occulted Io. Our results indicate that Loki Patera is resurfaced by two waves that propagate and converge around the central island. The different velocities and start times of the waves indicate a non-uniformity in the lava gas content and/or crust bulk density across the patera. Future applications of this technique can yield information on the time-evolution of Loki Patera as well as provide insight into how Io's other volcanoes operate. We observed Io with the Large Binocular Telescope (LBT) during a mutual occultation event in which Europa passed in front of Io (Figure 8.1). During the event, images were obtained with the LMIRcam camera at a wavelength of 4.8 μm , using the LBT Interferometer (LBTI) and adaptive optics (Esposito et al. 2011, Hinz et al. 2012, Leisenring et al. 2012). The sampling cadence of 120 ms corresponds to a 2-km advance of Europa's limb across Loki Patera between successive exposures. Although satellite occultations have been used for decades to study Io (Spencer

et al. 1994), advanced adaptive optics technology and dual-telescope interferometric imaging provide unprecedented sensitivity for individual, identifiable hot spots on Io, permitting high cadence sampling and thus high spatial resolution mapping. From the images, we extract a high-time-resolution occultation light curve (Figure 8.2) which we use to derive temperature and lava age maps of Loki Patera (Figure 8.3; see Methods). Although the calibrated 1σ uncertainty in the total flux density corresponds to only 1 K in temperature, many factors influence the conversion of flux density to temperature, including assumptions about the pixel filling factor and lava emissivity. Noise in the light curve, which is correlated on sub-second timescales, also introduces some uncertainty into the reconstructions. As discussed in Methods, the maps shown in Figure 8.3 are optimized to match the observations without over-fitting these artifacts. In addition, the temperature distribution at small ($\sim$ few km) spatial scales cannot be uniquely recovered, and structure in the maps at these scales can be viewed as a representative model that provides a good fit to the data and is consistent with the robust large-scale gradient.

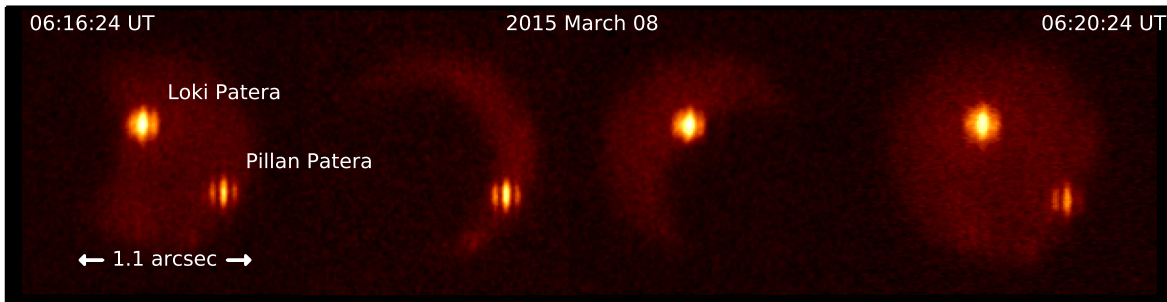


Figure 8.1: Observations of Europa occulting Io. Four of the ~ 3000 $4.8\text{-}\mu\text{m}$ images obtained on UT 8 March 2015 with LBTI as Europa occulted Io. Water ice on Europa’s surface absorbs incident sunlight, while Io’s surface is more reflective at this wavelength. The thermal emission from Loki Patera and Pillan Patera stand out prominently against Io’s disk. The fringe pattern of their emission is a product of interferometric imaging, which combines light from the two LBT telescopes.

Existing models for cooling silicate lavas (Davies 2007) relate the temperature map to a solidified lava age map (Figure 8.3). The age map reveals the presence of two resurfacing waves: one starting in the northwest corner (Location 1 in Figure 8.3) ~ 250 days prior to the date of our observations and moving at a rate of 1 km/day in the clockwise direction, and a second wave starting in the west (Location 2) ~ 180 days prior to our observations and proceeding at 2 km/day in the counter-clockwise direction (see Figure 8.4). These rates reflect the average temperature gradient across each region of the patera; the resurfacing rate may also vary locally. The waves converged in the southeast of the patera (Location 3) and began to solidify ~ 75 days prior to our observations. The specific distribution of lava ages across the patera encodes information about the resurfacing process.

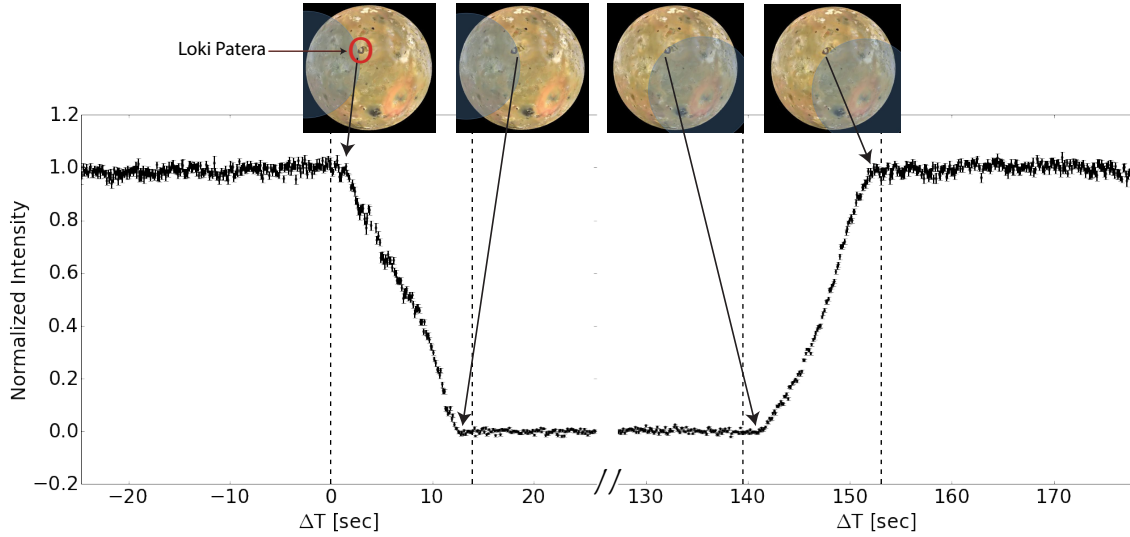


Figure 8.2: Occultation light curve. The occultation light curve with $1\text{-}\sigma$ uncertainties, normalized to the out-of-occultation intensity of Loki Patera (see Methods). The four panels at the top of the figure indicate the position of Europa (shown as a circular shadow) relative to Loki Patera at different times during the occultation. The vertical dashed lines separate the occultation datapoints that are used in the modeling from the baseline data. The pre-ingress and post-egress points are used to determine the baseline noise distribution. The time $T=0$ seconds represents the start of the occultation data used in the modeling.

The temperature and age maps show that the resurfacing mechanism within the patera is considerably more complex than previously modeled. The presence of a large-scale temperature gradient indicates a coherent process acting across the entire 200-km-wide feature. High-resolution *Galileo* observations imaged a smooth temperature gradient across part of the patera (Lopes-Gautier et al. 2000, Spencer et al. 2000, Rathbun et al. 2004, Davies 2003). Although the occultation technique cannot recover temperature structure at the small spatial scales probed by *Galileo*, the LBT data reveal that this is not a local effect; the presence of a temperature gradient that is coherent across large areas of the patera is a fundamental feature of the resurfacing process of the entire Loki Patera.

Time-series data from Keck and Gemini N indicate that Loki Patera’s episodic activity had been ongoing since at least 2013 (de Kleer and de Pater 2017). The LBT observations were obtained 6-8 months after the start of the preceding brightening event (Jul/Aug 2014), and 2-3 months after its conclusion (Dec 2014; de Kleer and de Pater 2017). The lava age map demonstrates that the majority of the patera floor is younger than 200 days, which matches the date this brightening began and confirms that the entire patera was resurfaced during the most recent event. In addition, the age of the youngest lava surface (~ 75 days old) is consistent with the end date of the most recent brightening episode, demonstrating that no localized activity has taken place since the end of the last event.

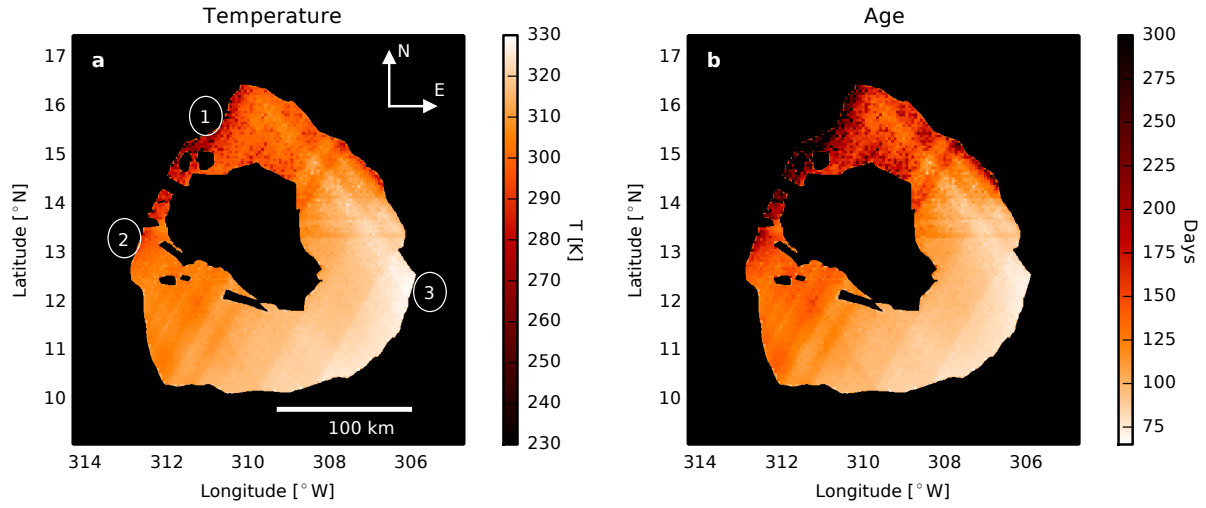


Figure 8.3: Temperature and age maps of Loki Patera. The outline of the patera and the cool central island are fixed based on spacecraft imaging data (Veeder et al. 2012), and the intensity distribution is determined by fitting a model to the occultation light curve. Locations 1 and 2 on panel (a) indicate the approximate regions where the two resurfacing waves originated; both waves progressed eastward around the island and converged at Location 3. The maps assume an emissivity of 1 and a basaltic lava composition. The striping effect is an artifact produced by correlated noise in the light curve (see Methods for details).

The two resurfacing waves began in the west margin at different dates ($\Delta T=50-100$ days) and moved around the central island until they converged in the southeast corner (Figures 8.3 & 8.4). Although the data do not allow a definitive identification of the resurfacing mechanism, the presence of a “double-wave” has implications for both the foundering lava lake crust and the lava flow models.

If Loki Patera is being resurfaced by lava flows, the episodic magma supply must consist of two steady pulses of magma reaching the surface at nearby yet distinct times and locations. The difference in areal resurfacing rate between the northern and southern parts of the patera also requires differences in magma properties or discharge rates between these locations. Although different flow rates could also be caused by local topography, the flatness of the patera floor as seen by *Galileo* (Turtle et al. 2004) disfavors this explanation. The resurfacing rate for the southern part of the patera is twice the rate observed in 2001 *Galileo* NIMS data in the same part of the patera (~ 1 km/day; Howell and Lopes 2007, Davies 2003), suggesting that the differences are due to variable lava properties rather than fixed localized effects.

In the lava lake foundering crust scenario (Rathbun et al. 2002, Davies 2003, Matson et al. 2006), the resurfacing rate is diagnostic of the bulk density structure of the crust. The presence of two resurfacing waves moving at different rates implies independent sources of magma along the western edge of the lake, with a higher bulk density in the southern magma source to explain the faster resurfacing. This density difference indicates either a difference

in magma composition or, more likely, a difference in the amount of gas in the magma, which forms voids in the crust as it solidifies and decreases the crust bulk density (Rathbun et al. 2002, Matson et al. 2006). A higher crust bulk density causes the crust to sink sooner after solidification, while a lower lava porosity slows the cooling of the crust, decreasing the rate of progression of the foundering wave.

The presence of the cool “island” in the middle of Loki Patera (Figure 8.3) is required to fit the data (see Methods). We confirm that the cool island is still present, and is therefore a long-term fixture of the patera, persisting for at least the 36 years since it was first seen during the *Voyager* encounter in 1979. The island has withstood the physical and thermal stresses imposed by the eruption of thousands of km^3 of lava adjacent to it, indicating that it is an anchored feature rising up through the surrounding lava, rather than a large raft on a sea of magma.

Temperature maps of portions of the patera have been previously derived from high-resolution *Galileo* NIMS observations obtained in 1999 and 2001 (Spencer and Lopes 2007, Lopes-Gautier 2000, Howell and Lopes 2007, Davies 2003). Although the intrinsic variability of Loki Patera limits the value of direct comparison between observations obtained years apart, the propagation rate of the resurfacing wave derived from our age maps is consistent with the 1-2 km/day rates derived from both these NIMS data and *Galileo* PPR observations (Rathbun et al. 2002, Spencer et al. 2000, Rathbun et al. 2004), as well as earlier *Voyager* data (Rathbun et al. 2002). In addition, the counter-clockwise progression of the wave in the southern part of the patera matches the direction derived from the *Voyager* and *Galileo* observations (Rathbun et al. 2002, Howell and Lopes 2007, Davies 2003). These results were seemingly contradicted by time-series adaptive optics data from the Keck and Gemini N telescopes (de Kleer and de Pater 2007), which suggest a clockwise resurfacing direction along the east side of the patera. The discovery of two resurfacing waves, one of which moves clockwise in the north, and the other counter-clockwise in the south, can reconcile these apparently contradictory results. Although the details of the resurfacing may vary between each brightening cycle, all past observations of Loki Patera are consistent with the overturn progression described herein, in combination with sporadic activity at the southwest margin.

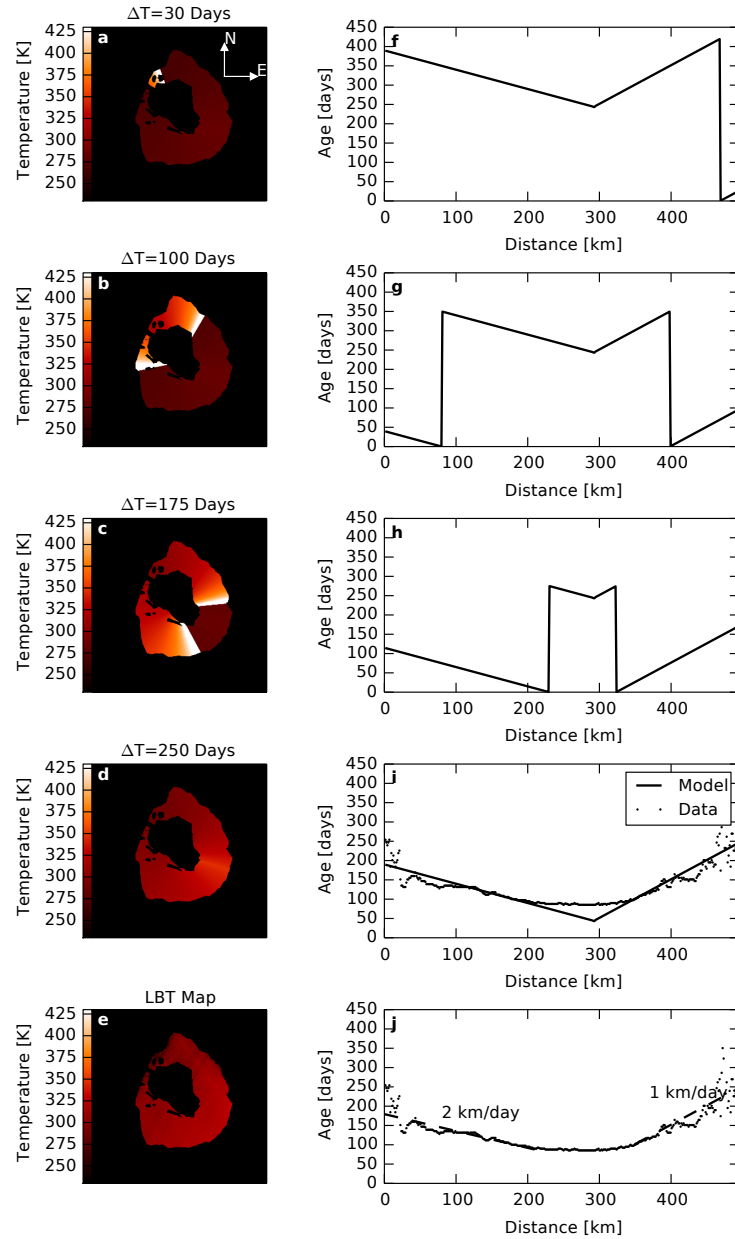


Figure 8.4: Overturn schematic. Model temperature maps (a-d) and patera surface age plots (f-i) for different stages of the dual-wave progression, assuming a smooth, continuous resurfacing. ΔT is the time since the resurfacing initiated, and the base temperature map at $\Delta T=0$ is the model temperature 450 days after the previous resurfacing. Ages are plotted as a function of distance counter-clockwise around the patera from the narrow, northwest corner. The last row (e & j) shows the corresponding properties retrieved from the data, which indicate resurfacing rates of 1 and 2 km/day for the northern and southern parts of the patera respectively.

8.1 Methods

8.1.1 Observations

We observed the occultation of Io by Europa on UT March 8, 2015 using Fizeau interferometric imaging with the Large Binocular Telescope Interferometer (LBTI; Hill et al. 2006, Hinz et al. 2012) and the LMIRcam near-infrared instrument (Leisenring et al. 2012, Leisenring et al. 2014), which has a platescale of $0.0107''/\text{pixel}$ (Maire et al. 2015; see Figure 8.1). Both telescopes were adaptive-optics corrected using Io as a natural guide star at R-Band for wavefront correction. During the occultation event, Europa entered the wavefront sensors' fields of view and contributed to the AO correction. Observations were acquired at M-Band ($4.6\text{--}5.0\ \mu\text{m}$), which is ideally suited to image the thermal emission from volcanic structures on the surface of Io. Europa's occultation of Loki Patera began at 6:16:23 UT and completed about 150 seconds later. Integration times were set to 15.4 msec per exposure, with an average of 120 msec between each exposure start. Data were acquired in sub-frame mode (512×512 pixels) to decrease camera overheads and maximize the imaging cadence. The details of the observations are given in Table 8.1.

Table 8.1: Observations. Data taking during the 150-second occultation event on UT 8 March 2015. The five rows correspond to the timing regimes shown in Figure 8.2*.

Phase	UT Range	ΔT [sec]	Frames	Notes
<i>Before</i>	06:15:23 - 06:16:22	59	480	Used for baseline noise distribution.
<i>Ingress</i>	06:16:22 - 06:16:36	14	110	Used in the fit.
<i>Occulted</i>	06:16:36 - 06:18:41	125	1020	Not used.
<i>Egress</i>	06:18:41 - 06:18:55	14	110	Used in the fit.
<i>After</i>	06:18:55 - 06:19:33	38	281	Used for baseline noise distribution.

*All frames were taken at M-band ($\lambda = 4.8\mu\text{m}$) with a per-frame integration time of 15.4 msec.

Fizeau observations with LBTI coherently combine the light from the LBT's two AO-corrected 8.4-meter mirrors to produce a characteristic interference pattern along the direction of the two-telescope baseline (Esposito et al. 2011, Hinz et al. 2012). These types of observations result in an increased spatial resolution across the diffraction fringes while also concentrating more of the light into the central core of the point spread function (PSF).

For this sequence of observations, and all Io observations with LBTI, the fringe sensor cannot operate because Io is completely resolved and Loki Patera is too faint in the near-infrared to serve as a point source for automated phase stabilization. The interference pattern therefore drifts around a central (white-light) fringe due to small changes in the path-length difference between the two telescopes caused by instrumental vibrations and atmospheric disturbance. Throughout the observations, phase stabilization was performed manually through tracking of the M-band fringes (Conrad et al. 2015).

Although the LBT’s Fizeau mode of operation delivers the ultimate diffraction-limited performance of the 22.8-meter effective diameter of the LBT, that resolution (30 milliarc-second diffraction limit at $4.8\ \mu\text{m}$) only corresponds to a 100-km spatial resolution at Io (Conrad et al. 2015), much lower than the 2 km frame to frame limb motion of Europa in the time-resolved occultation profiles. The primary advantage of the use of adaptive optics and Fizeau interferometry for the observation reported here is in resolving the individual volcanic sources on Io’s $\sim 1.0''$ diameter disk and maximizing the signal-to-noise ratio for each source by minimizing the angular size of the PSF and thus the local thermal background contributing to the noise.

Europa’s gradual occultation of Io’s surface systematically blocks flux from volcanic hot spots at each time step, providing spatial information along the direction of motion of Europa’s edge. With a limb motion of ~ 5.5 milliarcseconds/sec (20 km/sec) relative to Io’s disk, the 120 msec observing cadence corresponds to a spatial sampling resolution of 2.4 km. Due to the noise on individual datapoints, the effective spatial resolution is a factor of a few worse than this.

Mutual occultation events between the galilean satellites occur for periods of several months every six years. During each such period, there can be over a hundred occultations of Io by one of the other satellites. While not all are optimal for the LBTI techniques discussed here, nor observable from a given terrestrial hemisphere, the quantity of such events provides many opportunities for performing similar observations in the future. The experimental approach is also applicable to observations made with high-Strehl adaptive optic systems on any large (8-10-meter) near-infrared telescope, provided the AO system and camera are suitable.

8.1.2 Data reduction

Standard LMIRcam image reduction was performed, which consists of linearity correction, sky background subtraction, reference pixel correction, bad pixel removal, and distortion correction. Flat-fielding was not performed because the pixel response is intrinsically flat across LMIRcam’s entire detector and the region of interest is small ($1'' \times 1''$) compared to the instrument’s full field of view ($20'' \times 20''$). The final reduced images show excellent uniformity ($<1\%$ deviation) across the observed field. A series of background observations were acquired before and after the occultation with Io nodded to a separate detector position. For each Io science frame, the 500 background frames closest in time were median-combined and subtracted from the science frame. The removal of sky background also removes the detector bias and any dark current contributions.

8.1.3 Background removal

Individual images from the occultation event show Io as a bright disk covered with volcanic hot spots being occulted by a dark Europa (see Figure 8.1). Reflected sunlight makes the disk of Io visible, while strong water ice absorption causes Europa to reflect much less sunlight than Io. Precise aperture photometry of Io’s volcanoes requires a uniform back-

ground and thus modeling and removal of the “crescent” of the bright disk of Io. Gaussian convolution of a multi-parameter model with the telescope point spread function produces synthetic, volcano-free images for frame-by-frame subtraction from the data. The model parameters include the disk flux, the radii of Io and Europa, the angular offset between the centers of the bodies, and limb darkening. The final synthetic image is produced by optimizing these model parameters via a gradient descent algorithm. Prior to aperture photometry, the model is directly subtracted from the background-corrected data on a frame by frame basis, yielding a sequence of images of the hot spots alone. An example image is shown in Figure 8.5 before and after this correction is applied.

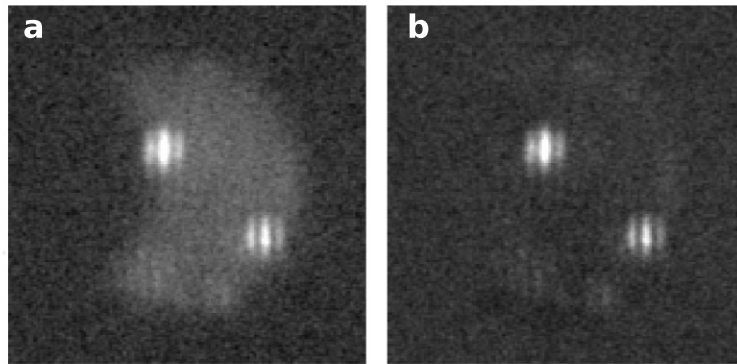


Figure 8.5: Io disk subtraction. Image of Io from the LBTI during the occultation, both (a) before and (b) after the subtraction of the reflected light from Io’s disk. The residual intensity around the limb in the subtracted image is the result of imperfect limb darkening correction.

8.1.4 Frame registration and alignment

The background-subtracted images are rotated to position Io’s polar axis in the horizontal direction. The relative positions of both Loki Patera and Pillan Patera are then tracked frame-to-frame using a combination of gaussian centering and cross-correlation with respect to a median-combined reference PSF. Monitoring of Pillan Patera’s position provides an extra check on the location of Loki Patera, particularly during Europa’s ingress. This method enables sub-pixel frame registration.

8.1.5 Light curve extraction

Aperture photometry provides the flux measurements contributing to the observed light curve (Figure 8.2). A circular aperture with a 13-pixel (~ 140 mas) radius optimized the

signal-to-noise ratio, and was used for the photometry. This corresponds to the approximate full width at half maximum of a single-aperture ($D = 8.4$ m) point spread function ($1.2\lambda/D$). Due to the lack of closed-loop phase stabilization, the fringed PSF oscillates around a central fringe, but generally stays contained within a region corresponding to the central core of a single-aperture Airy pattern (Leisenring et al. 2012). An aperture size similar to that of the central core (especially after frame registration) therefore collects the vast majority of the source flux even if the phasing is imperfectly aligned. The 13-pixel aperture radius corresponds to a full aperture width of ~ 1000 km on Io’s surface, or five times the physical width of Loki Patera. The images shown in Figure 8.1 demonstrate that Loki Patera is the only bright hot spot located within the extraction aperture. If small nearby hot spots were present within the aperture but indistinguishable from Loki Patera in the images, the occultation of these hot spots would be present in the light curve of Loki Patera at a time offset from that of the main ingress and egress. Since no additional dip in intensity is seen in the light curve (see Figure 8.2), the presence of other hot spots within the extraction aperture with flux density above the noise ($\sim 2\%$ of Loki Patera’s intensity) can be ruled out.

The flux density of the spatially-distinct Pillan Patera hot spot (see Figure 1) is simultaneously extracted to monitor any fluctuations during Europa’s transit. Because changes in atmospheric transmission or AO performance would affect the flux from both volcanoes similarly, Pillan Patera could function as a baseline to correct those fluctuations in Loki Patera’s light curve that would otherwise be indistinguishable from occultation effects. The baseline measurements of both Pillan Patera and Loki Patera show low-order variations of $\sim 2\%$ over 10’s of seconds, indicating good stability. We opted to exclude these corrections because of the negligible impact on the final light curve relative to the measurement uncertainties. Flux uncertainties are derived for each frame by measuring the pixel-to-pixel variations in the sky annulus. The uncertainty measurements closely match the standard deviation of baseline sections of the Loki Patera and Pillan Patera light curves.

8.1.6 Flux Calibration

The absolute unocculted intensity of Loki Patera is derived by calibrating to the standard star HD 81192, which was observed 1.5 hours after the occultation of Loki Patera. The reference star observations were performed in similar conditions as the Io observations (1.1 airmasses, 1” seeing, and 6 mm of precipitable water vapor). We assume that atmospheric transparency and AO performance stayed constant based on the consistent, stable weather conditions and the fact that observations of both Io and HD 81192 showed very little variations in the measured counts. For a given extraction aperture, the total counts for Loki Patera were measured relative to that of HD 81192. We used a variety of aperture sizes in order to determine if the extended nature of Loki Patera produced any significant flux loss. Count ratios were consistent for apertures radii greater than 10 pixels, and gave an intensity ratio of 3.660 ± 0.035 between HD 81192 and Loki Patera. Utilizing the Python code Pysynphot (Lim et al. 2015), a Phoenix model template for a G7III type star was normalized to the 2MASS and WISE measurements of HD 81192. The throughput curve of

LMIRcam’s M-Band filter transmission was then convolved with the normalized template to determine the apparent magnitude of HD 81192 as seen at M-Band. We calculate the total flux density of Loki Patera to be 0.950 ± 0.025 Jy. The uncertainties include propagated errors from the flux ratios, normalization uncertainties based on the 2MASS and WISE error bars, and possible mismatches to the spectral template.

8.1.7 Light curve modeling

The change in the integrated brightness of Loki Patera at each timestep during ingress and egress represents the amount of emission coming from the strip of the patera that is covered or un-covered during that time interval. The occultation light curve can therefore be used to re-construct the distribution of emission from the patera floor. The difference in orientation between the directions of motion of Europa’s limb across Loki Patera during ingress and egress permits a reconstruction of the full two-dimensional thermal emission map. We reconstruct this map by creating model emission maps, generating the model light curves, and fitting these light curves to the observations. The direct product of the modeling process is a map of the $4.8\text{-}\mu\text{m}$ intensity within the patera; this is converted to a temperature and lava age map as described later in the text. Retrievals using models that span a wide range of parameters, resolutions, and fitting algorithms all recover the same qualitative features in the intensity map.

8.1.8 Model intensity map

The base map for the intensity modeling is a patera outline derived from *Voyager* spacecraft imaging (Veeder et al. 2012; see Figure 8.3). The exact duration of ingress and egress yield the width of the warm patera area in the direction of motion to within a few kilometers. The widths derived for both ingress and egress match the *Voyager* shape to within uncertainties, indicating that the general size and shape of Loki Patera has not changed significantly in the past 36 years, and demonstrating that the use of this outline in the modeling does not introduce significant bias.

Within the fixed patera outline, the patera area is divided into pixels, and the value of each pixel is fit independently in the retrievals. Pixel sizes from 2 km up to 40 km are tested, and two shapes are used. Diamond pixel shapes follow the ingress and egress directions: the edges of the diamonds are parallel to Europa’s limb as it crosses that portion of the patera, minimizing the number of light curve points that constrain the value of each pixel. The diamond shape is useful for comparing between the light curve and the intensity distribution, and in particular for identifying artifacts that are caused by small numbers of anomalous points in the light curve. However, the final maps presented here make use of square pixels, where the value of each pixel is constrained by a larger number of timesteps. The pixel size determines the number of independently-fit intensity units within the patera. However, the model treats partial pixel coverage by Europa’s limb with an accuracy down to sub-km scales. The maps shown in Figure 8.3 use square pixels sized $2\text{ km} \times 2\text{ km}$.

8.1.9 Model light curve

Ephemeris information from the JPL Horizons database is used to determine the position of Europa’s limb relative to Loki Patera. The time resolution of the available ephemerides is lower than the observing cadence, and the ephemeris values are therefore linearly interpolated to each observation time based on the bracketing timesteps. At each timestep, the relative positions of Io and Europa are read from the ephemeris; the location of each point within Loki Patera is calculated relative to Io’s center; and the resultant distance from Europa’s center to each point within Loki Patera is compared to Europa’s radius to determine if that point is obscured. The total intensity in the unobscured portion of the patera corresponds to the simulated light curve value at that timestep. By using ephemeris information for each timestep, the movement of both Io and Europa are accounted for, as is Io’s rotation over the course of the event. Figure 8.6 demonstrates model light curves for simple models with uniform intensity distributions within the patera.

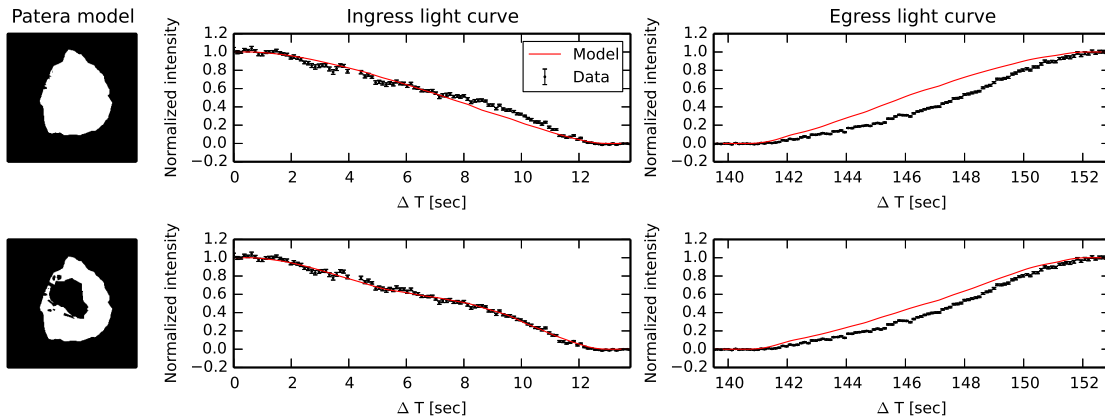


Figure 8.6: Uniform-intensity models. Model light curves for models with a uniform intensity distribution within the patera, with and without a central island, plotted with the data and 1- σ uncertainties. The patera outline is derived from *Voyager* imaging data[veeder2012]. The model light curves in each row correspond to the image in the left panel of that row. The patera shape and the central island produce the broad-scale features of the ingress light curve, even without postulating a non-uniform intensity distribution. However, the addition of a non-uniform intensity distribution is required to match the egress light curve, indicating that the main temperature gradient is in the direction of motion of Europa’s limb during egress (roughly northwest to southeast).

8.1.10 Fitting methods

The model light curves are fit to the observations by allowing all pixels in the model intensity map to vary as free parameters in the fit. Multiple fitting algorithms were tested, including Markov Chain Monte Carlo (MCMC) simulation (Forman-Mackey et al. 2013),

bounded limited-memory Broyden-Fletcher-Goldfarb-Shanno (BFGS) optimization (Byrd et al. 1995), and the Truncated Newtonian algorithm (TNC) (Dembo and Steihaug, 1983). All fitting methods produce similar qualitative results. The TNC algorithm is chosen for the fits presented here because it is significantly faster than MCMC and produces less artifacts in the intensity maps than the limited-memory BFGS optimization.

8.1.11 Model selection

The presence of correlated noise in the light curve (Figure 8.2) requires a careful analysis of goodness-of-fit metrics to avoid over-fitting the data and introducing artifacts into the modeled intensity maps. The fitting algorithms rely on minimizing χ^2 to within a specified fit tolerance. However, χ^2 is not a meaningful metric for determining fit quality or comparing between models because the model complexity is not accurately represented by the number of free parameters, nor is the model complexity easy to quantify (Andrae 2010a, Andrae et al. 2010b). It is therefore not possible to determine whether a model is under-fitting or over-fitting the data by looking at χ^2 alone.

An alternative method for determining whether the model provides a good fit is the Kolmogorov-Smirnov test (KS-test) p -value (Kolmogorov 1933, Smirnov 1948). The KS-test uses the distribution of the residuals from a given model to determine whether the residuals could have been drawn from a normal distribution, as would be the case for random noise. If the p -value is below 0.01, the hypothesis that the residuals are drawn from a normal distribution is rejected with 99% significance; a p -value greater than 0.01 indicates consistency with a normal distribution.

The standard KS-test is based on the assumption that noise in the dataset is random. However, the occultation light curve contains non-random noise, and the standard KS-test is therefore not a good assessment of model fit. Instead, the two-sample KS-test is employed, which compares the residuals to a more realistic noise distribution based on the dataset itself. Given a reference noise distribution, the two-sample KS-test evaluates whether the residuals from the light curve model fit are consistent with the reference noise level. Two reference noise distributions are considered in this analysis: the baseline noise of Loki Patera in the ~ 10 seconds prior to ingress and the ~ 10 seconds immediately post-egress, and the residuals on the simultaneous intensity of Pillan Patera. Because Pillan Patera was occulted during the Loki Patera egress, the latter method can only be applied to the Loki Patera ingress.

For a given pixel shape and size, the preferred model is chosen to correspond to the loosest fit whose residual distribution is consistent with the best noise distribution available. In the case of ingress, this is the simultaneous noise distribution of Pillan Patera, while on egress this is the post-egress baseline level of Loki Patera. Figure 8.7 shows example fits using square 8-km pixels (lower than the resolution of the final maps) for a range of fit tolerances. The corresponding model light curves are shown in Figure 8.8 and the p -values are given in Table 8.2. The preferred model is the loosest fit for which the residuals are consistent with the expected noise at 99% significance (Fit C in Figure 8.7). This requirement ensures that the light curve is neither under-fit nor over-fit.

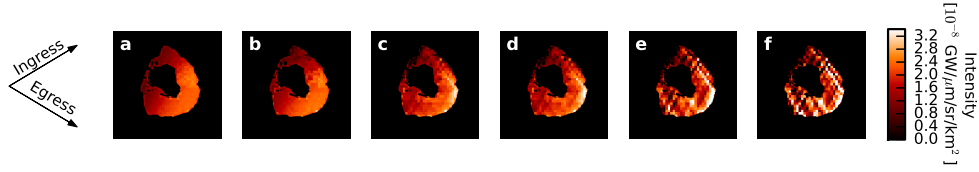


Figure 8.7: Intensity maps corresponding to progressively-closer fits. Intensity reconstructions with independently-fit pixels sized $8 \text{ km} \times 8 \text{ km}$ based on fits to the light curve. The series demonstrates the artifacts from systematic noise in the light curve that become increasingly prominent as the fits tighten. Panels a-f correspond to Fits A-F discussed in the text. The fit metrics are summarized in Table 8.2; Fit C is the preferred model at this resolution. The arrows at the left show the approximate direction of movement of Europa’s limb during ingress and egress, demonstrating that the orientation of the limb corresponds to the striping artifacts in Fits E and F.

Table 8.2: Goodness-of-fit metrics for different models.*

Fit	χ^2	p_{Ing}	p_{Eg}	$p_{2A,Ing}$	$p_{2B,Ing}$	$p_{2B,Eg}$
A	1178	0.0	5.11×10^{-15}	2.92×10^{-13}	7.26×10^{-18}	4.12×10^{-9}
B	741	7.56×10^{-5}	1.19×10^{-9}	0.021	1.77×10^{-3}	4.98×10^{-6}
C	534	4.31×10^{-4}	1.11×10^{-3}	0.067	0.013	0.03
D	501	9.51×10^{-3}	8.73×10^{-3}	0.24	0.047	0.11
E	399	0.043	0.034	0.4	0.18	0.38
F	360	0.043	0.091	0.24	0.34	0.5

* p_{Ing} and p_{Eg} are the KS-test p -values based on comparison to the normal distribution. The p_2 values are the p -values for the two-sample KS-test. $p_{2A,Ing}$ are the p -values from a test of whether the ingress residuals are drawn from the same distribution as the Pillan Patera residuals during ingress. $p_{2B,Ing}$ and $p_{2B,Eg}$ correspond to tests of the ingress residuals compared to the baseline immediately pre-ingress, and the egress residuals compared to the baseline immediately post-egress. The hypothesis that the residuals to fits A-D are drawn from a Gaussian distribution is rejected. Fit C is the loosest fit whose residuals are consistent (i.e. not excluded at the 99% level) with being drawn from the same distribution as both the nearby baseline noise and the simultaneous Pillan Patera noise, and is therefore the preferred model. All fits are to 220 data points with 250 free parameters; however, the degrees of freedom are not equal to the number of parameters, and the reduced χ^2 is therefore omitted to avoid confusion.

In addition, the optimal fit can be identified qualitatively as the closest fit that stays consistent with the broad-strokes distribution represented by the loosest fit (Fit A in Figure 8.7). As the fit constraints tighten, the big-picture distribution stays consistent but becomes more resolved. However, around Fits D-E the distribution deviates and prominent striping artifacts appear. Fits C and D demonstrate this turnaround point, where the light curve is being fit closely but artifacts are only just beginning to appear. Using this criterion, the retrieved intensity distribution on the patera floor is not highly sensitive to number of independent pixels that are fit for, nor to the shape of the pixels (see Figure 8.9).

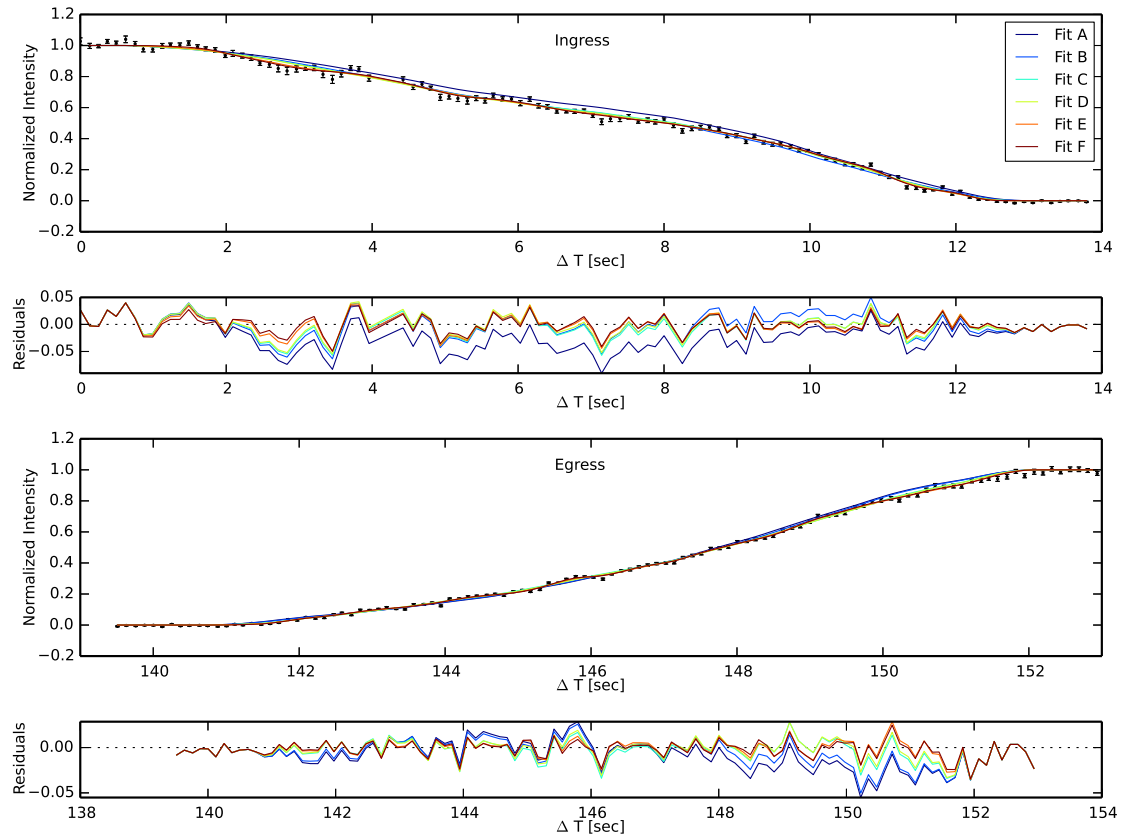


Figure 8.8: Model light curves and residuals. Model light curves corresponding to the intensity maps for Fits A-F shown in Figure 8.7, plotted with the observed light curve and $1\text{-}\sigma$ uncertainties.

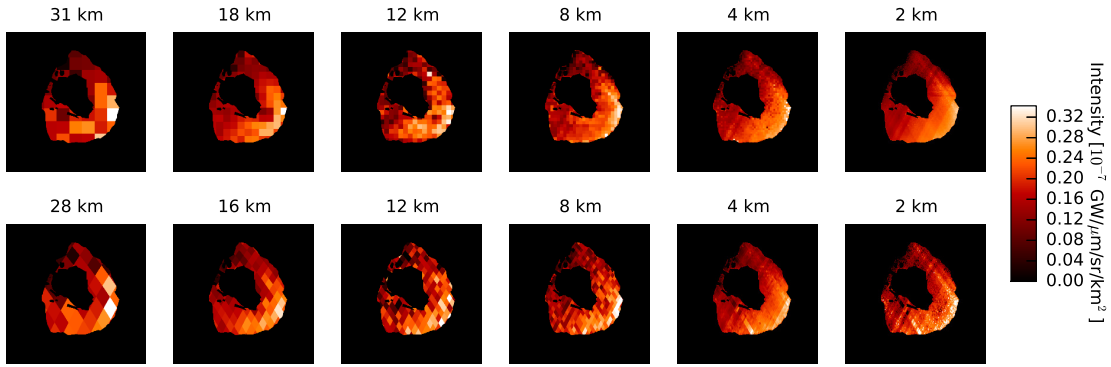


Figure 8.9: Preferred models for a range of pixel sizes and two pixel shapes. The image titles indicate the size of each pixel in km. The edges of the diamond pixels are parallel to the limb of Europa as it passes that portion of the patera. Note the artifacts in the small-pixel models with diamond pixel shapes; in these models, as few as two timesteps influence the value of each pixel, and the model is thus very sensitive to noise in the light curve. These images demonstrate that the retrieved intensity distribution is consistent across different model parameters and resolutions.

8.1.12 Retrieval accuracy

Our model selection is based on the assumption that the striping structure in Fits E and F is due to noise in the data, although we cannot rule out the possibility that some of this structure represents real temperature structure in the patera. The assumption that the striping is an artifact is supported by (1) the fact that presence of real structure within the patera that coincidentally aligns exactly along the directions of Europa's limb is improbable; and (2) the comparison between square and diamond pixel maps (Figure 8.9), which demonstrates that the striping effect arises primarily when the pixel shape is determined by the orientation of Europa's limb and thus constrained by the minimum number of light curve points.

In this type of reconstruction, there is some inherent non-uniqueness in the retrieved temperature structure. In particular, structure at small spatial scales cannot be uniquely recovered because the length of the limb of Europa across Loki Patera is many tens of kilometers and will homogenize variations over considerably smaller spatial scales. We test the sensitivity of the technique to discrete small-scale features in the patera using simulated intensity maps with gaussian features of different sizes and brightnesses superposed on a background patera of uniform brightness. We generate simulated light curves from the maps at the same time sampling as the data, add noise to each datapoint based on the noise in the dataset, and reconstruct the images using methods identical to those applied to the LBT data. Figure 8.10 shows retrievals of simulated bright spots within the patera that constitute 5-15% of Loki Patera's total brightness and vary from 10-40 km in size (full width half maximum of the bright feature). Localized features that contribute below 5% of Loki Patera's intensity are generally undetectable. The retrievals demonstrate that the existence and location of small, bright features can be recovered in most cases. However, in the case of small (≤ 20 km) features, the shape of the feature tends to be blurred out in the retrieved map. In addition, small bright features in certain locations produce artifacts along either of the two directions oriented with Europa's limb during the occultation (see Figure 8.10d & e).

The smoothness of the temperature map shown in Figure 8.3 should therefore be viewed with some caution, as the retrievals tend to smooth out small, discrete features and are additionally insensitive to localized features that constitute only a few percent of the total patera intensity. However, the presence of the broad-scale temperature gradient from the northwest to the southeast of the patera is not susceptible to these ambiguities. Thus while the LBT observations do not constrain the presence of localized non-uniformities in the resurfacing, the existence of a coherent volcanic process acting across both the northern and southern patera regions is robust.

As a simple test, we apply the same methods to retrieve the temperature map shown in Figure 8.4 for day $\Delta T=250$ days, which approximates the LBT map. Figure 8.11a & 8.11c demonstrate that the smooth gradient across the northern and southern parts of the patera is retrieved well. For comparison, we perform the same analysis on a simulated temperature map whose azimuthally-smoothed intensity profile is comparable to that of the LBT map, but which models the temperature gradient as a series of discrete bright features.

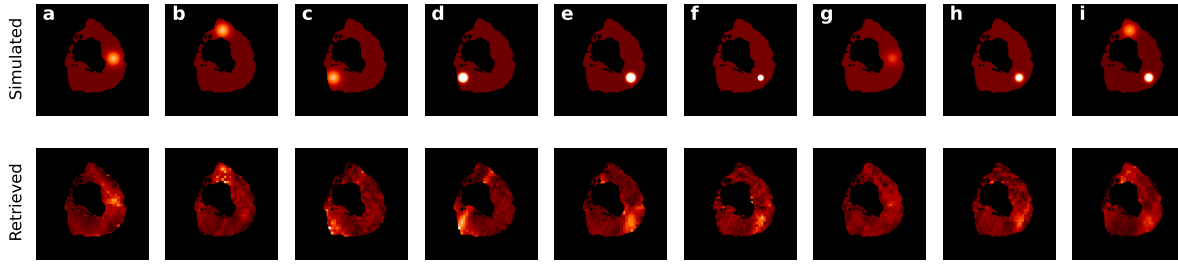


Figure 8.10: Retrieval of simulated temperature maps. The simulated maps (top row) include discrete hot features of gaussian brightness distribution on top of a uniformly-bright background patera. The bright spot constitutes $\sim 15\%$ of the patera’s total intensity in models (a) through (e), and $\sim 7.5\%$ of the intensity in models (f) through (h), and ranges in size from 10-40 km (full width half maximum of the feature). The retrieved maps (bottom row) are generated using the same methods applied to the LBT data, based on light curves corresponding to each intensity map with realistic noise added. The figure demonstrates that the presence and location of localized hot features of these brightness levels can be accurately retrieved by the analysis methods, but not their exact shape or size.

As demonstrated in Figure 8.11b & 8.11d, the discreteness of the underlying temperature map is evident in the reconstruction, despite the similarities between the model light curves (shown in Figure 8.11e & 8.11f).

8.1.13 Temperature map

The $4.8\text{-}\mu\text{m}$ intensity map derived by fitting the occultation light curve is converted to a brightness temperature map via the Planck function, which gives the spectral radiance as a function of wavelength and temperature. An emissivity value of $\epsilon = 1$ is used for this conversion, and it is assumed that the emission fills each pixel. The geometric foreshortening as a function of location within the patera is corrected for, but the change in the foreshortening during the occultation event is below 1% and is not corrected. The uncertainty in the flux calibration corresponds to an uncertainty in temperature on each pixel. However, the spectral radiance is very sensitive to small changes in temperature, and the flux calibration uncertainty leads to an uncertainty of only ± 1 K on the temperature map, well below the level of uncertainty resulting from systematic noise in the light curve.

8.1.14 Age map

The brightness temperature distribution within the patera is shown in Figure 8.3 alongside the lava age distribution based on a model which assumes a cooling lava crust on top of a basaltic lava lake (Matson et al. 2006; Davies et al. 2005). Newly exposed silicate lava cools predictably, allowing a derived surface temperature to be mapped to a time since emplacement (Davies 1996; Matson et al. 2006). Once lava thermophysical values are selected

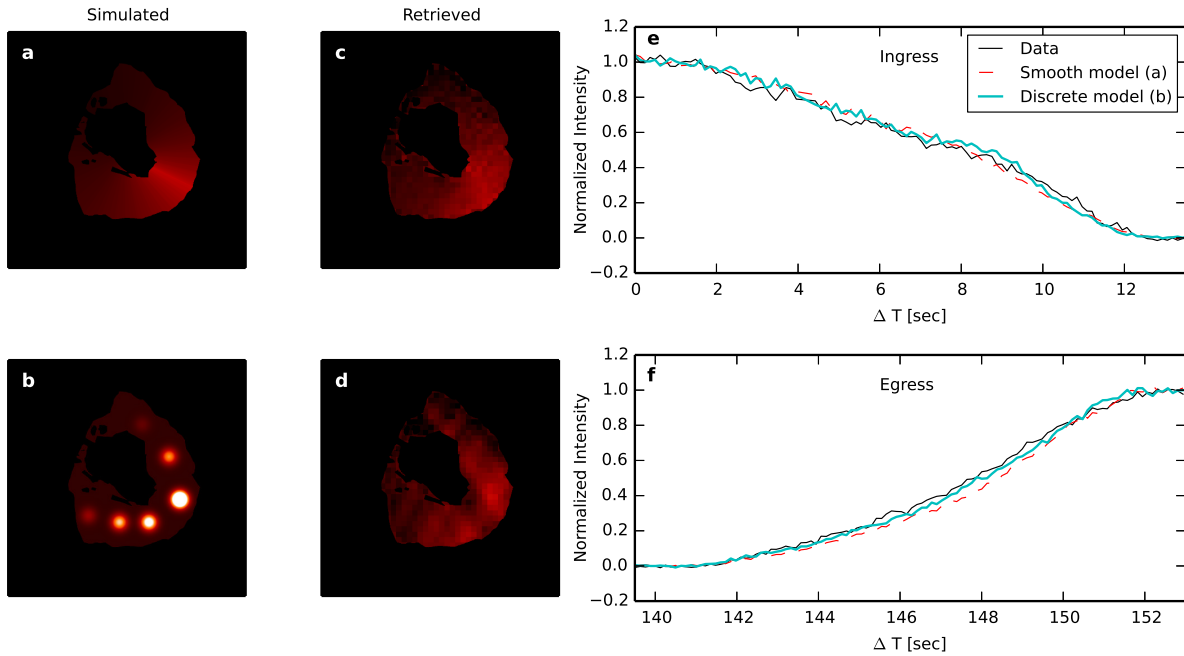


Figure 8.11: Retrieval of simulated temperature maps with global gradient. The simulated maps (a & b) demonstrate two possible models with similar azimuthally-smoothed intensity profiles and an overall increase in brightness toward the southeast of the patera. The retrieved maps (c & d) were produced using the same procedure by which the LBT map is produced, based on the simulated light curves (e & f), which include realistic noise. The retrieved maps demonstrate that these scenarios are clearly distinguished by the retrieval process, despite the similarities between the model light curves.

(we use values for basalt from Davies 2007; Davies et al. 2005), the model balances surface radiant heat loss with the conduction of heat through a thickening crust, including liberated latent heat as lava solidifies onto the base of the crust. Heat loss is buffered by the release of latent heat until the lava flow is completely solidified, after which the surface temperature falls off rapidly (Davies et al. 2005). A lava lake is treated as a semi-infinite body, so latent heat release is always present. The lava lake and lava flow surface cooling models diverge once the lava flow is completely solid. However, the periodic resurfacing of Loki Patera resets the lava cooling clock before complete solidification occurs, and this difference therefore cannot be used to distinguish between the two models.

Figure 8.4 demonstrates the determination of resurfacing rates in the northern and southern parts of the patera, based on the derived lava age map. The uncertainty on the derived ages resulting from uncertainty in the absolute flux calibration ranges from 2 days for the warmer parts of the patera (~ 330 K) to 12 days for the coolest temperatures (~ 270 K). The exact lava cooling ages in the cooler regions should therefore be viewed with caution, although in all parts of the patera uncertainties due to time-dependent noise and an in-

complete understanding of the thermal properties of the lava dominate over flux calibration effects.

In addition, if the differences in magma composition or volatile content between the northern and southern parts of the patera are significant, the corresponding cooling curves may also differ. Although this introduces some degeneracy between cooling rate and resurfacing rate, either interpretation points to a regional difference in magma composition or volatile content within the patera.

8.1.15 Central island

Models produced from basemaps of Loki Patera with and without a cool central island indicate that many of the large-scale features of the light curve can be reproduced by including this island (Figure 8.6). The ingress light curve in particular can be matched almost perfectly just by adding the island, although matching the egress light curve requires the addition of a non-uniform intensity distribution. In addition, in a model where the island pixels are also treated as free parameters in the fits, the presence of the island is recovered. As the fit is tightened, the values of the island pixels trend toward zero, and the fits thus recover the island even in the absence of any assumptions about it. Fits with $8 \text{ km} \times 8 \text{ km}$ pixels where the island pixels are free are shown in Figure 8.12; Fit C is the preferred model based on the distribution of the light curve residuals, and recovers the location and size of the island although not the exact outline seen in *Voyager* images (see Figure 8.3). The cracks through the island observed by *Galileo* (Lopes-Gautier et al. 2000) are below our detectability threshold (constituting less than one part in ten thousand of the total emission from Loki Patera), and were not included in our models.

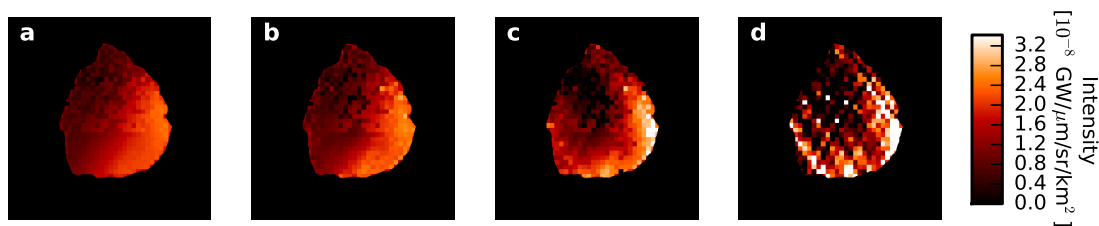


Figure 8.12: Model fits without the central island. Intensity reconstructions based on light curve fits using models with $8 \text{ km} \times 8 \text{ km}$ square pixels, permitting the pixels in the island as free parameters in the fit. Without any assumptions about the island, the fits recover it. Panels a-d demonstrate increasingly tight fits to the light curve; the preferred model based on the corresponding light curve residuals is panel c here.

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Chapter 9

Conclusions & Future Work

The solar system’s planets, satellites, and rings exhibit distinctive observational signatures from which active physical processes and evolutionary histories can be deduced. In this dissertation, I present new near-infrared observations that have shed light on the atmosphere and rings of Uranus, and the volcanic activity of Jupiter’s tidally-heated satellite Io.

The spectrum of a ring system encodes information on the size and composition of the ring particles, and thus the source of ring material and its collisional history. Rings composed of small particles exhibit characteristic spectral slopes depending on whether the particles are all of a similar size (blue) or follow the size distribution of a collisionally-evolved population (red). In contrast, macroscopic particles absorb instead of scattering incident sunlight, producing absorption features indicative of composition. In Chapter 2 I present spectrally- and spatially-resolved observations of the Uranus ring system from the Keck telescope. The three main ring groupings are spatially resolved, and exhibit grey spectra without absorption features. The lack of spectral slope indicates a macroscopic particle population, while the lack of spectral features and low albedo (0.028) suggests that the particles are coated in a dark material, in contrast to Saturn’s bright water-ice ring particles. Though confined to narrow annuli, Uranus’ main rings show large longitudinal variations in width; future observations at different viewing geometries would probe different portions of the rings, and illuminate any longitudinal variations in albedo or particle size.

Like Uranus’ rings, the planet’s atmosphere is also dark and featureless, in the sense of exhibiting limited cloud activity compared to the other giant planets. With an inclination near 90° , Uranus is the only giant planet whose solar insolation pattern changes drastically through its orbital period. In Chapter 3 I present spectrally- and spatially-resolved observations of Uranus’ atmosphere, which I analyze using radiative transfer forward modeling techniques and an MCMC retrieval algorithm. By testing models with a range of cloud properties, methane abundances, and particle properties, I find that the best fit to the data is obtained for a compact global cloud between 2-3 bars that thins toward the poles. This polar thinning is accompanied by a lower polar methane abundance, suggesting a global circulation pattern with downwelling in the polar regions. Although these observations capture the state of the atmosphere at a single point in time, comparison with past work places these results in the context of Uranus’ long-term atmospheric evolution. The bright southern collar

has faded since Uranus passed through equinox in 2007, while a corresponding bright band has emerged in the northern hemisphere. Continued observations, interpreted with radiative transfer models, would provide continued coverage as Uranus' north pole moves farther into sunlight. In particular, observations that cover the entire disk would place constraints on limb darkening parameters, which yield estimations of specific particle properties and thus remove degeneracies in the retrievals. Finally, time-domain tracking has the potential to reveal bright storm systems on Uranus such as was detected in 2014 (de Pater et al. 2015), and would force us to re-evaluate our assumptions about this planet's relative lack of dynamic cloud activity.

In the Jupiter system, the satellite Io exhibits bright volcanic eruptions that can be tracked to constrain the magma temperature and eruption style. Between August 2013 and the end of 2015, I observed Io with adaptive optics on the Keck and Gemini N telescopes on 100 nights, producing a high-cadence database of Io's thermal activity with the spatial resolution to identify individual volcanic centers. As a whole, this dataset provides insight into the variability and spatial distribution of Io's activity. I classify Io's volcanic sites into two categories: those that remain persistently active for 1 year or more at only moderate intensity, and those that are transient and (typically) bright.

Within the class of bright, transient eruptions are Io's highest-energy outburst eruptions. These eruptions may represent a different class of volcano on Io, perhaps with a deeper magma source than Io's other volcanoes, and provide unique constraints on Io's magma temperatures. Such events are rare. In August 2013 I detected one of the most energetic outburst eruptions ever seen on Io; this eruption produced between 15 and >25 TW of power, and the temperature fits to the spectrum indicate a temperature upwards of 1200-1300 K. The eruption likely involved high-volume effusive lava fountains feeding spreading lava flows, and the high eruption temperatures are consistent with both basaltic and ultramafic magma compositions. The event in August 2013 followed closely on two similar events detected two weeks prior (de Pater et al. 2014). The detection of three such events so closely spaced in time is unprecedented, and no other outbursts were detected in the subsequent three years. The timing of these eruptions, and the occurrence of other pairs of large eruptions close together in time and space, is suggestive of a mutual triggering mechanism. These eruptions often produce large gas and dust plumes that can impact the entire jovian system. An eruption at Kurdalagon Patera in 2015 coincided with a brightening of the jovian neutral and plasma environment, suggesting an influx of volcanic gasses associated with the eruption.

The spatial distribution of surface heat flow from a tidally-heated body provides important constraints on tidal heating models, and can reveal how deep within the body's interior the heat is deposited. However, the spatial distribution of Io's volcanic activity between 2013 and 2015 does not provide a good match to any tidal heating predictions. In particular, there is a strong asymmetry between the style of volcanism in Io's leading and trailing hemispheres. Io's leading hemisphere (longitudes of 0-180°) hosts a higher density of active volcanic centers, but they all fall at equatorial or mid-latitudes, and tend to be faint and/or persistent hot spots. In contrast, all bright eruptions occurred on Io's trailing hemisphere (longitudes of 180-360°), and the activity on this hemisphere occurred at higher latitudes than on the leading hemisphere. It may be that eruptions of different styles draw on magma

sources at different sub-surface depths, or perhaps that lithospheric differences between the hemispheres dominate over direct tidal controls.

Continued time-domain observations of Io’s volcanism will increase the size of the dataset, increasing our confidence in the observed distributions and revealing any temporal variations in the locations of major eruptions on Io’s surface. Of the two telescopes used in this study, Gemini N provided the bulk of the observations, enabled by its flexible, queue-based scheduling. In the future, higher-cadence observations with the Keck telescope would improve the results due to Keck’s higher spatial resolution, which allows for the detection of fainter hot spots. In addition, Keck’s ability to image at wavelengths out to $5\ \mu\text{m}$ allows for better constraints on the temperature and total power of each volcanic event. Time-domain campaigns have the potential not only to characterize global properties, but also to detect high-energy outburst eruptions such as was detected in 2013. Future detections of outbursts may provide more definitive constraints on Io’s magma composition, and will help unravel the triggering and occurrence rates of these events.

The timeline of activity on Loki Patera, a massive ($21,500\text{-km}^2$) volcanic feature on Io’s surface, includes detections on 70 different nights, and covers three brightening events at this volcano. Leveraging the high time resolution of the observations during the cooling phases of these events, I fit lava cooling curves to the data to constrain thermal properties of the material. I find evidence for low thermal conductivities ($\sim 0.7\ \text{W/m/K}$) consistent with a mafic magma composition, and use geometric arguments to postulate topographic shadowing of the patera. Currently, the largest uncertainty in the cooling model is the duration of the brightening phase; future observations with better time coverage during the early part of an event at Loki Patera would enable an improved characterization of the material properties of the lava.

In 2015, I used a mutual occultation of Io by Europa, observed with the Large Binocular Telescope Interferometer, to reconstruct the temperature distribution within Loki Patera at a resolution of $\sim 10\ \text{km}$ (5% of Loki Patera’s diameter). Using the thermal model previously optimized to Loki Patera’s cooling curve, I converted the temperature distribution to a lava crust age distribution, which gives the time since resurfacing for each region of the patera. The age map indicates two distinct resurfacing waves, which may be either lava flows or the fronts of two overturn waves on a magma sea. The waves began at slightly offset times and proceeded at different rates. The resurfacing rate is correlated with magma composition, and the variance in rate between the two halves of the patera suggests differences in gas content or bulk composition in the magma supply to each region. This dual-wave model could be validated by future mutual event observations (which become possible again in 2021) during different phases in Loki Patera’s brightening cycle. In addition, these observational and analysis tools can be applied to other volcanoes on Io to reconstruct their two-dimensional temperature distributions and draw conclusions about their volcanic styles.

Taken as a whole, this work has utilized cutting-edge telescope technologies to shed light on the compositions and dynamic processes of the outer solar system’s planets, satellites, and rings. Insight gained from Uranus and Io improves our understanding of ring systems, seasonal atmospheric phenomena, and tidally-powered geological activity throughout the solar system, and improves our framework for interpreting signals from exoplanets.

Science is an ongoing process, and as with all discoveries, this work has generated as many new questions as it has answered. The specific questions brought to light here can guide future investigations, while the tools utilized in these studies can be applied and expanded in future years to address the outstanding mysteries on these and other targets.

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Appendix A

Technical aspects of Io high-cadence program

A.1 An Assessment of Retrieval Uncertainties and Detection Limits

A robust characterization of the uncertainties on position and intensity retrievals is crucial for hot spot identification and correct interpretation of time variability. We systematically explore the accuracy of our position and flux density retrievals, in order to:

- (1) Set lower limits on detectable flux density as a function of filter, telescope, and hot spot position, in order to quantify non-detections and meaningfully interpret the variability in activity at a given hot spot; and
- (2) Realistically evaluate the uncertainties on our retrievals for hot spot position and flux density and increase the quoted errorbars if necessary.

Whether or not a hot spot is detectable on a given night is affected by: the PSF, which depends on the filter, telescope, and the atmospheric and seeing conditions; the intrinsic brightness of the hot spot; foreshortening due the hot spot's location relative to the limb; the locations of other hot spots on the disk; and the Earth-Io distance, which changes the effective resolution on Io's disk.

We test the accuracy of our retrieval methods on simulated datasets as follows. We create simulated hot spots by convolving a delta function of the desired flux density with a PSF derived from the standard star for that night. The flux densities are corrected for geometric foreshortening according to the standard cosine law, and added to real observations in a region of the disk relatively free from bright hot spots. We test 15 different flux densities between 1 and 100 GW/ $\mu\text{m}/\text{sr}$, inserted at 12 different values of μ between 0.99 (disk center) and 0.1 (limb). Figure A.1 shows the result of inserting a simulated hot spot of moderate brightness at different disk locations.

After creating the simulated datasets, we retrieve the hot spot flux densities by the same method used in our analysis (see Section 5.3.1), including correcting the flux density according to the retrieved emission angle, which may differ from the actual emission angle if

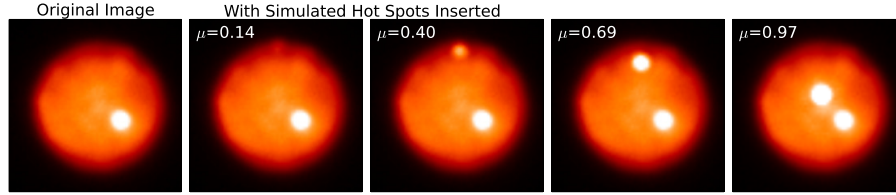


Figure A.1: Simulated hot spots inserted into a Gemini N L'-band observation. The value of μ for the simulated hot spot is indicated on each plot; all simulated hot spots have an intrinsic flux density of $30 \text{ GW}/\mu\text{m}/\text{sr}$ before geometric foreshortening is applied.

the position retrieval is poor. We perform this analysis on base images from multiple different nights, for data in the L' and Ms filters on Keck, and in the L' filter on Gemini N. The errors in the retrieved flux densities and positions are shown in Figure A.2 for each choice of flux density and μ , averaged over all the nights for which we performed this analysis.

As expected, hot spots become increasingly difficult to detect at fainter intrinsic brightnesses, at locations nearer the limb, and in the vicinity of brighter hot spots. For each telescope and filter, we determine and parameterize the approximate flux density $F(\mu)$ where a hot spot becomes undetectable. On a typical night, in a region of Io's disk free of bright hot spots, we can detect a hot spot when the following conditions are met:

- **Keck Lp:** $F(\mu) > -17.7 \times \mu + 10.9 \text{ GW}/\mu\text{m}/\text{sr}$
- **Keck Ms:** $F(\mu) > -15.0 \times \mu + 8.1 \text{ GW}/\mu\text{m}/\text{sr}$
- **Gemini Lp:** $F(\mu) > -20.0 \times \mu + 13.9 \text{ GW}/\mu\text{m}/\text{sr}$

These conditions give an approximate upper limit on the flux density in cases when we observe the location of a known hot spot but do not detect emission. The conditions are shown as dashed lines on Figure A.2, and the detectability regimes are compared in Figure A.3. We find that we can make detections closer to the limb with the Ms filter than the L' filter; the disk is dimmer at longer wavelengths, improving the hot spot contrast. We also have a much greater chance of detecting a hot spot with the Keck telescope over Gemini N. For example, at a disk position of $\mu=0.5$, we can detect hot spots down to $\sim 2 \text{ GW}/\mu\text{m}/\text{sr}$ with Keck, while a hot spot needs to be twice as bright to be detected by Gemini N at the same location. In all observations, the detection limit very near the limb ($\mu \leq 0.2$) is highly sensitive to various factors and cannot be simply quantified; a hot spot at these locations may not be detected even if it meets the above conditions.

In addition to quantifying our limits on hot spot detections, we use this analysis to evaluate uncertainties on our position and intensity retrievals. The deviations between retrieved values and actual values are shown in Figure A.2. We define a region of accurate intensity retrieval where the intensity is retrieved to within $\sim 15\%$. The boundary of this region is shown as a dashed line in Figure A.2, and compared between telescopes and filters in Figure A.3. For position retrievals, we define three regions for where the error in the retrieved position (in degrees of latitude/longitude) is $>5^\circ$, $\sim 3^\circ$, and $\leq 1^\circ$. The boundaries between these

regions are also shown in Figure A.2, and shown for each telescope and filter in Figure A.4. For very faint hot spots, or very high emission angles, retrievals are additionally uncertain, and are particularly sensitive to observing conditions, phase angle, and nearby hot spots. Flux density uncertainties are in the 50% range for hot spots detected by Gemini N with $F_{L'} < 3 \text{ GW}/\mu\text{m}/\text{sr}$, and in the 25% range for hot spots detected at Keck with $F < 1.5 \text{ GW}/\mu\text{m}/\text{sr}$ in both filters. In addition, at locations limb-ward of $\mu = 0.3$, positions cannot be confidently established to better than 3° .

We apply these results to our analysis as follows:

- We adjust the uncertainties on our retrieved positions so that they are no smaller than 3° or 5° depending on which region of Figure A.4 they fall within. We detected no hot spots within the undetectable zone (dark gray), but we increased the uncertainties on 30-45% of hot spots falling within the $\sigma \sim 3^\circ$ zone (light gray) in order to satisfy this criterion.
- We adjust the uncertainties on our retrieved flux densities by increasing them to 50% when the detection does not fall into the zone of accurate intensity retrieval. No Ms-band detections fell within this range, but $\sim 5\%$ of L'-band detections were modified by this criterion.
- For faint hot spots (<1.5 or $<3.0 \text{ GW}/\mu\text{m}/\text{sr}$ at Keck and Gemini N respectively), we adjust retrieved flux density uncertainties to be no less than 50%. This adjustment affected 10-15% of hot spot detections.
- For hot spots near the limb ($\mu < 0.35$ or < 0.65 for Keck and Gemini N respectively), we adjust retrieved position uncertainties to be no less than 3° . This adjustment had a minimal effect on retrieved positions, since hot spot detections in these regions were few, and original position uncertainty estimates were already high.

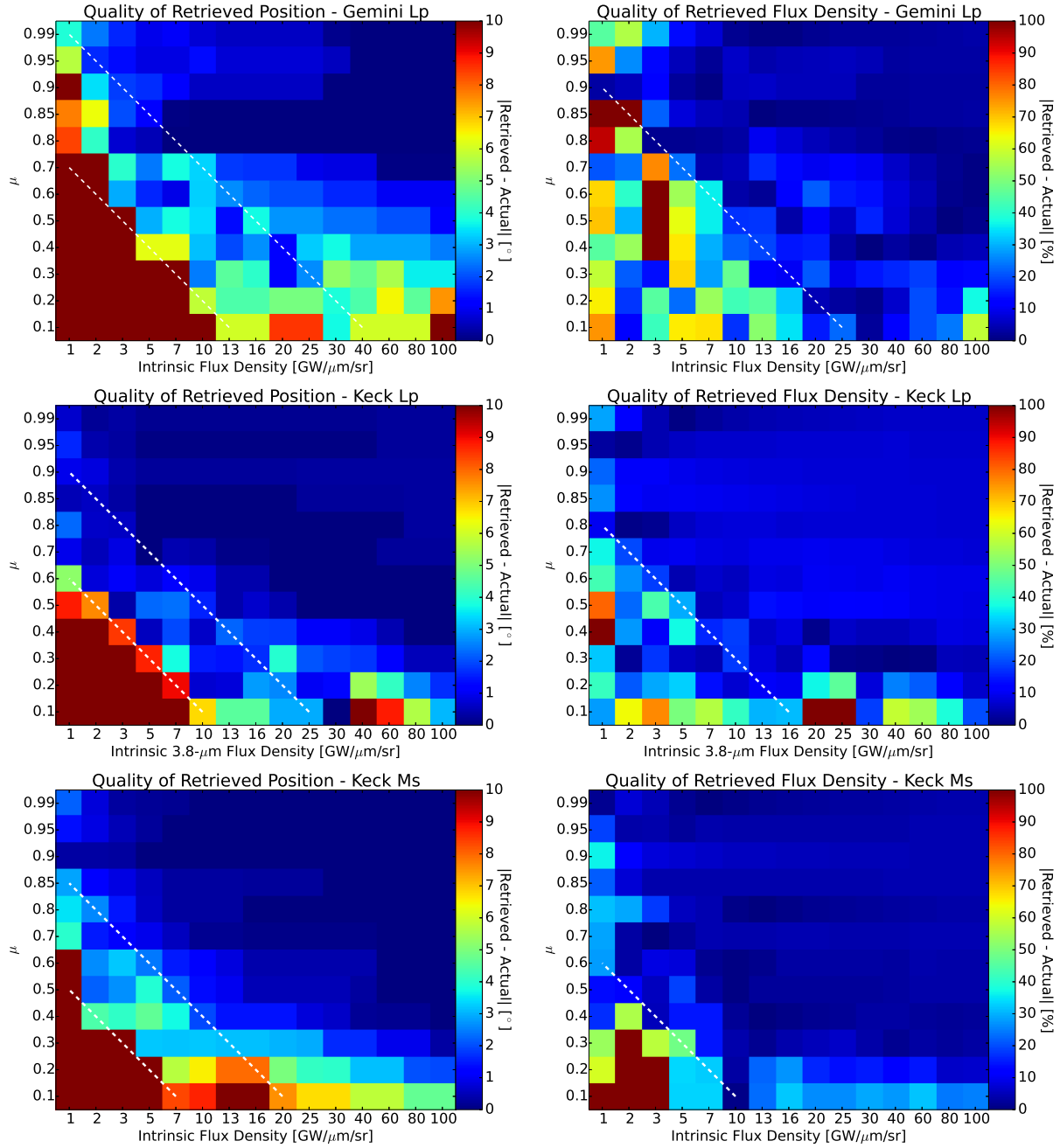


Figure A.2: Error in the retrievals of positions and flux densities of fake hot spots inserted into real Io data, as a function of the cosine of the emission angle μ and intrinsic flux density (see Section A.1). The white dashed lines mark the approximate boundaries in this parameter space where the retrievals begin to fail, and are the basis for the detectability criteria and retrieval uncertainty regimes discussed in the text. Errors in position retrievals are given in degrees of latitude/longitude, and errors in flux density retrievals are given in percent of actual flux density.

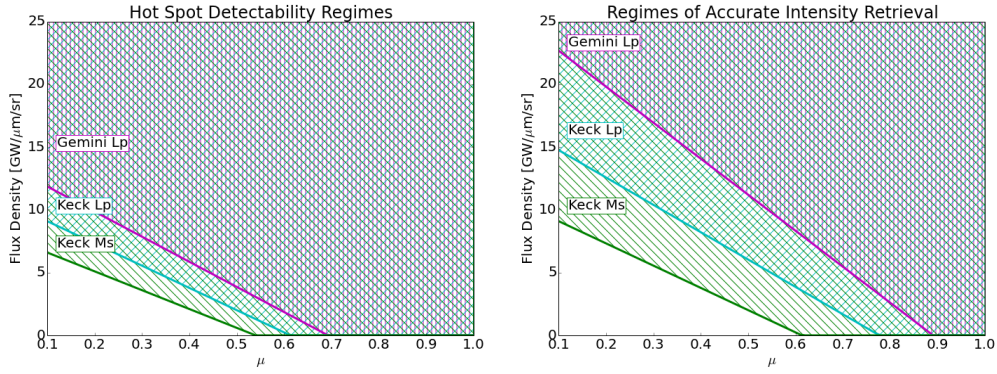


Figure A.3: (Left) Summary of the hot spot detection limits for our observations. The curves indicate the lower limit on the flux density that can be detected at a given disk position; the hatched areas indicate regions where detection is possible. (Right) Summary of flux density-emission angle combinations where intensities can be accurately retrieved. The hatched regions indicate where intensities can be retrieved to $\sim 15\%$. In both cases these limits may vary from night to night due to observing conditions and the distribution of hot spots on Io's disk.

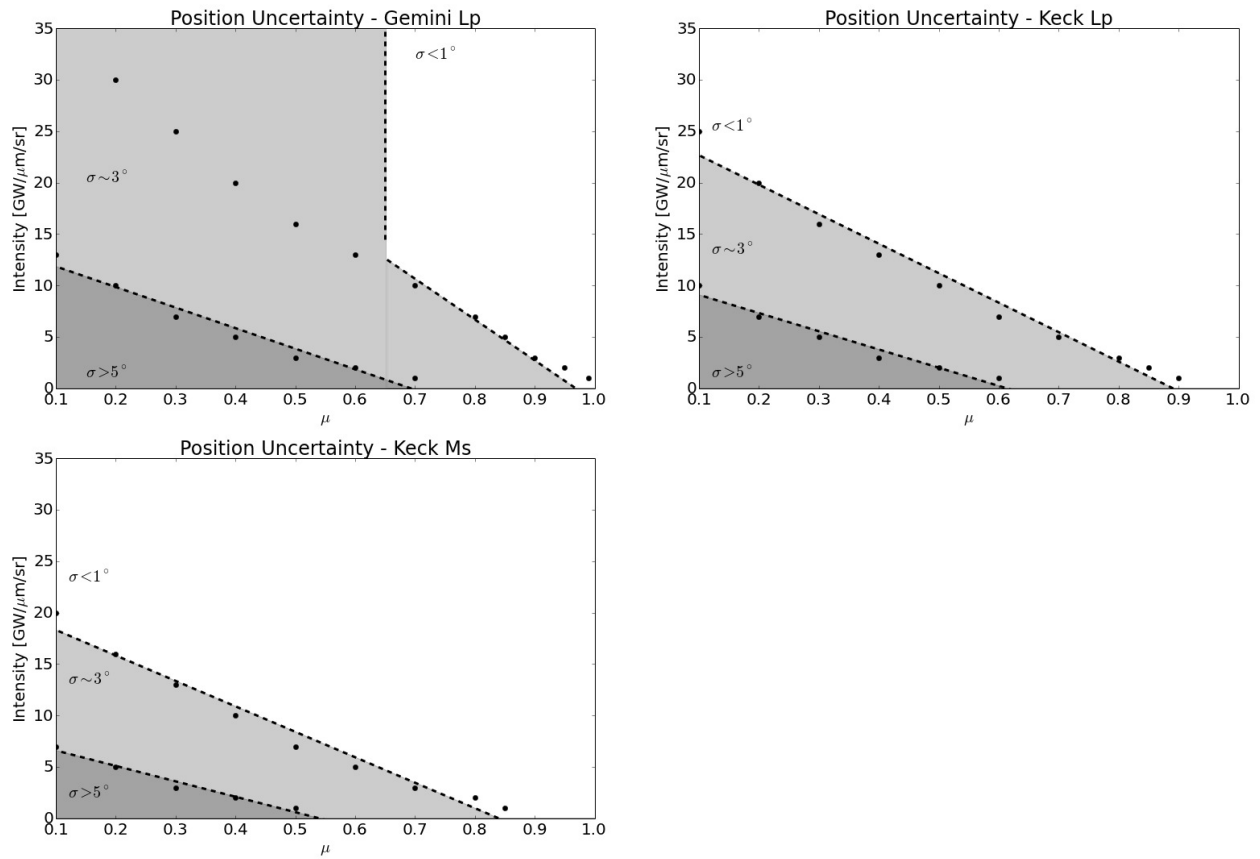


Figure A.4: Comparison of position uncertainty regimes for the Keck L' and Ms filters and the Gemini N L' filter based on simulated hot spot analysis.

A.2 Tables

Table A.1: Observations

UT Date	Telescope/Instrument	CML ^a	Filters
2013-08-15	Keck/NIRC2	337°	Kc-Ms
2013-08-20	Keck/NIRC2	275°	Kc-Ms
2013-08-21	Keck/NIRC2	115°	Kc-Ms
2013-08-22	Keck/NIRC2	319°	Kc-Ms
2013-08-23	Keck/NIRC2	161°	Kc-Ms
2013-08-29	Gemini N/NIRI	301°	L'
2013-08-30	Gemini N/NIRI	144°	L'
2013-09-01	Gemini N/NIRI	191°	L'
2013-09-02	Gemini N/NIRI	34°	L'
2013-09-03	Gemini N/NIRI	237°	L'
2013-09-04	Gemini N/NIRI	81°	L'
2013-09-05	Gemini N/NIRI	284°	L'
2013-09-06	Gemini N/NIRI	127°	L'
2013-09-07	Gemini N/NIRI	331°	L'
2013-09-09	Gemini N/NIRI	17°	L'
2013-09-10	Gemini N/NIRI	221°	L'
2013-11-18	Keck/NIRC2	215°	Kc-Ms
2013-11-26	Gemini N/NIRI	55°	L'
2013-11-27	Gemini N/NIRI	258°	L'
2013-11-28	Gemini N/NIRI	102°	L'
2013-11-29	Gemini N/NIRI	305°	L'
2013-12-02	Gemini N/NIRI	154°	L'
2013-12-03	Gemini N/NIRI	26°	L'
2013-12-04	Gemini N/NIRI	202°	L'
2013-12-05	Gemini N/NIRI	81°	L'
2013-12-06	Gemini N/NIRI	274°	L'
2013-12-12	Gemini N/NIRI	72°	L'
2013-12-13	Gemini N/NIRI	232°	L'
2013-12-14	Gemini N/NIRI	119°	L'
2013-12-15	Gemini N/NIRI	321°	L'
2014-01-20	Keck/NIRC2	33°	Kc-Ms
2014-02-08	Keck/NIRC2	274°	Kc-Ms
2014-02-10	Keck/NIRC2	318°	Kc-Ms
2014-03-07	Gemini N/NIRI	36°	Kc,L'
2014-03-10	Gemini N/NIRI	259°	Kc,L'
2014-03-11	Keck/NIRC2	132°	Kc-Ms
2014-03-11	Gemini N/NIRI	100°	Kc,L'
2014-03-12	Gemini N/NIRI	303°	Kc,L'
2014-03-14	Gemini N/NIRI	25°	Kc,L'
2014-03-27	Gemini N/NIRI	130°	Kc,L'
2014-03-28	Gemini N/NIRI	338°	Kc,L'
2014-04-03	Gemini N/NIRI	105°	Kc,L'
2014-10-03	Gemini N/NIRI	308°	Kc,L'
2014-10-09	Gemini N/NIRI	87°	Kc,L'
2014-10-10	Gemini N/NIRI	291°	Kc,L'
2014-10-22	Gemini N/NIRI	210°	Kc,L'

2014-10-23	Gemini N/NIRI	56°	Kc,L'
2014-10-24	Gemini N/NIRI	258°	Kc,L'
2014-10-25	Gemini N/NIRI	95°	Kc,L'
2014-10-27	Gemini N/NIRI	146°	Kc,L'
2014-10-30	Keck/NIRC2	38°	Kc-Ms
2014-10-31	Keck/NIRC2	242°	Kc-Ms
2014-11-25	Gemini N/NIRI	284°	Kc,L'
2014-11-27	Gemini N/NIRI	334°	Kc,L'
2014-11-28	Gemini N/NIRI	153°	Kc,L'
2014-11-29	Gemini N/NIRI	22°	Kc,L'
2014-11-30	Gemini N/NIRI	228°	Kc,L'
2014-12-01	Gemini N/NIRI	71°	Kc,L'
2014-12-02	Keck/NIRC2	275°	Kc-Ms
2014-12-06	Gemini N/NIRI	329°	Kc,L'
2014-12-08	Gemini N/NIRI	50°	Kc,L'
2014-12-09	Gemini N/NIRI	259°	Kc,L'
2014-12-10	Gemini N/NIRI	98°	Kc,L'
2014-12-15	Gemini N/NIRI	40°	Kc,L'
2014-12-16	Gemini N/NIRI	247°	Kc,L'
2014-12-18	Gemini N/NIRI	293°	Kc,L'
2015-01-10	Gemini N/NIRI	296°	Kc,L'
2015-01-11	Keck/NIRC2	138°	Kc-Ms
2015-01-12	Keck/NIRC2	338°	Kc-Ms
2015-01-13	Gemini N/NIRI	134°	Kc,L'
2015-01-14	Gemini N/NIRI	328°	Kc,L'
2015-01-15	Gemini N/NIRI	231°	Kc,L'
2015-01-16	Keck/NIRC2	74°	Kc-Ms
2015-01-22	Gemini N/NIRI	154°	Kc,L'
2015-01-26	Gemini N/NIRI	250°	Kc,L'
2015-03-25	Gemini N/NIRI	149°	Kc,L'
2015-03-26	Gemini N/NIRI	29°	Kc,L'
2015-03-27	Gemini N/NIRI	213°	Kc,L'
2015-03-28	Gemini N/NIRI	42°	Kc,L'
2015-03-29	Gemini N/NIRI	244°	Kc,L'
2015-03-31	Keck/NIRC2	292°	Kc-Ms
2015-04-01	Keck/NIRC2	134°	Kc-Ms
2015-04-02	Keck/NIRC2	338°	Kc-Ms
2015-04-04	Keck/NIRC2	28°	Kc-Ms
2015-04-05	Gemini N/NIRI	231°	Kc,L'
2015-04-06	Gemini N/NIRI	70°	Kc,L'
2015-04-09	Gemini N/NIRI	322°	Kc,L'
2015-04-17	Gemini N/NIRI	149°	Kc,L'
2015-04-19	Gemini N/NIRI	197°	Kc,L'
2015-04-20	Gemini N/NIRI	40°	Kc,L'
2015-04-21	Gemini N/NIRI	244°	Kc,L'
2015-04-22	Gemini N/NIRI	89°	Kc,L'
2015-04-26	Gemini N/NIRI	206°	Kc,L'
2015-04-27	Gemini N/NIRI	24°	Kc,L'
2015-04-29	Keck/NIRC2	73°	Kc-Ms
2015-05-05	Keck/NIRC2	213°	Kc-Ms
2015-06-05	Keck/NIRC2	38°	Kc-Ms

2015-11-23	Keck/NIRC2	212°	Kc-Ms
2015-12-22	Keck/NIRC2	327°	Kc-Ms
2015-12-25	Keck/NIRC2	106°	Kc-Ms

^a CML = Central Meridian Longitude of Io

Table A.2: Hot Spot Detections

ID	Date	Latitude [°N]	Longitude [°W]	μ	F_{Kc}	F_{H2O} [all intensities in GW/μm/sr]	F_{PAH} [all intensities in GW/μm/sr]	$F_{L'}$	F_{Ms}	T [K]	P [GW]
A	12-03-13	-33.8±2.0	20.1±2.1	0.83				2.7±1.3			
	01-20-14	-34.9±0.8	20.9±0.8	0.79			1.6±0.2	3.1±0.5	5.4±0.8	441 ⁺³⁴ ₋₇₀	230 ⁺⁹⁰ ₋₇₀
	02-10-14	-34.1±0.5	23.4±2.1	0.35				5.1±2.6	4.6±0.9	590 ⁺²³⁰ ₋₁₇₀	110 ⁺¹²⁰ ₋₆₀
	03-07-14	-34.9±2.0	25.9±2.2	0.81				2.2±1.1			
	03-14-14	-34.7±2.0	24.8±2.1	0.82				3.3±0.5			
	10-30-14	-33.7±0.8	21.2±0.8	0.79				3.0±0.4	5.8±0.9	430 ⁺⁷⁰ ₋₆₀	260 ⁺¹⁹⁰ ₋₁₁₀
	11-29-14	-35.5±2.1	20.6±2.1	0.81				3.2±0.6			
	12-08-14	-34.1±1.6	19.1±2.5	0.71				3.4±1.7			
	12-15-14	-34.2±1.8	19.6±2.3	0.77				2.9±1.4			
	01-12-15	-35.4±1.0	22.6±1.8	0.59				3.2±1.6	4.9±0.7	470 ⁺¹⁶⁰ ₋₁₀₀	170 ⁺²⁴⁰ ₋₁₀₀
	01-16-15	-34.1±1.0	21.0±1.8	0.49				3.4±1.7	4.6±0.7	520 ⁺¹⁹⁰ ₋₁₄₀	130 ⁺¹⁶⁰ ₋₇₀
	03-26-15	-37.0±2.0	22.1±2.2	0.79				3.4±0.5			
	03-28-15	-34.6±1.8	25.3±2.3	0.79				3.2±0.5			
	04-02-15	-33.5±0.6	23.9±1.3	0.59				3.5±0.8	4.7±0.7	540 ⁺¹⁴⁰ ₋₁₁₀	121 ⁺⁷⁸ ₋₄₇
	04-04-15	-33.9±0.5	24.8±0.5	0.83				3.9±0.6	6.1±0.9	490 ⁺⁸⁰ ₋₇₀	190 ⁺¹¹⁰ ₋₇₀
	04-20-15	-34.6±1.9	27.2±2.2	0.80				3.7±0.6			
	04-27-15	-35.8±2.0	24.4±2.1	0.81				4.0±0.6			
	04-29-15	-34.7±0.7	23.4±1.2	0.53				4.1±0.9	5.4±0.8	550 ⁺¹²⁰ ₋₁₀₀	139 ⁺⁷⁷ ₋₅₀
	06-05-15	-32.2±0.7	23.5±0.9	0.81			3.3±0.5	4.8±0.7	7.1±1.1	514 ⁺⁴⁹ ₋₄₅	210 ⁺⁷⁰ ₋₅₀
	11-23-15	-35.5±0.7	21.3±1.9	0.48				3.3±1.7	5.2±0.8	490 ⁺¹⁷⁰ ₋₁₃₀	160 ⁺²²⁰ ₋₉₀
	12-25-15	-34.6±0.6	22.7±1.9	0.48				4.0±1.4	6.1±0.9	470 ⁺¹³⁰ ₋₁₀₀	210 ⁺²⁴⁰ ₋₁₁₀
Average		-34.4±0.9	22.8±2.1								
<i>Uta</i> <i>Patena</i>		-36	22								
	01-20-14	-17.3±0.7	32.3±1.1	0.95				1.5±0.4	3.3±0.5	400 ⁺⁸⁰ ₋₆₀	190 ⁺²¹⁰ ₋₁₀₀
	10-30-14	-19.1±1.2	30.9±0.7	0.94				1.0±0.4	1.5±0.2	490 ⁺¹⁶⁰ ₋₁₂₀	49 ⁺⁶⁶ ₋₂₈
	01-16-15	-16.6±1.8	31.3±2.3	0.70					1.4±0.7		
	04-02-15	-15.7±0.8	34.4±1.9	0.55					1.4±0.5		
	04-04-15	-17.6±0.9	35.2±0.5	0.94				1.0±0.5	2.0±0.3	420 ⁺¹⁴⁰ ₋₁₀₀	100 ⁺¹⁶⁰ ₋₆₀
	04-29-15	-15.2±1.0	36.5±1.2	0.77					1.4±0.5		
	06-05-15	-16.1±1.5	34.5±0.6	0.96					1.3±0.4		
	Average	-16.8±1.2	33.8±1.9								
		-15 to -21	32 to 36								
<i>Kanehekili</i> <i>Fluctus</i> C		-15 to -21	32 to 36								
	09-02-13	-4.5±1.4	37.0±1.4	1.00				5.0±0.7			
	09-04-13	-4.4±1.7	36.2±2.4	0.73				4.6±0.8			
	09-07-13	-4.6±1.4	37.3±3.5	0.46				10.8±2.3			
	09-09-13	-5.0±1.3	36.5±1.4	0.97				5.2±0.8			
	11-26-13	-4.8±1.1	37.9±1.1	0.96				3.5±0.5			
12-03-13		-4.0±1.0	37.7±1.1	0.97				6.1±1.1			

		Average		38.3±1.5	74.4±2.8		
<i>Zal</i> <i>Patera</i>				39.5	74.5		
H	08-21-13		3.6±0.6	78.1±0.8	0.79	2.0±0.3	
	12-05-13		2.5±1.0	73.4±1.0	0.99	1.0±0.5	
	12-12-13		2.5±1.0	74.4±1.0	1.00	1.2±0.6	
	12-14-13		2.8±1.7	75.1±2.4	0.72	1.9±1.0	
	01-20-14		2.1±0.6	74.1±0.9	0.83	2.0±0.5	
	03-11-14		3.7±0.9	75.1±1.8	0.54	1.6±0.2	
	01-11-15		2.7±0.8	74.8±1.9	0.45	3.5±0.5	
	01-16-15		4.2±0.6	76.3±0.6	1.00	3.9±0.6	
	04-01-15		3.7±0.6	76.5±1.3	0.52	1.4±0.7	
	04-29-15		3.1±0.5	76.8±0.6	0.99	3.5±1.2	
Tawhaki <i>Patera</i>	06-05-15		4.3±1.3	77.2±1.6	0.78	1.7±0.4	
	Average		3.2±0.7	75.8±1.3		1.9±0.3	
			3.5	76		1.5±0.2	
	01-11-15		41.5±1.3	91.6±2.6	0.52	4.6±0.7	
	01-16-15		42.0±2.2	88.7±2.0	0.72	1.8±0.3	
	Average		41.7±1.3	89.9±1.6			
			44	92			
	11-26-13		14.5±1.7	87.9±2.4	0.81	2.9±1.4	
	11-28-13		15.7±1.1	87.0±1.2	0.93	2.2±1.1	
	12-03-13		15.4±1.1	90.2±3.5	0.41	7.4±3.7	
Aluna <i>Patera</i>	12-05-13		15.8±1.1	87.3±1.1	0.96	2.4±1.2	
	12-12-13		14.5±1.1	86.1±1.2	0.94	1.8±0.9	
	01-20-14		15.2±0.5	89.5±0.9	0.63	3.3±1.3	
	03-11-14		16.1±1.1	90.5±1.7	0.72	1.9±0.3	
	01-11-15		14.5±1.0	89.3±1.8	0.64	5.4±0.8	
	01-13-15		14.2±1.5	89.6±2.5	0.69	3.8±1.9	
	01-16-15		14.7±0.6	88.7±0.4	0.94	5.4±0.8	
	04-01-15		16.1±1.2	91.9±1.2	0.70	1.3±0.5	
	04-04-15		15.9±1.3	90.7±2.6	0.44	4.9±2.4	
	04-29-15		15.2±0.3	89.8±0.7	0.93	0.9±0.3	
Gish Bar <i>Patera</i>	Average		15.2±0.6	89.0±1.5		1.4±0.5	
			15.5	90		4.1±0.5	
	08-21-13		-36.5±1.2	91.1±0.8	0.73	5.0±1.2	
	Average		-36.5±1.2	91.1±0.8		8.0±1.2	
			-37	93		480±100	
	08-21-13		33.5±0.7	100.0±0.9	0.80	2.2±0.3	
	01-20-14		32.0±1.1	92.9±1.7	0.55	2.6±0.5	
	04-29-15		34.2±1.5	95.6±1.4	0.76	0.8±0.4	
						260±210	
						480±100	
P207 L	08-21-13		33.5±0.7	100.0±0.9	0.80	2.2±0.3	
	01-20-14		32.0±1.1	92.9±1.7	0.55	2.6±0.5	
	04-29-15		34.2±1.5	95.6±1.4	0.76	0.8±0.4	
						260±210	
						480±100	
						260±210	
						480±100	
						260±210	
						480±100	
						260±210	

<i>Amirani</i> Q	04-22-15	22.4±1.7	116.5±2.4	0.82	4.2±0.6	450 ⁺¹¹⁰ ₋₉₀	160 ⁺¹⁶⁰ ₋₈₀
	04-29-15	20.7±0.7	113.2±1.0	0.72	2.3±0.6	370 ⁺⁴⁷ ₋₄₂	380 ⁺³³⁰ ₋₁₈₀
	12-22-15	21.6±0.6	112.5±0.5	0.93	1.9±0.3		
	Average	20.9±1.0	113.7±2.8				
		<i>20 to 32</i>	<i>112 to 116</i>				
<i>Dusura</i> <i>Patara</i> R	03-11-14	36.4±0.6	121.1±0.9	0.78	7.5±1.3	700 ⁺¹²⁰ ₋₁₀₀	137 ⁺²⁷ ₋₂₃
	03-27-14	35.4±1.5	121.0±1.6	0.81	8.1±1.2		
	04-03-14	36.8±1.7	124.0±2.4	0.76	6.9±1.3		
	Average	36.2±0.8	121.6±1.3				
		<i>37.5</i>	<i>119</i>				
<i>Malak</i> <i>Patara</i> S	08-21-13	-32.2±0.5	127.6±1.4	0.83	3.3±0.8	600 ⁺¹⁵⁰ ₋₁₂₀	88 ⁺⁴¹ ₋₂₈
	08-23-13	-31.0±0.9	130.2±1.3	0.73	3.0±0.7	720 ⁺¹⁹⁰ ₋₁₅₀	55 ⁺¹⁴ ₋₁₁
	03-11-14	-33.6±0.6	129.9±0.6	0.83	1.3±0.6		
	01-11-15	-32.9±1.6	127.3±1.1	0.82	1.7±0.3	720 ⁺¹⁴⁰ ₋₁₂₀	33 ⁺⁷ ₋₆
	01-16-15	-33.5±0.9	125.9±1.8	0.52	6.9±1.0	670 ⁺¹¹⁰ ₋₁₀₀	140 ⁺³⁰ ₋₂₅
<i>Thor</i> T	01-22-15	-34.7±1.7	129.6±2.4	0.75	2.4±1.2		
	04-01-15	-32.4±1.0	132.0±0.8	0.84	1.5±0.3	560 ⁺¹³⁰ ₋₁₁₀	47 ⁺²⁴ ₋₁₆
	04-29-15	-35.1±1.2	130.3±2.7	0.49	3.2±0.5		
	Average	-33.0±1.2	129.4±1.8				
		<i>-34</i>	<i>129</i>				
<i>P123</i> U	01-11-15	41.6±2.0	133.0±2.1	0.74	1.5±0.7		
	04-01-15	39.5±1.5	136.4±1.4	0.77	1.2±0.4		
	Average	40.4±1.2	135.0±1.6				
		<i>38</i>	<i>132</i>				
	01-11-15	-42.0±1.2	138.6±1.4	0.74	2.9±0.4	770 ⁺¹⁶⁰ ₋₁₄₀	51 ⁺⁷ ₋₆
<i>Trupan</i> <i>Patara</i> V	04-01-15	-41.2±0.7	143.4±0.9	0.74	2.5±0.4	720 ⁺¹⁰⁰ ₋₈₀	53 ⁺⁹ ₋₈
	12-22-15	-41.8±1.1	135.4±1.3	0.65	4.6±0.7	470 ⁺⁸⁰ ₋₆₀	280 ⁺¹⁸⁰ ₋₁₁₀
	Average	-41.6±0.6	139.8±3.2				
		<i>-42</i>	<i>138</i>				
	01-11-15	-18.2±0.8	139.2±0.7	0.95	1.3±0.6	540 ⁺²²⁰ ₋₁₈₀	43 ⁺⁵⁵ ₋₂₄
<i>Trupan</i> <i>Patara</i> V	04-01-15	-17.7±1.0	143.7±1.0	0.94	0.8±0.3	510 ⁺¹⁸⁰ ₋₁₃₀	34 ⁺²⁴ ₋₂₀
	12-22-15	-17.4±1.0	136.9±1.2	0.82	1.7±0.2	409 ⁺⁵⁷ ₋₅₀	190 ⁺¹⁴⁰ ₋₈₀
	Average	-17.8±0.5	140.1±2.8				
		<i>-19</i>	<i>140</i>				
	03-25-15	21.5±1.2	148.7±1.2	0.93	2.7±1.3		
<i>Trupan</i> <i>Patara</i> V	04-01-15	21.9±0.9	148.8±0.7	0.90	3.6±0.5	440 ⁺⁷⁰ ₋₆₀	270 ⁺¹⁸⁰ ₋₁₁₀
	04-17-15	21.0±1.3	150.0±1.3	0.93	2.0±1.0		
	05-05-15	20.6±1.0	151.1±2.8	0.47	5.0±0.8		
	Average	21.3±0.5	149.3±0.9				
		<i>-19</i>	<i>140</i>				

	11-18-13	-24.4±0.6	208.5±0.6	0.88	3.4±0.5	4.8±0.7	6.7±1.0	9.2±1.4	527 ⁺³⁷ ₋₃₄	260 ⁺⁷⁰ ₋₆₀
	11-27-13	-27.9±1.3	203.3±2.9	0.51			5.4±2.7			
	12-02-13	-22.5±1.2	209.1±2.9	0.54			5.8±2.9			
	12-04-13	-23.4±1.1	210.0±1.2	0.91			4.6±0.7			
	12-13-13	-23.7±1.9	210.7±2.2	0.86			3.7±0.6			
	02-08-14	-23.8±1.1	213.3±2.0	0.44			8.3±1.2	6.5±1.0	720 ⁺¹¹⁰ ₋₁₀₀	139 ⁺²² ₋₁₉
	03-10-14	-24.0±1.5	215.1±2.5	0.67			5.4±1.0			
	10-22-14	-24.7±1.5	208.6±1.5	0.91			5.7±0.9			
	10-31-14	-23.2±0.8	210.0±0.5	0.76			6.5±1.0	9.0±1.4	530 ⁺⁹⁰ ₋₈₀	250 ⁺¹²⁰ ₋₈₀
	11-30-14	-25.0±1.3	208.0±1.6	0.85			5.5±0.8			
	12-02-14	-23.5±0.9	213.2±1.5	0.44			5.4±1.9	8.4±1.3	480 ⁺¹³⁰ ₋₁₀₀	280 ⁺²⁸⁰ ₋₁₄₀
	12-09-14	-23.5±1.5	207.9±2.5	0.68			3.8±1.9			
	12-16-14	-25.4±1.5	206.8±2.5	0.69			4.0±2.0			
	01-11-15	-23.7±0.8	205.5±2.8	0.35				7.6±1.1		
	01-15-15	-23.5±1.1	212.2±1.4	0.87			4.0±0.6			
	01-26-15	-23.8±1.5	211.0±2.5	0.71			2.9±1.5			
	03-27-15	-24.8±1.2	211.1±1.2	0.91			4.6±0.7			
	03-29-15	-25.7±1.6	211.1±2.4	0.75			5.6±1.1			
	04-01-15	-22.2±0.7	217.4±6.1	0.18				8.5 ^{+10.1} _{-2.1}		
	04-05-15	-23.4±1.6	215.9±2.4	0.75			3.6±0.7			
	04-19-15	-24.7±1.3	215.2±1.6	0.86			5.3±1.0			
	04-21-15	-24.3±1.7	215.4±2.4	0.80			4.4±0.8			
	04-26-15	-23.9±1.3	215.7±1.5	0.90			4.1±0.6			
	05-05-15	-23.7±0.5	214.4±1.0	0.92	4.3±0.6	3.6±0.5	5.7±0.8	10.5±1.6	509 ⁺⁴⁴ ₋₄₀	270 ⁺¹⁰⁰ ₋₇₀
	Average	-23.9±1.3	210.7±3.4							
<i>Marduk</i> <i>Fluctus</i> AB		-21 to -29	210 to 215							
	11-18-13	-45.3±1.1	214.9±1.0	0.69			2.2±0.8	2.2±0.3	640 ⁺²⁵⁰ ₋₁₈₀	47 ⁺³⁸ ₋₂₁
	01-26-15	-48.6±1.1	219.4±2.0	0.54	81±12		56±9		1180 ⁺¹³⁰ ₋₁₂₀	950±60
	03-27-15	-50.0±1.9	219.4±2.3	0.64			15.5±3.0			
	03-29-15	-49.6±1.7	223.8±2.5	0.61			13.6±2.7			
	03-31-15	-50.0±0.9	224.5±2.3	0.26			6.7 ^{+3.4} _{-1.0}	12.3 ^{+9.2} _{-2.7}	740 ⁺¹³⁰ ₋₁₁₀	172 ⁺⁶⁰ ₋₄₄
	04-05-15	-47.7±1.2	223.7±2.0	0.57	120±18	11.4±2.5	68±11		1290 ⁺¹²⁰ ₋₁₁₀	1251±34
	04-17-15	-50.4±2.1	224.2±2.0	0.16			52 ^{+∞} ₋₂₃			
	04-19-15	-50.0±1.9	224.4±3.6	0.57			36±7			
	04-21-15	-49.7±1.9	223.3±2.7	0.61			21.8±4.3			
	04-26-15	-49.6±1.9	223.7±2.9	0.62			18.5±3.6			
	05-05-15	-48.4±2.1	222.3±1.1	0.66						
	Average	-48.8±1.4	221.3±2.8							
		-49 to -54	217-221							
<i>Kurdalagon</i> <i>Patara</i> AC	08-20-13	17.0±0.7	226.0±2.4	0.61			2.9±1.4	6.1±0.9	400 ⁺¹¹⁰ ₋₉₀	340 ⁺⁴⁸⁰ ₋₂₀₀
	08-23-13	18.2±1.1	221.8±2.7	0.48				5.9±0.9		

<i>Susanoo/Muhungu</i>										
<i>Paterae</i>										
AD	11-18-13	21.5±1.1	218.2±1.0	0.92	0.6±0.1	1.8±0.3	3.8±0.7	7.8±1.2	355 ⁺¹⁵ ₋₁₄	830 ⁺²⁹⁰ ₋₂₁₀
	12-04-13	20.0±1.9	221.2±2.2	0.89			1.3±0.7			
	12-13-13	18.9±2.0	220.8±2.1	0.93			1.1±0.6			
	02-08-14	18.4±1.2	225.7±1.3	0.63			1.6±0.6	1.8±0.3	610 ⁺²²⁰ ₋₁₆₀	39 ⁺³⁰ ₋₁₇
	10-31-14	20.6±0.8	220.6±1.0	0.85				1.1±0.5		
	05-05-15	16.6±1.0	223.3±1.4	0.94			0.5±0.2	0.9±0.3	440 ⁺¹⁵⁰ ₋₁₁₀	35 ⁺⁷⁶ ₋₂₄
	Average	18.8±1.6	221.9±2.4							
		<i>22.5</i>	<i>220</i>							
		<i>17.5</i>	<i>218</i>							
	08-29-13	29.6±1.7	225.7±9.2	0.15			>500			
	08-30-13	29.1±1.7	227.2±6.1	0.14			390 ⁺⁸²⁰ ₋₂₀₀			
	09-01-13	29.1±1.6	226.9±2.6	0.72			73±11			
	09-03-13	28.6±1.5	227.5±1.8	0.85			27.0±4.1			
	09-05-13	29.5±1.6	227.6±3.9	0.47			19.8±4.7			
201308C	09-10-13	28.4±1.5	228.0±1.6	0.88			12.4±1.9			
	11-18-13	29.4±0.9	228.2±0.5	0.87	1.2±0.2	2.4±0.4	3.0±0.5	4.4±0.7	486 ⁺³⁰ ₋₂₈	150 ⁺⁴³ ₋₃₃
	02-08-14	29.2±1.0	234.5±1.2	0.68			1.6±0.4	1.8±0.3	620 ⁺¹⁶⁰ ₋₁₃₀	40 ⁺¹⁸ ₋₁₂
	10-31-14	31.5±0.9	231.4±1.0	0.83				1.8±0.3		
	12-02-14	27.4±0.8	230.3±1.4	0.64			3.0±0.5	2.5±0.4	810 ⁺¹⁷⁰ ₋₁₄₀	50.2 ^{+4.9} _{-4.5}
	05-05-15	28.1±0.7	232.4±1.1	0.84			1.0±0.4	1.5±0.3	520 ⁺¹⁸⁰ ₋₁₃₀	41 ⁺⁵¹ ₋₂₃
	Average	29.0±1.0	229.8±2.5							
	12-04-13	21.3±1.7	232.1±2.4	0.81			5.0±0.8			
	12-06-13	20.2±1.6	234.7±2.4	0.74			5.4±1.0			
	12-13-13	22.3±1.1	233.5±1.1	0.92			4.6±0.7			
	Average	21.4±0.8	233.5±1.2							
<i>East</i>										
<i>Girru</i>										
AF	11-18-13	-57.7±1.9	237.1±2.3	0.52				4.0±0.6		
	Average	-57.7±1.9	237.1±2.3							
AG	03-27-15	-11.8±1.1	243.2±1.5	0.85			7.6±1.1			
	03-29-15	-12.1±1.1	245.4±1.2	0.98			6.5±1.0			
	03-31-15	-11.4±0.4	248.7±1.3	0.70		3.1±0.5	6.2±0.9	14.9±2.2	392 ⁺²⁸ ₋₂₆	930 ⁺⁴⁴⁰ ₋₃₀₀
	04-05-15	-11.3±1.2	245.4±1.2	0.98			5.3±0.8			
	04-21-15	-12.1±1.2	244.6±1.2	0.98			4.1±0.6			
	04-26-15	-11.8±1.6	244.4±2.4	0.77			3.3±0.6			
	05-05-15	-11.1±0.6	245.3±0.8	0.84			3.7±0.5	11.2±1.7	337 ⁺³⁵ ₋₃₂	1400 ⁺¹¹⁰⁰ ₋₆₀₀
	Average	-11.5±0.4	245.4±1.5							
<i>Pullan</i>										
<i>Patera</i>										
AH		<i>-12</i>	<i>243.5</i>							
	10-22-14	65.1±3.5	245.6±12.0	0.34			57±19			

<i>Chors</i> <i>Patara</i>	10-24-14	65.1±3.4	245.3±4.3	0.41	35±8 23.0±3.5 7.4±1.1 13.9±2.1 3.0±1.5	398 ⁺⁴³ ₋₃₉	3100 ⁺¹⁸⁰⁰ ₋₁₂₀₀
	10-31-14	66.4±2.6	243.8±1.2	0.42		440 ⁺⁷⁰ ₋₆₀	590 ⁺⁴⁰⁰ ₋₂₄₀
	12-02-14	63.0±1.0	248.5±1.5	0.41			
	03-31-15	66.3±1.6	254.5±4.7	0.33			
	Average	64.8±1.2	246.7±3.7				
	<i>68.5</i>	<i>250±2</i>					
<i>Pele</i>	08-20-13	-17.4±0.4	255.1±1.6	0.89	2.1±0.5	480 ⁺¹¹⁰ ₋₉₀	108 ⁺⁸⁹ ₋₆₉
	11-18-13	-18.1±0.9	251.6±0.8	0.85	2.7±0.8	430 ⁺²⁵ ₋₂₃	173 ⁺⁶³ ₋₄₆
	02-08-14	-17.6±0.6	257.3±0.4	0.91	2.2±0.3	630 ⁺¹³⁰ ₋₁₁₀	53 ⁺¹⁷ ₋₁₃
	10-31-14	-18.1±0.7	253.1±0.4	0.94	2.7±0.4	580 ⁺¹²⁰ ₋₁₀₀	78 ⁺³⁰ ₋₂₂
	12-02-14	-20.3±1.6	253.6±0.5	0.87	3.4±0.5	458 ⁺²⁷ ₋₂₅	191 ⁺⁵⁶ ₋₄₃
	01-26-15	-19.2±2.0	255.2±2.1	0.94	0.3±0.2		
	03-31-15	-19.4±0.7	260.2±2.5	0.80	1.1±0.4	574 ⁺⁴⁷ ₋₄₃	41 ⁺¹¹ ₋₉
	04-19-15	-16.7±1.2	258.2±3.6	0.47	7.0±3.5		
	05-05-15	-19.2±1.0	257.9±1.8	0.67	1.5±0.6		
	11-23-15	-17.3±0.7	256.7±2.9	0.31			
	Average	-18.1±1.0	255.0±2.5		4.1±0.7		
	<i>-19</i>	<i>256</i>					
	01-10-15	-59.8±2.1	264.3±4.4	0.43	55±12		
	01-12-15	-57.7±0.8	269.6±6.0	0.19	13.4 ^{+12.6} _{-3.2}	430 ⁺²⁰⁰ ₋₁₄₀	530 ⁺⁴⁸⁰ ₋₂₅₀
<i>Mithra</i> <i>Patara</i>	01-15-15	-57.3±1.9	263.5±4.9	0.45	8.5±4.2		
	03-31-15	-58.3±0.9	266.9±1.8	0.48	3.1±0.5		
	Average	-58.1±0.9	266.2±2.4				
	<i>-59</i>	<i>266.5</i>					
	02-08-14	-38.6±0.3	289.5±0.4	0.75	15.9±2.4	570 ⁺⁸⁰ ₋₇₀	430 ⁺¹⁴⁰ ₋₁₀₀
	02-10-14	-38.3±0.3	290.6±0.4	0.71	17.6±2.6	561 ⁺⁵⁰ ₋₄₆	550 ⁺¹⁵⁰ ₋₁₂₀
	03-12-14	-42.2±1.9	292.4±2.2	0.73	7.9±1.5		
	10-31-14	-37.9±1.0	286.5±1.8	0.59	4.7±0.7	850 ⁺¹⁶⁰ ₋₁₃₀	69.8 ^{+3.2} _{-3.1}
	12-02-14	-37.0±0.9	289.1±1.0	0.77	1.9±0.3		
	03-31-15	-37.0±1.0	293.6±0.8	0.79	1.1±0.2	590±60	40 ⁺¹¹ ₋₉
	04-02-15	-38.4±1.1	290.6±2.7	0.54	2.5±0.5		
	12-25-15	-38.8±0.5	285.9±1.6	0.56	4.3±0.6	521 ⁺³⁹ ₋₃₆	320 ⁺¹⁰⁰ ₋₇₀
	Average	-38.4±1.5	290.0±2.4		7.1±1.1	12.1±1.8	
	<i>-41</i>	<i>287</i>					
<i>PV59</i> <i>AL</i>	11-18-13	-56.8±1.4	279.7±4.7	0.32	2.7±1.4		
	12-06-13	-58.0±2.0	285.7±3.1	0.52	7.1±3.6		
	02-10-14	-56.1±1.0	294.0±1.5	0.52	4.0±0.6		
	10-31-14	-56.0±1.4	281.1±1.9	0.44	5.6±1.4	630 ⁺¹⁵⁰ ₋₁₂₀	119 ⁺⁴⁷ ₋₃₄
	12-02-14	-60.0±1.1	284.1±1.3	0.50	5.4±1.2	720 ⁺¹⁷⁰ ₋₁₄₀	89 ⁺²¹ ₋₁₇
	03-31-15	-57.5±2.9	295.2±0.8	0.54	3.2±1.1	890 ⁺¹¹⁰ ₋₁₀₀	63.1 ^{+4.6} _{-4.3}
	11-23-15	-58.3±1.7	285.3±2.5	0.39	3.3±0.5	470 ⁺¹⁴⁰ ₋₁₁₀	250 ⁺²⁸⁰ ₋₁₃₀
	Average	-58.1±1.7	285.3±2.5		7.0±1.1		

<i>N Lerna</i> <i>Regio</i>	12-25-15	-56.6±1.0	290.6±2.4	0.42					3.1±1.1	4.3±0.6	510 ⁺¹⁶⁰ ₋₁₂₀	120 ⁺¹²⁰ ₋₆₀
	Average	-57.3±1.2	288.8±5.3									
<i>Amaterasu</i> <i>Patera</i>	12-25-15	39.4±0.8	304.3±1.1	0.71	16.3±2.4	28.0±4.2	43±6	108±16			412 ⁺²³ ₋₂₂	5300 ⁺¹⁹⁰⁰ ₋₁₄₀₀
	Average	39.4±0.8	304.3±1.1									
<i>AN</i>	08-15-13	38±1	306.5±2									
	08-15-13	-40.5±2.2	305.5±2.6	0.60	500±80		320±80				1230 ⁺¹⁵⁰ ₋₁₃₀	5550 ⁺⁵³⁰ ₋₄₉₀
<i>AN</i>	08-20-13	-40.1±1.4	302.1±1.4	0.70	4.0±1.9		23.0±3.5				560 ⁺¹⁰⁰ ₋₈₀	750 ⁺⁶⁰⁰ ₋₃₆₀
	08-22-13	-39.3±1.8	305.4±1.8	0.74			21.0±3.2	35±5			460 ⁺⁸⁰ ₋₅₀	1380 ⁺⁷⁵⁰ ₋₄₉₀
<i>AN</i>	09-07-13	-41.0±1.9	304.8±2.9	0.66			7.7±1.5					
	11-29-13	-42.1±2.1	304.9±2.1	0.74			4.3±0.6					
<i>AN</i>	12-15-13	-39.7±1.8	303.0±2.3	0.73			2.9±1.4					
	02-10-14	-37.8±0.4	307.9±1.1	0.78		3.5±0.5	3.3±0.5	2.6±0.4			860 ⁺¹¹⁰ ₋₁₀₀	54.1 ^{+3.1} _{-2.9}
<i>AN</i>	03-10-14	-41.9±1.6	300.2±3.8	0.55			5.2±2.6					
	03-12-14	-39.0±1.9	309.9±2.2	0.77			2.7±1.4					
<i>AN</i>	03-28-14	-37.2±1.6	306.0±2.5	0.68			4.9±1.0					
	01-12-15	-33.7±1.4	304.9±1.5	0.69			1.9±0.3	2.0±0.3			690 ⁺¹⁵⁰ ₋₁₂₀	40 ⁺¹⁰ ₋₈
<i>AN</i>	03-31-15	-37.4±1.1	307.2±1.0	0.76		2.8±0.4	1.6±0.4	1.0±0.4			940±60	29.3±0.8
	04-02-15	-39.0±2.9	308.3±1.2	0.66			2.2±0.8	1.3±0.5			680 ⁺²⁹⁰ ₋₂₀₀	29 ⁺¹⁵ ₋₁₀
<i>AN</i>	04-09-15	-39.1±1.9	309.0±2.2	0.76			5.5±0.8					
	Average	-38.7±2.0	306.0±2.6									
<i>Rarog</i> <i>Patera</i>		-42	304									
	08-15-13	-55.2±2.1	307.5±2.1	0.47	92±15		270±70				720 ⁺¹⁰⁰ ₋₉₀	4800 ⁺²⁸⁰⁰ ₋₁₈₀₀
<i>AO</i>	08-20-13	-53.0±2.1	304.0±3.0	0.54	4.9±2.4		40±6				530 ⁺⁷⁰ ₋₅₀	1500 ⁺¹²⁰⁰ ₋₇₀₀
	08-22-13	-55.6±1.7	309.5±1.7	0.53	9.3±2.6		50±8	69±11			577 ⁺⁴³ ₋₄₀	1580 ⁺³⁷⁰ ₋₃₀₀
<i>AO</i>	08-29-13	-55.7±2.5	309.2±3.0	0.56			31±6					
	09-05-13	-55.0±2.5	307.1±4.6	0.53			14.6±3.1					
<i>AO</i>	09-07-13	-56.2±2.5	307.5±4.3	0.49			17.1±3.8					
	04-02-15	-57.9±0.8	305.0±1.9	0.44				2.8±0.4				
<i>AO</i>	Average	-56.0±1.3	307.2±1.8									
<i>Heno</i> <i>Patera</i>		-57±1	309-314									
	08-15-13	12.0±1.4	309.0±1.4	0.87	7.7±1.4		60±10				550 ⁺³³ ₋₃₁	2000 ⁺⁷⁰⁰ ₋₅₀₀
<i>AP</i>	08-20-13	11.9±0.8	308.7±1.2	0.83	13.0±3.3		133±27	200±33			514 ⁺²⁹ ₋₂₇	5800 ⁺¹⁴⁰⁰ ₋₁₀₀₀
	08-22-13	11.7±1.2	308.4±1.0	0.97	7.5±1.3		136±20	205±34			470±16	7600 ⁺¹⁶⁰⁰ ₋₁₃₀₀
<i>AP</i>	08-29-13	11.3±1.4	307.1±1.4	0.98			126±19					
	09-03-13	10.9±1.5	308.4±4.7	0.38			50±14					
<i>AP</i>	09-05-13	11.3±1.4	307.4±1.6	0.91			73±11					
	09-07-13	12.0±1.4	307.0±1.7	0.87			84±13					
<i>AP</i>	09-09-13	10.2±1.5	310.3±5.0	0.27			37±19					

<i>Tol-Ava</i> <i>Patera</i>	12-06-14	1.0±1.2	327.0±1.2	1.00	0.9±0.4 1.0±0.5
	01-14-15	0.6±1.1	327.3±1.1	1.00	
	Average	0.7±0.7	326.2±1.2		
<i>Fuchi</i> <i>Patera</i>	02-10-14	28.3±1.1	328.7±1.1	0.86	1.1±0.4
	Average	28.3±1.1	328.7±1.1		
AS	12-02-14	-50.0±1.1	324.9±3.2	0.42	11.7±1.7 7.2±1.1 2.1±0.4 2.5±0.4 4.0±0.6 540 ⁺⁷⁰ ₋₆₀ 160 ⁺⁸⁰ ₋₅₀ 99 ⁺³⁸ ₋₂₇
	12-06-14	-47.9±2.0	327.8±2.1	0.67	
	12-25-15	-46.0±0.9	329.3±1.4	0.69	
	Average	-47.8±1.6	327.9±1.8		
<i>PV170</i> AT	02-10-14	44.2±1.7	336.4±2.4	0.66	1.0±0.5 1.5±0.2
	01-12-15	44.6±2.0	331.7±2.1	0.71	
	Average	44.3±1.3	334.0±2.3		
<i>Surt</i> AU	10-30-14	38.1±0.9	358.5±2.4	0.62	2.4±0.7 4.4±0.7 3.1±0.5 1.2±0.4 440 ⁺¹⁰⁰ ₋₈₀ 190 ⁺²¹⁰ ₋₁₆₀
	01-12-15	41.8±0.8	352.9±0.8	0.72	
	04-02-15	41.7±1.2	357.7±1.7	0.71	
	Average	40.5±1.7	355.2±2.4		
<i>Pfu1063</i> AV	04-02-15	-42.1±1.5	359.6±1.6	0.69	1.0±0.4
	Average	-42.1±1.5	359.6±1.6		
<i>Paive</i> <i>Patera</i>		-46±1	358.5		

NOTES:

- (1) Data from 2013 Aug 15, 20, and 22 were previously published in de Pater et al. (2014a), and data from 2013 Aug 29 through Sep were previously published in de Kleer et al. (2014). Observations of Pillan Patera have been previously published in de Pater et al. (2016a). Flux densities and temperatures re-derived in this work are consistent with the published values.
- (2) Uncertainties for close pairs of hot spots may be higher than quoted if emission arises from both sources. These include Kanehekili Fluctus/Janus Patera, and Sigurd/Itzamna Paterae.
- (3) The hot spot at Rarog Patera may cover two unresolved hot spots; the locations are consistent with Sengen and Rarog Paterae.
- (4) The locations of the hot spots identified as Susanoo/Mulungu Paterae and Gabija/Sethlaus Paterae are consistent with either source.
- (5) On 03-31-15 and 04-01-15, the detected emission attributed to Kurdalagon Patera and Gabija/Sethlaus Paterae may include a component from the other of these two sources.
- (6) Locations of surface features from Williams et al. (2011a; 2011b)

Appendix B

Thermal timelines for the Loki Patera dual-wave resurfacing model

The temperature and lava age maps of Loki Patera derived from the LBTI occultation observations (Chapter 8) are at significantly higher spatial resolution than all previous ground-based observations of this volcanic site. To facilitate comparison with past observations and models, I show here thermal timelines of the emission from the entire patera surface in the dual-wave resurfacing model presented in Chapter 8.

The total thermal power produced by the patera as a function of days since the start of resurfacing is shown in Figure B.1. Figure B.2 shows the single-wavelength thermal power over the same range of dates for example near-infrared wavelengths. Figure B.3 shows the timelines for the specific wavelengths that correspond to the centers of the L-prime and Ms filters (3.8 and 4.7 μm), and compares with data taken during the 2014 brightening (de Kleer & de Pater 2017), which is the event probed by the LBT observations (de Kleer et al. 2017). This figure also compares with the model timelines for the standard single-wave overturn on an elliptical lake (Matson et al. 2006; de Kleer & de Pater 2017), assuming an overturn velocity of 1.2 km/day.

Although the specific shape of the thermal timeline varies between the single- and dual-phase overturn models, there are broad-scale similarities between the model predictions. The time to reach peak brightness is 100-150 days for single-wave models, and 130-200 days for the dual-phase model fit to the LBTI observations. However, the rate of brightening differs between the models: for a single-wave model and an elliptical patera geometry, the brightening is the most rapid at the start and later slows, while the dual-wave model and realistic patera geometry show more gradual brightening early on, and a more complex brightness evolution throughout the event. The peak power in the dual-phase model (19 TW) is also somewhat higher than the Matson et al. (2006) model prediction (15-16 TW).

The comparison with data (Figure B.3) demonstrates that the data from the 2014 event are not at sufficiently high temporal resolution during key phases of the overturn to distinguish between the models. Future high-cadence observations of Loki Patera during the brightening phase, and constraints on the exact time of brightening initiation in particular, could differentiate between these models. However, the details of the resurfacing at Loki

Patera may differ between each brightening episode, and results from observations during future brightening episodes are not necessarily applicable to past activity at this highly-time-variable patera.

The total brightness of the patera increases gradually over the first 100+ days of the brightening episode as a larger and larger area of old, cool crust has been replaced by new, hot crust. Observations from Keck and Gemini N (de Pater et al. 2017; de Kleer & de Pater 2017) show that the peak of the emission from the patera arises from the eastern side during the bright phase, while bright emission is very rarely localized to the northern point of the patera despite indications from the LBT modeling that resurfacing initiates there. This apparent discrepancy can be understood from the relatively slow brightening of the patera at the beginning of a resurfacing event. Initially, the emission from the small resurfaced area in the north is not large enough to dominate the emission from the patera as a whole. A few months into the event, when a sufficiently large area of the patera has been resurfaced, the resurfacing wave has reached the eastern side of the patera and the position as determined by adaptive optics imaging is therefore in the northeast or east. The model then predicts that the location of peak emission will move down the east side of the patera, as is seen in Keck data from past brightening episodes (de Pater et al. 2017).

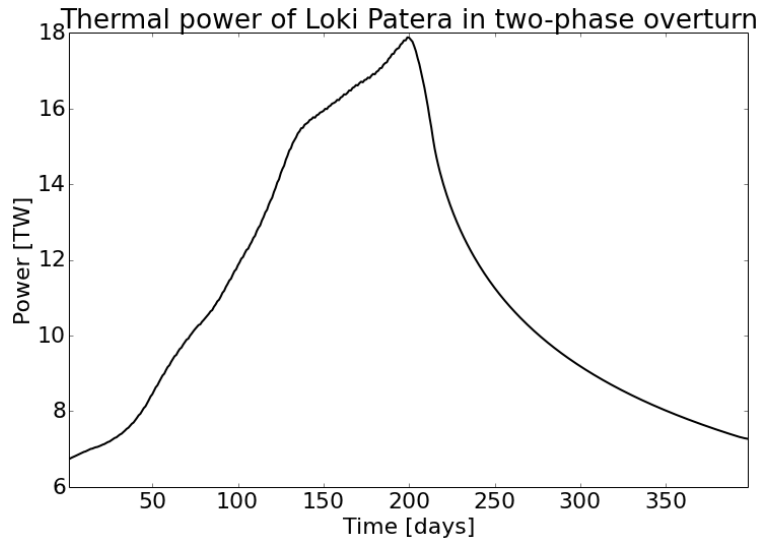


Figure B.1: Thermal intensity of Loki Patera as a function of time for the dual-wave model described in Chapter 8. The starting time of zero days represents the first day of the overturn.

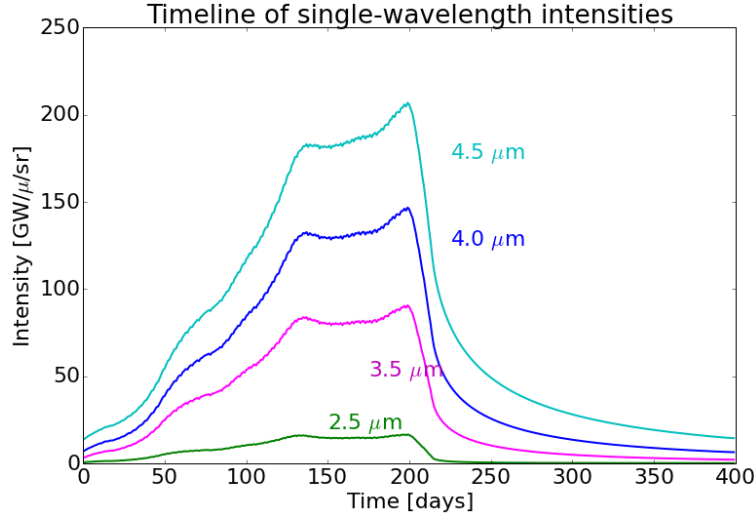


Figure B.2: Thermal intensity of Loki Patera as a function of time for the dual-wave model described in Chapter 8, shown at characteristic near-infrared wavelengths. The starting time of zero days represents the first day of the overturn.

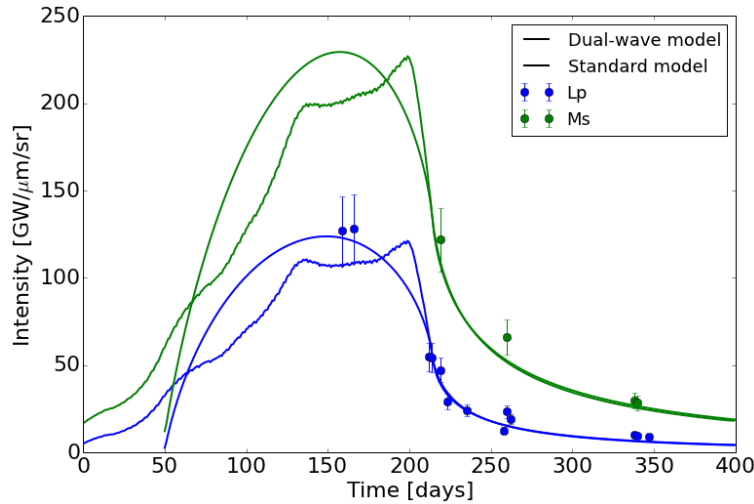


Figure B.3: Thermal timelines at wavelengths corresponding to the centers of the Lp and Ms filters (3.8 and 4.7 μm respectively), for the standard single-wave overturn model (Chapter 7) and the dual-wave model (Chapter 8). Adaptive optics data from the Keck and Gemini N telescopes during the 2014 overturn are plotted for comparison. In the plot, the dual-wave model overturn starts 50 days before the standard model overturn; these start times are chosen to match the data.