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(CO₂) Production Rates of Comets Observed by the Near Earth Object Wide-Field
Infrared Survey Explorer (NEOWISE) Reactivated Mission

A dissertation submitted in partial satisfaction
of the requirements for the degree
Doctor of Philosophy in Geophysics and Space Physics

by

Dave Gerald Milewski

2024

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ABSTRACT OF THE DISSERTATION

Activity in Comets and Asteroids and the Carbon Monoxide (CO) and Carbon Dioxide (CO₂) Production Rates of Comets Observed by the Near Earth Object Wide-Field Infrared Survey Explorer (NEOWISE) Reactivated Mission

by

Dave Gerald Milewski

Doctor of Philosophy in Geophysics and Space Physics

University of California, Los Angeles, 2024

Professor David C. Jewitt, Chair

Active solar system small bodies are investigated from the presently operational NEOWISE space-based mission with follow-up from ground-based observatories. The latter include the Keck, JCMT, ATLAS, and C28 telescopes. The primary focus of this work is to quantify the gas and dust production rates of active bodies in the solar system in contemporaneous, if not closely-temporal observational arcs over different stages of their orbital evolution. Specifically, the quantification of the gaseous species carbon monoxide (CO) and carbon dioxide (CO₂) as well as dust are performed. Few measurements of these gases exist in the scientific literature and quantifying CO₂ is essentially impossible from the ground due to severe telluric contamination from Earth's CO₂-rich atmosphere. The small fraction ($\sim 0.04\%$) of CO₂ in Earth's atmosphere is significant enough to 'blind' ground-based telescopes from determining whether or not potential detection(s) of CO₂ are coming from these active bodies. Other follow-up results are presented regarding the characterization of activity in comets and asteroids which imply new processes are involved when compared to long-standing historical

models such as Whipple (1950, 1951) in our understanding of why small bodies suddenly become active in the solar system and elsewhere. This study also investigates the long-term (multi-year) monitoring of the morphological evolution of these bodies that are ultimately subject to perhaps the major source of activity, being the influence of continual irradiation from the Sun.

Work in the last two decades (e.g., Ootsubo et al. 2012; Jewitt et al. 2015a; Bauer et al. 2015, 2017, 2021; Bouziani & Jewitt 2022) and this Dissertation demonstrates the importance of characterizing the influence of gas and dust in observed activity for these objects. With further investigations of activity in distant small bodies that began in the 1990s such as 29P/Schwassmann-Wachmann 1 (SW1) by Senay and Jewitt (1994) and continuing in 1997 when Comet C/1995 O1 (Hale-Bopp) came to perihelion, the scientific community became further aware of the major significance of CO’s role in activity observed in comets. A few decades later, in 2020, the emergence and discovery of comet C/2020 F3 (NEOWISE) was the most recent bright comet to become active at the naked eye level in the northern hemisphere. This has led to further investigation of the drivers of activity in solar system small bodies, and to more frequent observations of these objects by both the amateur and scientific communities alike. Should CO and CO₂ be the culprits and ‘major suspects’, the work presented in this Dissertation posit that we must characterize the activity, especially at multiple stages in their evolutionary journey.

We use previous terminology and metrics such as $Af\rho$ as a proxy to quantify the dust production and describe the overall nature of ‘activity’ that has been commonplace in the literature first described by A’Hearn et al. (1984). $Af\rho$ has been used as a standard metric for measuring the dust production of active bodies with those being ~ 1000 cm or more are thus considered to be ‘hyperactive’. In this Dissertation, the objects investigated have been found to be active at times and regions where previous models would indicate activity must be caused by a process other than the sublimation of water-ice. Further, the objects investigated in this study have $Af\rho$ as low as several hundred cm (minimum < 277 ; C/2014

B1 (Schwartz) for UT 2016 November) and as high as several thousand cm (maximum 6370; C/2017 K2 (Pan-STARRS) for UT 2022 August). Gas production rates, denoted by Q in units of molecules per second (mol s^{-1}) have all been found between $\sim 10^{27}$ and $\sim 10^{29}$ mol s^{-1} , respectively, if one assumes the excess emission is attributed to either all CO or all CO₂. Previous values of Q (specifically with regards to CO and/or CO₂; e.g., Q_{CO} & Q_{CO_2}) that exist in the literature for comets have found most to be on the order of $\sim 10^{25}$ and $\sim 10^{26}$ mol s^{-1} with a few (rare) measurements of these species on the order of $\sim 10^{27}$ to 10^{28} mol s^{-1} depending on the measurement technique used and the part of the electromagnetic spectrum where measurements have been performed.

This work presents a subset of the many NEOWISE observed comets with specific focus placed on the exceptionally active comets, C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), C/2010 U3 (Boattini), and 29P/Schwassmann-Wachmann 1 (SW1). Comets observed by NEOWISE typically first appear active at ~ 5 or 6 astronomical units (au). Most objects beyond this distance evade detection by current software algorithms as they appear too faint (see Chapter 2). All objects studied here were found to be active at distances up to about double (e.g., ~ 12 au for K2) the aforementioned detection distance of around 5 to 6 au. For this reason, K2 was studied from 2019 to 2022 as it was inbound. With SW1 being a short-period comet (SPC) with an atypical ($\sim$ circular) orbit residing in the near-vicinity of the outer solar system, it was possible to investigate over the years 2014 to 2022 using the same instrumentation and measurement techniques in Chapter 3. Moreover, all observational epochs are used where these objects appear in the co-added data that boost the signal-to-noise allowing for further analysis to be performed.

The dissertation of Dave Gerald Milewski is approved.

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University of California, Los Angeles

2024

For my family, friends, teachers, mentors, and anyone I have come into contact with that has taught me the value of perseverance and the continual pursuit of knowledge.

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TABLE OF CONTENTS

1	Introduction	1
1.1	Background	1
1.1.1	The History of Cometary and Small-Body Activity in the Solar System	1
1.1.2	Outline of the Dissertation and Scientific Objectives	8
1.2	The Origins of Active Bodies (Comets and Asteroids) in the Solar System and Their Source Regions	10
1.2.1	Comets and ‘Hyperactive’ Comets	11
1.2.2	The ‘Active Asteroids’ and Our Current Understanding of Solar System Activity	13
1.3	Observations of Active Bodies by Spacecraft	15
1.3.1	Predecessor Spacecraft Observations of Active Bodies	15
1.3.2	The Wide-field Infrared Survey Explorer (WISE) and Near-Earth Object (NEOWISE) Reactivated Mission	21
1.3.3	NEOWISE Observations and Data Collection	25
1.3.4	NEOWISE Methods and Aperture Photometry	26
1.3.5	NEOWISE Dust and Gas Production Rates	27
1.3.6	NEOWISE Results	31
	References	35
2	NEOWISE Observations of Distant Active Long-period Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini) . . .	41
2.1	Overview	41

2.2	Introduction	42
2.2.1	Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini)	43
2.3	Observations and Data Collection	44
2.4	Methods and Aperture Photometry	47
2.4.1	Methods	47
2.4.2	Aperture Photometry	48
2.5	Results and Discussion	49
2.5.1	Dust Production Rates	49
2.5.2	CO and CO ₂ Production Rates	50
2.5.3	Simultaneous Observations of C/2017 K2 (Pan-STARRS) by the James Clerk Maxwell Telescope (JCMT) and the NEOWISE Satellite on UT 2021 April 1	52
2.5.4	Evolution of Cometary Activity with Heliocentric Distance r_H	56
2.6	Summary	58
2.7	Additional NEOWISE Spectral Energy Distribution (SED) Diagrams	61
	References	69
3	Activity of Dust and Gas Emission of Active Centaur 29P-Schwassmann-Wachmann 1 (SW1) Observed By The NEOWISE Reactivated Mission . .	73
3.1	Overview	73
3.2	Introduction	74
3.2.1	NEOWISE (Infrared) Data	76
3.2.2	ATLAS (Visual) Data	77

3.3	Methods and Analysis	79
3.4	Discussion	85
3.4.1	Dust and Gas Activity and Comparison With Previous Studies	85
3.4.2	The Speed of the Dust	96
3.5	Summary	99
3.6	Additional NEOWISE Spectral Energy Distribution (SED) Diagrams	100
	References	115
4	Concluding Remarks	119
4.1	NEOWISE Observations of Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS) and C/2010 U3 (Boattini)	119
4.1.1	Hyperactive Comets Summary	119
4.1.2	Future Investigations of Hyperactive Comets	121
4.1.3	Future Observational Facilities	122
4.2	Distant Active Centaur 29P/SW1	123
4.2.1	Activity of 29P/SW1 Summary	123
4.2.2	Future Observations of 29P/SW1 and Monitoring Outbursts	125
4.3	Conclusions	126
	References	130

LIST OF FIGURES

1.1	Halley's Comet Throughout History	3
1.2	Examples of Two Spectacular Comets C/1995 O1 (Hale-Bopp) and C/2010 F3 (NEOWISE)	7
1.3	Distant Oort Cloud Comet C/2017 K2 (Pan-STARRS)	9
1.4	Suspected Cometary Populations Flow Diagram	11
1.5	Active Asteroid P/2016 G1 (Pan-STARRS) Absolute Magnitude H Versus Day Of Year (DOY) Diagram	15
1.6	Spitzer Space Telescope (SST) Observed Comets - $3.6\ \mu\text{m}$ and $4.5\ \mu\text{m}$ Flux Measurements Versus Heliocentric Distance r_H	19
1.7	AKARI Ratios of Q_{CO} to Q_{CO_2} Versus Heliocentric Distance r_H	20
1.8	Discovery Images of WISE/NEOWISE Comets Shown in 3-Colors	24
1.9	WISE Spectral Energy Distribution (SED) Diagram for Comet C/2009 P1 (Garradd)	29
1.10	WISE/NEOWISE Observed Comets - Gas Production Measurements LPCs and SPCs Versus Heliocentric Distance (r_H)	33
1.11	NEOWISE (Year 1; 2013-2014) Observed Comets - Gas Production Measurements for LPCs and SPCs Versus Heliocentric Distance (r_H)	34
2.1	Hyperactive NEOWISE Observed Comets Shown in 3-Colors	45
2.2	NEOWISE Spectral Energy Distribution (SED) Diagram for Hyperactive Comet C/2014 B1 (Schwartz).	51
2.3	Hyperactive NEOWISE Observed Comets Dust Production $Af\rho$ Versus Heliocentric Distance (r_H)	54

2.4	Hyperactive NEOWISE Observed Comets Gas Production Rates (Q_{CO_2}) Versus Heliocentric Distance (r_H)	55
2.5	Same as Figure 2.2 for Hyperactive Comet C/2017 K2 (Pan-STARRS).	61
2.6	Same as Figure 2.2 for Hyperactive Comet C/2017 K2 (Pan-STARRS).	62
2.7	Same as Figure 2.2 for Hyperactive Comet C/2017 K2 (Pan-STARRS).	63
2.8	Same as Figure 2.2 for Hyperactive Comet C/2017 K2 (Pan-STARRS).	64
2.9	Same as Figure 2.2 for Hyperactive Comet C/2017 K2 (Pan-STARRS).	65
2.10	Same as Figure 2.2 for Hyperactive Comet C/2017 K2 (Pan-STARRS).	66
2.11	Same as Figure 2.2 for Hyperactive Comet C/2017 K2 (Pan-STARRS).	67
2.12	Same as Figure 2.2 for Hyperactive Comet C/2017 K2 (Pan-STARRS).	68
3.1	NEOWISE 29P/SW1 Measured $W1$ and $W2$ Fluxes	82
3.2	NEOWISE Spectral Energy Distribution (SED) Diagrams for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1).	83
3.3	Evolution of Gas and Dust Production Rates for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1)	89
3.4	Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) Observed by NEOWISE Shown in 3-Colors	90
3.5	The 2020 July-September Dust Outburst Event Coverage of Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) Observed by NEOWISE (Infrared) and ATLAS (Visual)	91
3.6	The 2014-2022 Secular Lightcurves of Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) Observed by NEOWISE (Infrared) and ATLAS (Visual)	95
3.7	The Speed of Dust Measured for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) Observed by ATLAS (Visual)	97

3.8	NEOWISE Spectral Energy Distribution (SED) Diagram for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2014 Feb.	100
3.9	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2014 Aug.	101
3.10	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2016 Apr.	102
3.11	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2016 Sep.	103
3.12	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2017 May	104
3.13	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2017 Oct.	105
3.14	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2018 Jun.	106
3.15	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2018 Nov.	107
3.16	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2019 Jul.	108
3.17	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2019 Dec.	109
3.18	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2020 Aug.	110
3.19	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2021 Jan.	111

3.20	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2021 Sep.	112
3.21	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2022 Feb.	113
3.22	Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1) - 2022 Oct.	114

LIST OF TABLES

2.1	Orbital Elements for NEOWISE Observed Comets	43
2.2	Observation Geometry and Summary of Photometry for NEOWISE Observed Comets	46
3.1	Summary of Photometry and Flux Analysis for Comet 29P/Schwassmann-Wachmann 1 (SW1) from NEOWISE Data	81

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— Val McDermid

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and...

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...for *me*!

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Chapter 2 is adapted from the peer-reviewed paper titled "NEOWISE Observations of Distant Active Long-period Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini)" by Milewski et al. which has been published in the *Astronomical Journal* (Milewski, D. G. et al. 2024, *AJ*, Volume 167, Number 3, Article/Page Number 199. DOI: 10.3847/1538-3881/ad0cf4). Being the lead author, I performed searches for each of these objects in the individual and stacked data in addition to writing the codes for the photometry, data analysis, and led the research on these hyperactive comets. The co-authors Joseph R. Masiero, Jana Pittichová, Emily A. Kramer, Amy K. Mainzer, and James M. Bauer are all members of the NEOWISE Science Team and contributed to the data collection and quality assurance process, checking of my codes, analysis, results, and provided comments on the manuscript. This material is based upon work supported by the National Aeronautics and Space Administration under grant No. 80NSSC17K0407 issued through the NASA Education Minority University Research Education Project (MUREP) through the award of a NASA Harriett G. Jenkins Graduate Fellowship.

This publication makes use of data products from NEOWISE, which is a project of the University of Arizona and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration, funded by the Planetary Science Division of the National Aeronautics and Space Administration. This research has made use of the NASA/IPAC Infrared Science Archive, which is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology. This research made use of Photutils, an Astropy package for detection and photometry of astronomical sources (Bradley et al. 2022).

The Near-Earth Object Wide-field Infrared Survey Explorer Reactivation Mission (NEOWISE; Mainzer et al. 2014) is a NASA Planetary Science Division space-based survey to detect, track and characterize asteroids and comets, and to learn more about the popula-

tion of near-Earth objects, including those that could pose an impact hazard to the Earth. NEOWISE systematically images the sky at 3.4 and 4.6 μm , obtaining multiple independent observations on each location that enable detection of previously known and new solar system small bodies by virtue of their motion. Because it is an infrared survey, NEOWISE detects asteroid thermal emission and is equally sensitive to high and low albedo objects.

The Single-exposure Source Database is a compendium of position and flux information for source detections made on the individual NEOWISE 7.7 s *W1* and *W2* Single-exposure images. Because NEOWISE scanned the same region of the sky multiple times, the Single-exposure Database contains multiple, independent measurements of objects. Positions, magnitudes in the two NEOWISE bands, astrometric and photometric uncertainties, flags indicating measurement quality, the time of observations and associations with the AllWISE Source Catalog and 2MASS Point Source Catalog are presented for entries in the Database.

This dataset or service is made available by the Infrared Science Archive (IRSA) at IPAC, which is operated by the California Institute of Technology under contract with the National Aeronautics and Space Administration.

Chapter 3 is adapted from the publication to be submitted to the Astronomical Journal titled "Activity of Dust and Gas Emission of Active Centaur 29P/Schwassmann-Wachmann 1 (SW1) Observed By The NEOWISE Reactivated Mission", (Milewski, D. G. et al. 2024). Being the lead author, I looked for all instances of 29P/SW1 in the NEOWISE data including the individual and stacked data. Likewise as in Chapter 2, I performed the data analysis, and led the research specifically for this next Chapter on 29P/SW1. In addition, I had to find and compile all data of 29P/SW1 found in the ATLAS telescope project publicly released data from the years 2015 to 2022. In order to confirm that the *W1* and *W2* observations from NEOWISE taking place around UT 2020 August were indeed from an outburst, I

performed substantial follow-up by looking deeper into the ATLAS data (specifically between UT 2020 July to September when determining the outburst appeared to be a single event) and then used all the available data during that time frame to determine the speed of the expanding dust shell. To date, there are very few measurements (spanning several decades) of the dust ejection speed for 29P/SW1. This specific outburst event has not yet been published anywhere in the scientific community at the present time and reports by amateurs seem to have initially reported on this much later than it actually began. The co-authors Joseph R. Masiero, Jana Pittichová, and Amy K. Mainzer are all members of the NEOWISE Science Team. Masiero is the Deputy P.I. and Mainzer is the P.I. of NEOWISE Mission, respectively. The co-authors and contributed to the data collection and quality assurance process, analysis, results, and provided comments on the manuscript. This material is based upon work supported by the National Aeronautics and Space Administration under grant No. 80NSSC17K0407 issued through the NASA Education Minority University Research Education Project (MUREP) through the award of a NASA Harriett G. Jenkins Graduate Fellowship.

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VITA

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PUBLICATIONS

Milewski, D. G., Masiero, J. R., Pittichová, J., and Mainzer, A. K. (2024). Activity of Dust and Gas Emission of Active Centaur 29P/Schwassmann-Wachmann 1 (SW1) Observed By The NEOWISE Reactivated Mission. To be submitted to the Astronomical Journal (2024).

Milewski, D. G., Masiero, J. R., Pittichová, J., Kramer, E. A., Mainzer, A. K., and Bauer, J. M. (2024). NEOWISE Observations of Hyperactive Long-Period Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini). The Astronomical Journal (AJ), Volume 167, Number 3, Article/Page Number 199. DOI: 10.3847/1538-3881/ad0cf4. Published 08 February 2024.

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CHAPTER 1

Introduction

1.1 Background

1.1.1 The History of Cometary and Small-Body Activity in the Solar System

Throughout history, comets have been described as ‘mysterious visitors’ in various forms of text, artwork, and even oral tradition. We first consider the historical nature of comets in the context of the modern scientific understanding of comets. Much of what was known about comets throughout history comes from records kept by ancient peoples of Europe, the Middle East, and Asia. Chinese records extend Before the Common Era (BCE) while civilizations in Europe produced a shorter track record. Some of the records which have survived over the passage of thousands of years were later compared and contrasted, and ultimately linked (historically) to the same phenomena and objects experienced by people all around the world. It was only after scientific revolutions in the understanding the motions of planetary bodies in our solar system which came mostly due to the work of Johannes Kepler and Edmond Halley in describing the orbits and motions of such objects including cometary bodies.

Comets have been associated with omens, good fortune, disaster, the apocalypse, destiny, and spectacular coincidences in nature for millennia. One of the most well-known examples comes from historical accounts of the Battle of Hastings and the events leading up to the Norman conquest of England, occurring in 1066. Prior to this event, William the Conqueror had sought to reclaim his throne being held by King Harold II and changed the course of

history in Europe. In the spring of 1066, William the Conqueror amassed a rather large army to attack Harold II. Around this time, the emergence of a rather spectacular comet, appeared in the sky and was reported even beyond Europe. While William the Conqueror may have portrayed this event as a predictor of his subsequent victory, it spelled disaster and death for Harold II who died in battle, and the coronation of William took place on Christmas Day, 1066. The surviving artwork depicts a comet on the Bayeux Tapestry seen in Figure 1.1 (Top Left & Top Right) that summarized the events leading to the penultimate defeat of King Harold II by William the Conqueror.



Figure 1.1: Examples of Halley's Comet Throughout History - Top (Left): The events of the Battle of Hastings in 1066 seen on Bayeux Tapestry. (Right): A close-up of the comet seen on the Bayeux Tapestry. Credit: Images courtesy Anglo-Saxon Archaeology. Middle: Engraving depicting the 1682 apparition of Halley's Comet over Augsburg, Germany. Credit: Duluth News Tribune (Bob King) Bottom: Mark Twain portrait superimposed on an image of 1P/Halley from its 1986 apparition; image modified by D. Milewski

By another coincidence, 576 years later on December 25th, 1642, also in England, Sir Isaac Newton would be born. Newton contributed pioneering work in physics with the invention of calculus and most famously his monumental *Philosophiæ Naturalis Principia Mathematica* (Newton 1687). Ultimately, this work led to greater scientific understanding of the orbits of bodies in the solar system, the laws of gravity and physics, and a more complete account of the nature of planetary motion in the solar system. Another English astronomer and mathematician, Edmond Halley, also contributed to the *Principia* and to the modern understanding of comets and their orbits. Halley had used the *Principia* from Newton (1687), observations of the appearance of a comet in 1682 also seen by others around the world (see Figure 1.1, Middle Panel), and what was previously known from Johannes Kepler’s laws of planetary motion having been published several decades which culminated in the *Synopsis of the Astronomy of Comets* (Halley 1705). In this work, it was predicted that the same comet having been observed in 1682 would return again in 1758. Halley did not live long enough to see its return but he presciently noted that:

“If it should return, according to our predictions, about the year 1758, impartial posterity will not refuse to acknowledge that this was first discovered by an Englishman.”

— Edmond Halley

Coincidentally again, the date of December 25th would mark the first recovery of this comet which came on that date in the year 1758. The return of comet Halley was first reported by a farmer in Germany named Johann Georg Palitzsch. Surely enough, the work of Newton, Halley, and the scientific method remained triumphant in the end. This comet came to be known as 1P/Halley’s Comet, with its alphanumeric designation simply referring to the periodic nature of comets. 1P/Halley orbits the Sun in an elliptical orbit that takes roughly 75-76 years on average to complete. Being the first such (periodic) object to orbit in this fashion, it has been given the designation ‘1P’ and credited to the very person who determined its orbit. Likewise, many comets which are discovered today are also named in this fashion. The significance of Halley’s Comet and the story behind it marked a mon-

umental triumph for astronomy and the true birth of cometary science, as previous ideas had suggested comets only appeared once, to never return again. Historical records from other civilizations, later showed that the same object could be linked as far back in time as 240 BCE (Yeomans et al. 1986). Yeomans also provided ephemerides for the upcoming 1986 apparition of Halley's comet first successfully (re)-discovered and led by Englishman D. Jewitt along with E. Danielson (Jewitt et al. 1982). This would the stage for the arrival of "Halley's Armada" in 1986 and the first spacecraft observations of a comet.

While these are some of the more spectacular accounts of comets in history, other events such as Khan Temüjin (known in the west as Ghenghis Khan) marked his 1222 westward expansion of the Mongol Empire across Europe, even the sudden appearance of Halley's Comet in 1835, the birth of American author Mark Twain, as well as his death in 1910, which he seemingly eerily predicted one year earlier as Halley's Comet was making another return to the inner solar system. He famously said in 1909:

"I came in with Halley's Comet. It is coming again next year. The Almighty has said, no doubt, 'Now there are these two unaccountable freaks; they came in together, they must go out together.'"

— Mark Twain, 1909

Sure enough, one day after Halley's Comet had reached perihelion, Twain died of a massive heart attack, adding yet another account to the mysterious nature of comets. (Figure 1.1, Bottom Panel)

Several more recent accounts of public fascination with comets have occurred in the last several decades, especially in 1997, with the appearance C/1995 O1 (Hale-Bopp) (Figure 1.2, Left). It still remains memorable to many due to how spectacular it appeared in the sky and that it was visible to the naked eye for nearly a year and a half. However, Hale-Bopp did lead to some public misconception of its arrival causing mass hysteria about the apocalypse. Similarly, the 1910 apparition of 1P/Halley had been associated with poisonous gases causing widespread fear and panic. The worldwide COVID-19 pandemic in 2020 resulted in the

cease of operations for many ground-based telescopes on Earth which could have prevented potential discoveries of new objects. Luckily, a spacecraft had been in operation outside of Earth’s atmosphere since 2010 and first detected a new comet, of which was the first one since Hale-Bopp to be visible in the Northern Hemisphere due to its brightness. This comet, C/2020 F3 (NEOWISE) (Figure 1.2, Right) was credited to the name of the mission that had discovered it, of which this research was conducted alongside the NEOWISE Science Team.

It is also important to consider the appearance of both comets Hale-Bopp and NEOWISE side-by-side. The brightness of the comet nucleus in addition to the stunning blue ion tail has been linked to the presence of Carbon Monoxide (CO^+). Only as of the last few decades, Carbon Monoxide had been discovered as a constituent source of radio emission observed in the Orion Nebula in 1970 (Wilson, Jefferts, & Penzias 1970) that has long-standing implications for the detection of carbon monoxide for astronomical sources including protoplanetary disks, nebulae, as well as comets. The importance of CO (and later on) CO_2 species in comets began to take shape as early as the 1990s and continues into the present era. New models suggest the importance of CO in protoplanetary disks that are the initial stages of planet formation as well as estimation of the ages of these disks (Powell et al. 2022). As such, the importance of CO and CO_2 species in comets now present issues for long-standing models that have been previously used to explain cometary activity. CO and CO_2 may even provide better explanations for observed phenomena in active bodies in the solar system, and beyond. We currently live in an era with many new classifications for solar system small bodies that were not around a few decades ago. Today, we may be on the cusp of the addition of another new subset of active bodies in the solar system, these being the comets that are active at large distances (e.g., 20 au and beyond) from the Sun.



Figure 1.2: Two prominent examples of spectacular comets that were visible to the naked eye in the Northern Hemisphere. C/1995 O1 (Hale-Bopp) (Left side) at Joshua Tree, California (USA) in 1997 and was visible to the naked eye for nearly 18 months. Credit: Wally Pacholka, Time Magazine. C/2020 F3 (NEOWISE) (Right side) that could be seen by the naked eye in 2020. This was the first such naked eye comet visible in the Northern Hemisphere and discovered by the NASA NEOWISE Mission. This image appeared on NASA's Astronomy Picture of the Day (APOD) website for 2021 March 8: <https://apod.nasa.gov/apod/ap210308.html> Both comets have a strong blue ion tail pointing away from the direction of the Solar wind. Credit: Nicolas Lefaudeaux, NASA Astronomy Picture of the Day

1.1.2 Outline of the Dissertation and Scientific Objectives

The focus of this Dissertation addresses and seeks to answer several fundamental scientific questions:

1. What is the significance of CO and CO₂ gaseous species to activity of bodies in the solar system?
2. Do the Long-Period Comets (LPCs) retain more of their gas and dust since they visit the solar system less frequently than the Short-Period Comets (SPCs)? This is because LPCs have orbital periods of 200 years or more for one orbit versus a few years for SPCs.
3. Can the activity produced by gas and/or dust be linked in any way and does activity correspond with distance from the Sun?
4. Does the long-standing Whipple Model (1950, 1951) still sufficiently explain activity or are newer ones needed?

The ensuing Sections and Chapters are outlined as follows: Section 1.2 discusses the origins of these active bodies (as well as their source regions) including the significance and importance of CO and CO₂ species as well as dust in the activity observed for these objects and presently known populations in the solar system. This is mainly due to extensive research that began as recently as the 1990s. Section 1.3.1 discusses previous spacecraft missions (such as AKARI and EPOXI/Deep Impact) important to our understanding of active bodies, and more recently, the NEOWISE Spacecraft. The nature and capabilities of NEOWISE (currently still in operation at the time of the writing of this Dissertation) is absolutely essential in the detection and quantification of the amounts of dust, CO and CO₂ gaseous species outside of Earth's atmospheric environment.

Subsequent Chapters then detail several studies of active bodies that have been observed by the NEOWISE Spacecraft. Specifically, Chapter 2 focuses on three hyperactive comets,

(C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini)) that have been observed by NEOWISE. K2 was tracked extensively on the ground (Hui et al. 2018; Yang et al. 2021) as well as in space including with the Hubble Space Telescope (Jewitt et al. 2017, 2019a, 2021). It was then the farthest known active inbound comet (Figure 1.3. The results of Milewski et al. 2024 presented in Chapter 2 were published in the *Astronomical Journal* (AJ). In Chapter 3, results are presented from all of the presently available NEOWISE data from (2014–2022) that focuses on one of the most infamous distantly active bodies in the solar system (also being an SPC) being that of comet 29P/Schwassmann-Wachmann 1 (SW1). These results are from a publication to be submitted shortly to the *Astronomical Journal*. SW1 has been in a persistently active state almost for as long as it has been discovered, nearly a century ago (in 1927). This study specifically addresses points 2 and 3 mentioned above for this Dissertation. Finally, in Chapter 4, some concluding remarks detail what has been done along with recent findings, what can be done, and the future of research of activity in small bodies for the solar system.

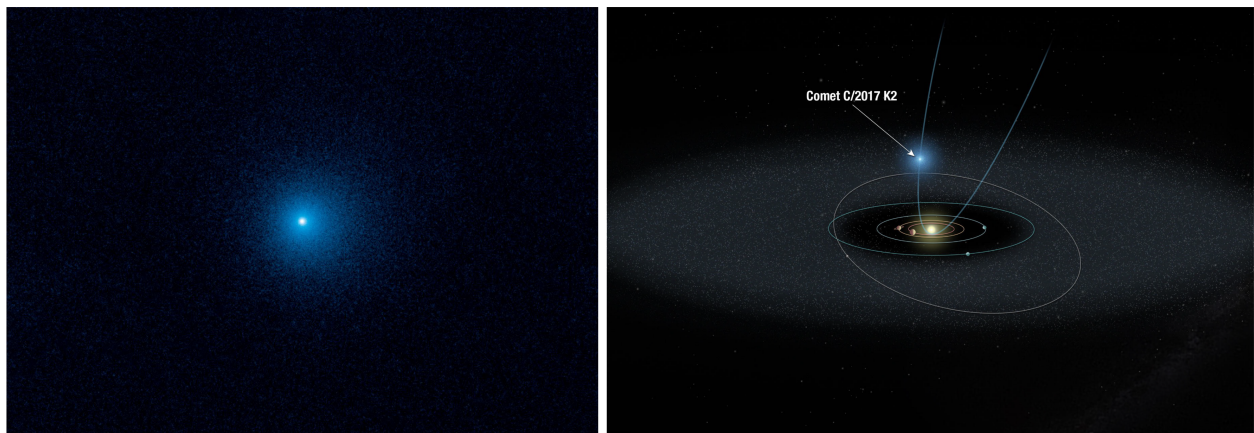


Figure 1.3: Distant active Oort cloud comet C/2017 K2 (Pan-STARRS) (Left side) HST image taken of K2 as it was inbound on UT 2017 June 26 Credit: NASA, ESA, D. Jewitt (UCLA). C/2017 K2 (Pan-STARRS) (Right side) along with the trajectory of its orbit as it was inbound to the solar system. Credit: NASA, ESA, and A. Feild (STScI)

It should also be noted that while the research was being conducted for this Dissertation,

it marked a unique period in time for which the only other operational space-based observatory capable of measuring CO, CO₂, and dust in these objects could come from the Spitzer Space Telescope (SST). It was decommissioned on UT 30 January 2020 and the (then) to be launched James Webb Space Telescope (JWST) came on UT 25 December 2021, finally becoming fully operational on UT 11 July 2022. The present NEOWISE spacecraft originally began as WISE that was launched on UT 14 December 2009, went into hibernation on UT 1 February 2011 and was reactivated on UT 13 December 2013 (renamed as NEOWISE). It will continue operations until July 2024 when it will become unusable. The NEOWISE spacecraft is discussed in detail in Section 1.3.2

1.2 The Origins of Active Bodies (Comets and Asteroids) in the Solar System and Their Source Regions

Comets and asteroids comprise the inventory of primordial materials left over from the formation of the solar system. As of the last few decades, the distinction between comets and asteroids has become less clear. Asteroids were once originally thought of as rocky and metallic objects residing in the main asteroid belt between the orbits of Mars and Jupiter at 2–3 astronomical units (au), lacking activity. The comets, in contrast, were objects devoid of metals, friable, containing volatiles often in the form of ices, and usually exhibited tails as they moved closer to the Sun where solar irradiation would sublimate these ices from their surfaces. The present population of comets can further be distinguished between the short and long period comet populations (SPCs and LPCs, respectively); with the LPCs having orbital periods at, or exceeding 200 years (Levison et al. 2002, Jewitt 2015). The asteroids can be divided into those that are inactive (e.g., behaving as point sources and not displaying comae or tails) and the ‘active asteroids’, Jewitt et al. (2015a) the newest subclass of solar system small bodies that sometimes behave as the former, and later exhibit activity via comae or tails on subsequent observations. As now both comets and asteroids are capable

of activity, further research is needed to explain the observed phenomena (Figure 1.4).

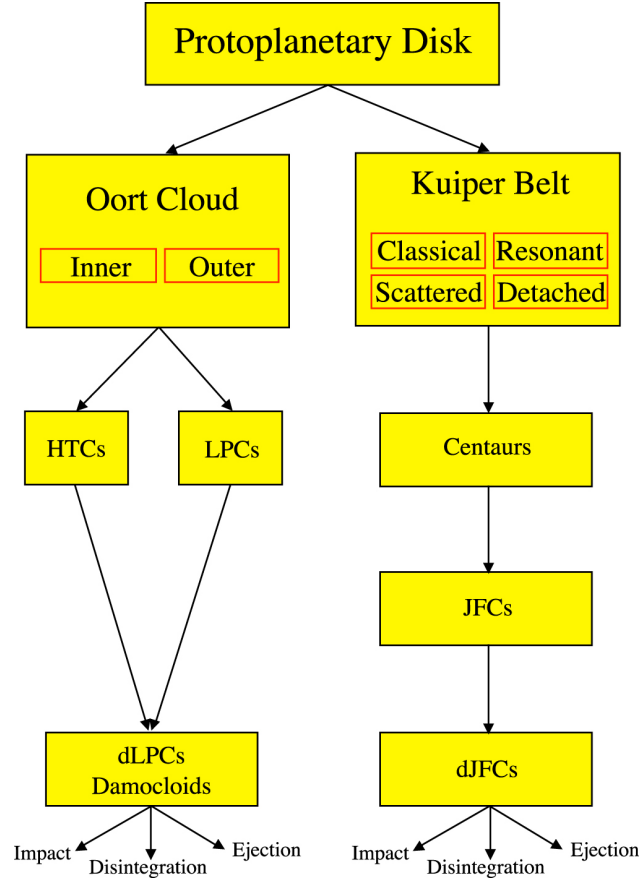


Figure 1.4: Schematic flow diagram highlighting suspected connections between cometary populations. Numbers give the approximate lifetimes of the different stages. SPC—short-period comet, LPC—long period comet, HTC—Halley-type comet, dLPC and dJFC are defunct LPCs and JFCs, respectively. Figure reproduced from Jewitt (2015).

1.2.1 Comets and ‘Hyperactive’ Comets

Comets are 4.6 billion-year-old surviving relics of the Sun’s protoplanetary disk. In addition to water, they contain inventories on the order of 10–20% in composition for CO and CO₂ volatiles. Source regions for comets are thought to be the Oort Cloud (Oort 1950) and Kuiper belt (Jewitt and Luu 1993) at temperatures of ~ 10 K and ~ 40 K, respectively.

The most famous model for cometary mass loss is based on Whipple (1950, 1951) where mass loss results from the sublimation of water ice from a central nucleus. A further sub-classification of comets is in that of the Centaurs which are a subset of bodies beyond the orbit of Jupiter (5.2 au) that sometimes exhibit activity like the comets in the form of comae and outbursts from the central body. Beyond 5 au, other processes must be responsible for cometary activity since temperatures are too low for sublimation of water-ice. CO and CO₂ gases are difficult or impossible to study through the Earth’s CO₂ rich atmosphere. This makes ground-based observatories less-useful in studies of CO and CO₂ species in comets with the need to resort to observing outside of the Earth’s atmosphere by using space-based observatories.

While comets will display dust and ion tails in addition to comae, more remarkable comets can be defined as ‘hyperactive’ on the basis of two criteria; one is that which has been in use in the scientific literature since the definition of the $Af\rho$ parameter, first described by A’Hearn et al. (1984). Since then, it has been used as a standard metric for measuring the dust production of active bodies by both the amateur and scientific community alike. For a coma in steady state, $Af\rho$ should be an aperture ρ independent parameter with assumptions for the bond albedo, A , filling factor, f which includes the number of dust grains populating the aperture. This assumption does not hold for non-idealized behavior such as when the coma is not in steady state. However, if an active body such as a comet is considered to be ‘hyperactive’, the measured $Af\rho$ value is often on the order ~ 1000 cm or more. The other criterion for cometary hyperactivity is due to comets having high fractions of surface activity with hyperactive comets emitting more water than can be expected for known nucleus sizes. This is explained further in Lis et al. (2019) as well as Bauer et al. (2021) for the case of hyperactive comet 46P/Wirtanen.

As sublimation of water-ice can drag large dusty grains within the coma, especially with the interaction of CO and CO₂ species, these three volatiles often work in concert for hyperactive comets. Bouziani & Jewitt (2022) have also suggested that these CO and

CO₂ rich ‘supervolatiles’ in addition to water could be responsible for the cause of cometary activity beyond the solar system’s planetary region, perhaps as far as ~ 100 au. This would explain the recent discoveries and arrivals of interstellar objects such as the discovery of the first such object, 1I/Oumuamua first discovered on UT 19 October 2017 which was initially designated C/2017 U1, A/2017 U1, and finally 1I/2017 U1, or simply ‘1I’ as it is the first such interstellar object arriving from beyond the solar system due to its rather high eccentricity, $e = 1.20113 \pm 0.00002$. Its distinction between asteroid or comet status remains uncertain. The first ever-report in the literature was by Masiero (2017) who found that from spectral data, 1I’s surface features indicated it contained a very red surface. As more observations had targeted this object, Micheli et al. (2018) reported non-gravitational acceleration, possibly due to outgassing even though no visible coma was observed. Trilling et al. (2018) performed follow-up observations using the SST thus setting upper limits on its $4.5 \mu\text{m}$ gas flux. As observations of 1I are limited in scope due to its rapid discovery and exit from the solar system, it remains unknown whether or not it was hyperactive. In addition, the new classification of interstellar objects can serve as a comparative benchmark with the known solar system hyperactive comets as more interstellar objects become discovered, including their activity level when compared with heliocentric distance.

1.2.2 The ‘Active Asteroids’ and Our Current Understanding of Solar System Activity

The active asteroids are a population of about ~ 30 or so known small solar system bodies that exhibit the dynamical properties of asteroids, but also ejection of materials producing comae and dust tails. From observations and previous literature, about a third of the known active asteroids have been reported to exhibit activity (a likely indication of sublimation) on more than one occasion including, but not limited to: 133P/Elst-Pizarro (Hsieh et al. 2010), 238P/Read (Hsieh et al. 2011), P/2008 R1 (Garradd) (Jewitt et al. 2009; Hsieh et al. 2021), 288P/(300163) 2006 VW₁₃₉ (Agarwal et al. 2017; Hsieh et al. 2018a) 313P/Gibbs

(Jewitt et al. 2015b), 324P/La Sagra (Jewitt et al. 2016), 358P/Pan-STARRS (P/2012 T1) (Agarwal & Mommert 2018; Hsieh et al. 2018b), and (6478) Gault (Kleya et al. 2019; Jewitt et al. 2019; Ye et al. 2019). The mechanisms proposed to drive activity include rotational mass loss, impacts, thermal disintegration, sublimation of volatiles at the surface, electrostatics and gardening, and radiation pressure sweeping (Jewitt et al. 2015a). Of the presently known active asteroid population, a ‘threshold’ Tisserand parameter (with respect to Jupiter), T_J , (Kresak 1982) of 3.08 has been set to distinguish between objects known to have exhibited activity on one or more occasions and is further described in Jewitt et al. (2015a).

One of these active asteroids, P/2016 G1 (Pan-STARRS); hereafter ‘G1’, was discovered on UT 2016 April 1, by Weryk and Wainscoat using the 1.8-m Pan-STARRS1 (PS1) telescope in Haleakala Observatory in Hawaii, USA. Immediately, data were collected on this object to investigate the cause of its activation. While G1 was hardly studied by the solar system small body community, from limited datasets on this object, the studies of Moreno et al. (2016; 2017) suggested the cause of activation was a catastrophic impact of the main body. Another competing study by Milewski & Rich (submitted) showed that by using aperture photometry on a larger dataset in both pre- and post-perihelion follow-up observations, the cause of activation is most likely due to spin-up torques but could also be due to impact. The major results of that study also found that the absolute magnitude, H , of G1 seen to fade with time, suggesting the cause of activity could be attributed to spin-up torques as well as impact from aperture photometry and order of magnitude estimates. (Figure 1.5) As the number of ‘Active Asteroids’ continues to grow, CO and CO₂-species have not yet been detected in any of the active asteroids, however Milewski & Rich (submitted) also used the available NEOWISE data to search for any indication of gas or dust activity which was inconclusive. Nevertheless, ground and space-based observations often provide necessary constraints on physical properties of the bodies as well as the presence of any activity caused by the ejection of dust as well as emission of gaseous species.

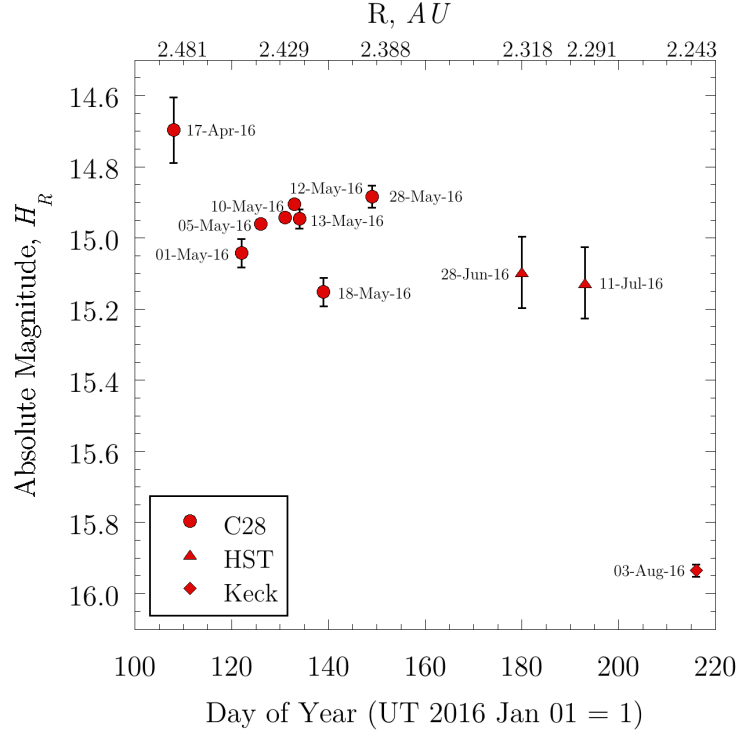


Figure 1.5: Absolute H_R magnitude versus Day of Year for G1 with Day 01 = UT 2016 January 1 . The HST values for H_R have been extrapolated using our ground based color indices determined from our UT 2016 Aug 03 data from Keck-I. Circles, triangles, and diamonds denote data taken with C28, HST, and Keck-I, respectively. Also plotted at the upper x -axis is heliocentric distance, R . C28 and Keck-I error bars correspond to statistical errors while HST error bars are systematic errors. Figure taken from Milewski & Rich (submitted).

1.3 Observations of Active Bodies by Spacecraft

1.3.1 Predecessor Spacecraft Observations of Active Bodies

One such historical notion attributed to comets containing ‘poison gases’ which *has* survived throughout the years, and is *actually* true comes from some gaseous species observed in these comets. These gases are otherwise not directly dangerous to any lifeforms on Earth especially due to the large separation between the comets. Another fact remains that most bright comets active at sufficiently far enough distances from the Sun can be linked to the

presence of carbon monoxide (CO), and/or carbon dioxide (CO₂) gas species (Sekanina et al 1992; Biver et al. 1996; Jewitt et al. 1996). 1986 was the year that also marked the first time ever in history where comets like 1P/Halley were now able to be studied in detail for the first time outside of the Earth’s atmosphere. “Halley’s Armada” consisted of at least six space probes which include Giotto (ESA), Vega 1 and Vega 2 (USSR/France Intercosmos), Suisui and Sakigate (ISAS), as well as the International Comet Explorer (ICE) by NASA. There are far too many publications that have resulted from these investigations of 1P/Halley, but another triumph for cometary science was that direct measurements of properties of comets could be taken since spaceflight was only achievable as of the late 1950s and early 1960s. Prior to this, studies of comets could only be performed from the ground on Earth.

After the importance of cometary chemistry became established from previous spacecraft observations of 1P/Halley, successor missions would include the launches of the Spitzer Space Telescope (SST), Rosetta, EPOXI/Deep Impact, and AKARI, respectively in 2003, 2004, 2005, and 2006. These were all fundamental missions to the current understanding of direct properties of active bodies in the solar system such as comets and asteroids. With these missions, better understanding of the very nature of cometary volatiles and gaseous species (in addition to quantifying the amounts of dust, CO and CO₂ gaseous species) outside of Earth’s atmospheric environment became possible. SST provided numerous observations of active bodies in the solar system and beyond over 16 years that helped our understanding of these materials (Lisse et al. 2020). A major advantage included the potential to be able to now measure CO₂ from space due to the CO₂ and CO emission lines both falling within SST’s 4.5 μm channel.

In a survey of 23 comets observed by SST, Reach et al. (2013) found that when comparing differences in the 3.6 μm and 4.5 μm channels, the activity and observed morphology was due to the ejection of solid material (dust) by gaseous CO₂+CO emission. For cases where the quantities of CO and CO₂ were comparable, it could be assumed that emission was due to CO₂ as its emission line strength is an order of magnitude stronger than that of CO. The

problem is that both CO and CO₂ have very close emission line strengths and given the wide bandpass of the SST 4.5 μm channel, it would be impossible to actually separate the specific gaseous species contribution(s). In addition, due to the variation of dust and gas production rates, there is a wide scatter for comets especially over a large range of heliocentric distances (Figure 1.6). This same study also found that some of the observed gas jets and spirals could not be connected to dust coma features. In addition, as the line strength of CO₂ is about an order of magnitude greater than that produced by CO, for some comets it was possible to infer the presence of a CO₂ dominated gas coma. In comparison with this pivotal SST study, A'Hearn et al. (2011) previously showed that during a flyby of comet 103P/Hartley 2, it contained a rather small nucleus but the activity observed was primarily due to CO₂ emission. Reach et al. (2013) were able to further correlate the strength of the gas coma with previously used 'depleted' and 'normal' terminology used by A'Hearn et al. (2011). The results of Meech et al. (2011) also showed that 103P/Hartley 2 was also dominated by CO₂ driven activity near perihelion. Pittichová et al. (2008) reported studies of hyperactive comet 21P/Giacobini-Zinner that showed CO₂ could likely be the dominant species and was observed by SST. As the first results of the importance of CO₂ being an important volatile in explaining cometary activity, future surveys and studies sought to catalogue the CO₂ inventory especially in various stages of the orbital evolution of these active bodies.

The AKARI spacecraft observed 18 comets including both Oort cloud and Jupiter-family comets, of which Ootsubo et al. (2012) showed that the most prominent emission bands of the observed spectra were due to fundamental vibrational bands of water at 2.7 μm and CO₂ at 4.3 μm . The resultant dataset (obtained from 2008-2010) also consisted of at least two observations for each comet at heliocentric distances between 1 and 4 au. In a few instances some of the observed comets were observed at different heliocentric distances allowing for comparison as they were either on the inbound or outbound leg of their orbits. Comet 29P/SW1 was most notably studied in this survey as it was the only comet that was at a

larger heliocentric distance compared to the rest of the objects at a much farther distance at 6.19 au. In this case, Ootsubo et al. (2012) set further constraints that CO emission (and not CO₂) was the dominant species that could explain its persistent activity. Further, as most of the comets observed are within the region of the solar system where the sublimation of water-ice is possible due to solar irradiation, constraints were set on the relative CO₂ to water production rate ratios. This became the largest homogeneous database of CO₂ to water production rate ratios and has frequently been cited among publications that focus on the quantification of dominant volatile species for active bodies in the solar system. Other conclusions from Ootsubo et al. (2012) suggested that CO is expected to be depleted in cometary nuclei in subsequent passages around the Sun even though CO is more volatile than CO₂ and that CO may be indicative of primordial ices in the solar system that are preserved in the deep interiors of these bodies. Given the location of its orbit, the presence of CO could also explain the activity of 29P/SW1 given its distance (Figure 1.7).

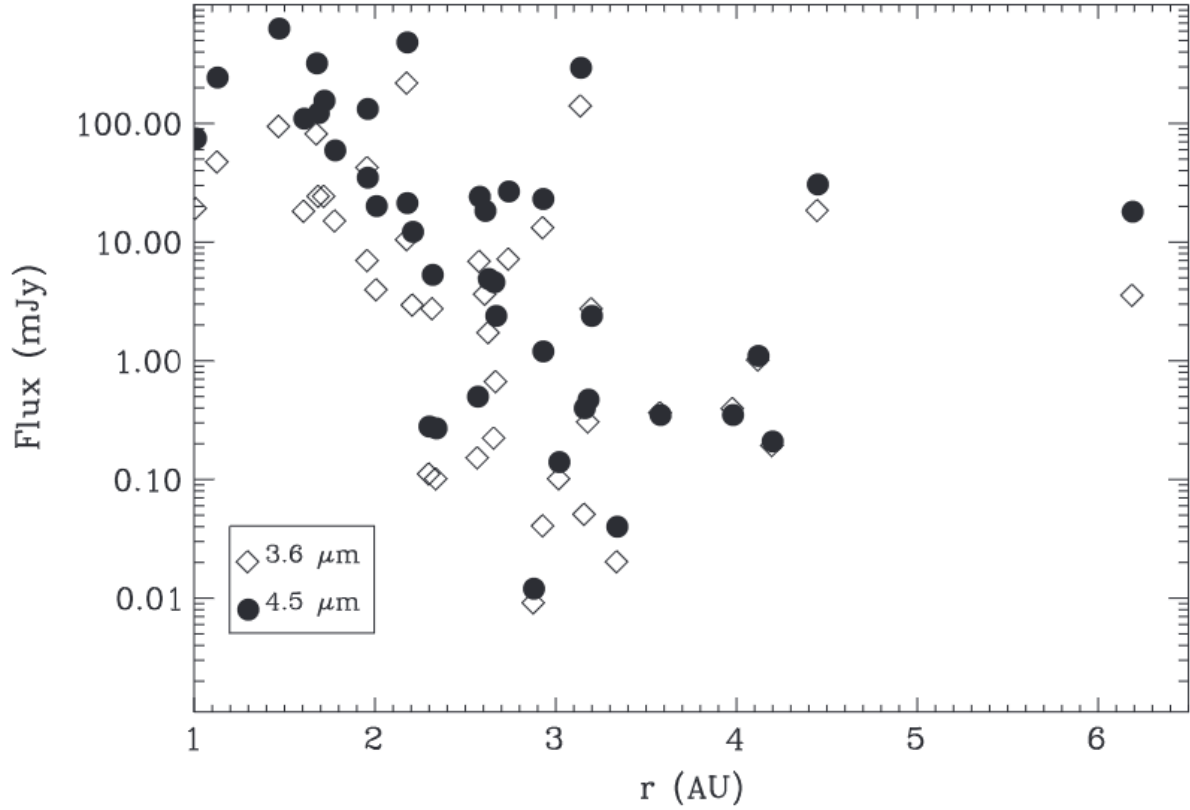


Figure 1.6: Flux densities at 3.6 μm (open diamonds) and 4.5 μm (filled circles) for each comet observation, plotted versus the heliocentric distance at which the comet was observed. A variety of comets have been observed that include Oort cloud comets in addition to SPCs. While most of these SSTs fluxes are for comets in heliocentric distance ranging from ~ 1 to 4 au, there are a few exceptions beyond this distance, most notably comet 29P/SW1 at 6.19 au. Figure reproduced from Reach et al. (2013).

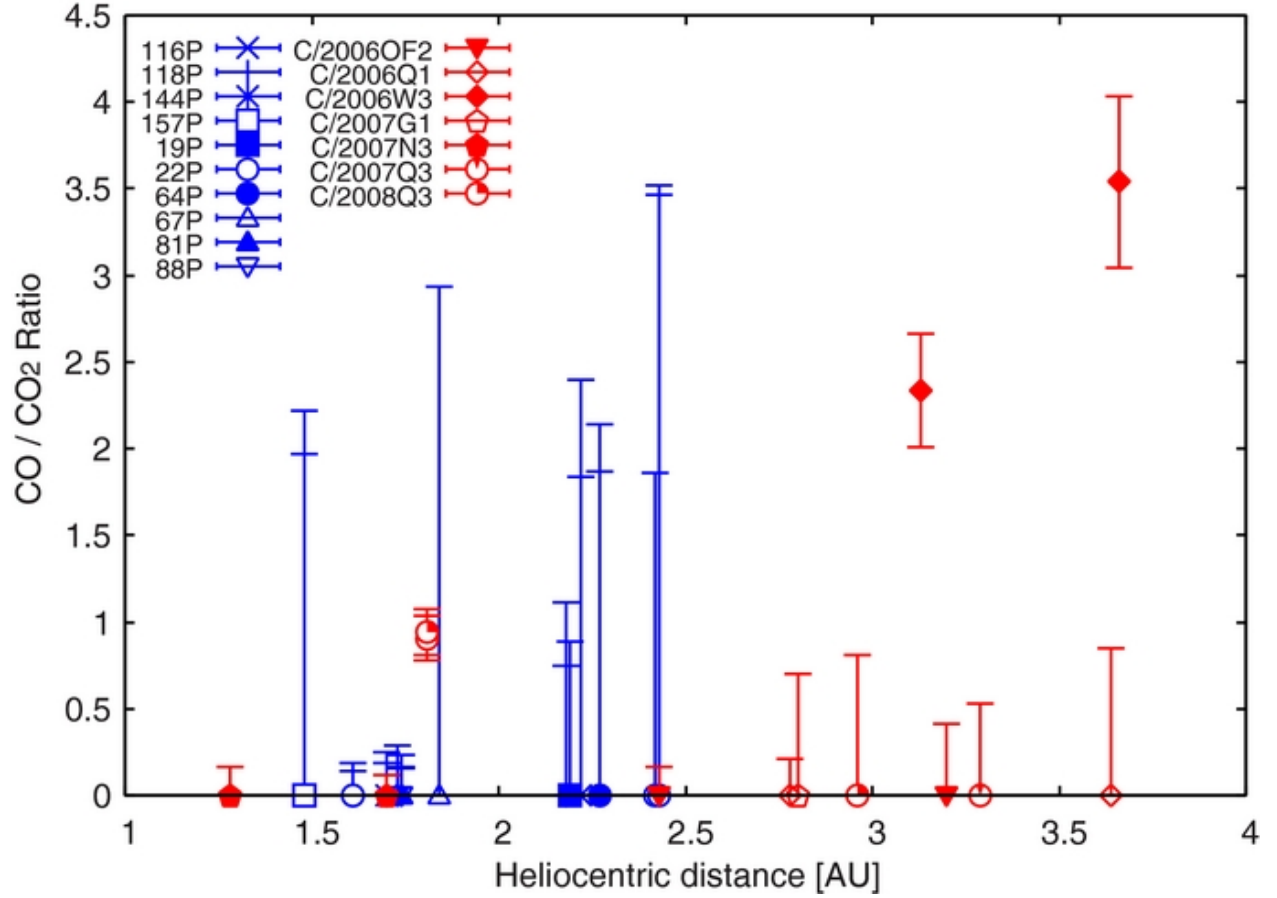


Figure 1.7: Gas production rate ratios of CO are plotted with respect to the CO₂ in the 17 (of 18) comets; comet 29P/SW1 has been omitted from this figure. The Oort Cloud Comets (OCs) are depicted in red and the Jupiter Family Comets (JFCs) are in blue. CO is expected to be depleted for comets inwards of 4 au, likely as CO is converted to CO₂ via reaction with OH. Hence, comets with CO probably contain more pristine materials compared to those with CO₂ which are often found at shorter heliocentric distances. Figure taken from Ootsubo et al. (2012).

The AKARI spacecraft also observed comet 67P/Churyumov-Gerasimenko to which the Rosetta mission was en-route. AKARI provided some initial flux measurements of the abundances of water, CO₂ and CO which became especially useful for future studies that investigated the sublimation of volatiles at the surface of 67P. Feldman et al. (2015) concluded that CO₂ molecules released from its nucleus into the coma were due to the photoionization of water molecules near the comet surface. Also investigating the link between the activity of 67P with respect to water and CO₂, Bockelée-Morvan et al. (2015) concluded that CO₂ was outgassing from beneath the surface in both illuminated and non-illuminated regions, while water production is weak in areas with low solar illumination. Soon afterwards, these results of the measurements of CO and CO₂ species in comets could then be verified and tested with the WISE/NEOWISE spacecraft that has provided an unbiased all-sky survey in the infrared with follow-up measurements of 67P (Bauer et al. 2012) and 103P (Bauer et al. 2011). As the focus of this Dissertation relies on direct measurements coming from the WISE/NEOWISE spacecraft. Section 1.3.2 will explain in detail its capabilities and the fact that it can simultaneously assay the gaseous species CO and CO₂ species including the dust of which is a central component of this Dissertation.

1.3.2 The Wide-field Infrared Survey Explorer (WISE) and Near-Earth Object (NEOWISE) Reactivated Mission

The Wide-Field Infrared Survey Explorer (hereafter WISE) spacecraft was launched on UT 2009 December 14, with the goal of conducting a full infrared all-sky survey in the thermal bands 3.4 μm , 4.6 μm , 12 μm , and 22 μm (hereafter *W1*, *W2*, *W3*, and *W4*; Wright et al. 2010) in the mid-infrared spectrum, building on that of Infrared Astronomical Satellite. After its cryogenics were depleted, the WISE spacecraft was put into hibernation on UT 1 February 2011. It was later reactivated on UT 13 December 2013 and renamed as the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) because it continued a 2-band infrared survey (Mainzer et al. 2011). The first images were returned on shortly thereafter.

The goal of the NEOWISE Reactivation Mission is to find and characterize potential solar system small bodies such as asteroids and comets that may pose a threat to the Earth under NASA’s strategic goal for planetary defense. The NEOWISE Reactivated Mission differs from the WISE-prime mission by using only the *W1* and *W2* channels and being passively cooled to approximately 75 K, allowing a continuation of an infrared all-sky survey for solar system small bodies. There are a total of 283 comets as of 2024 March that have been detected by the NEOWISE spacecraft. In addition, over 1.5 million infrared measurements have been made that comprise of 43,982 different solar system objects, of which include 1,575 Near-Earth Objects (NEOs). NEOWISE is now 60% of the way through the 21st coverage of the full sky since the start of the Reactivation mission.

For comets that have been observed by NEOWISE, sometimes a number of them may appear more than once in the data each year. Over subsequent years, this results in multi-year coverage of specific comets that get observed by NEOWISE. However, about half the number of the population of NEOWISE observed comets consist of short-period comets (SPCs), while the other half are considered to be long period comets (LPCs); (Bauer et al. 2017). SPCs have orbital periods of $\lesssim 200$ yr, while the LPC orbital periods often exceed 200 yr (Vokrouhlický et al. 2019). At $3.4\ \mu\text{m}$, the *W1* channel is sensitive to sunlight reflected from cometary dust particles when they are close to the Sun, as well as thermal emission from them. The *W2* channel at $4.6\ \mu\text{m}$ is also sensitive to reflected sunlight and thermal emission from dust, but emission from the $4.67\ \mu\text{m}$ and $4.23\ \mu\text{m}$ bands of CO and CO₂ are also detectable. These peak wavelengths refer to the fundamental CO $\nu = 1-0$ and CO₂ ν_3 emission lines, respectively (Mainzer et al. 2014; Bauer et al. 2015).

At the time of publication, Bauer et al. (2015) presented the largest infrared survey to date of comets which provided constraints on dust, nucleus size, and CO+CO₂ production rates. This study focused on 163 comets that had been observed during the WISE/NEOWISE prime mission and was a substantial improvement on previous multi-comet measurements of CO and CO₂ production rates that had been performed by seminal studies such as Ootsubo

et al. (2012) and Reach et al. (2013). By using the operational NEOWISE *W1* and *W2* channels both sensitive to dust and thermal emission, after subtraction of the dust, the active comets that showed an excess of signal in the $4.6\ \mu\text{m}$ were attributed due to the presence of CO+CO₂ gaseous species. This could also be confirmed by visual inspection of the images. Figure 1.8 shows many of the comets that were observed by WISE/NEOWISE in addition to a color scheme used to trace the presence of the dust and gas species. For all intents and purposes, the NEOWISE Science Team has adopted the convention employed by Bauer et al. (2015) (and references therein) where for the WISE prime mission, the color scheme have the $22\ \mu\text{m}$ image mapped to red, the $12\ \mu\text{m}$ image mapped to green, and the $4.6\ \mu\text{m}$ image mapped to blue colors. For the NEOWISE Reactivated Mission, the $4.6\ \mu\text{m}$ image is mapped to red, and the $3.4\ \mu\text{m}$ image to both green and blue. This allows for effective visual inspection of the gas and dust species.

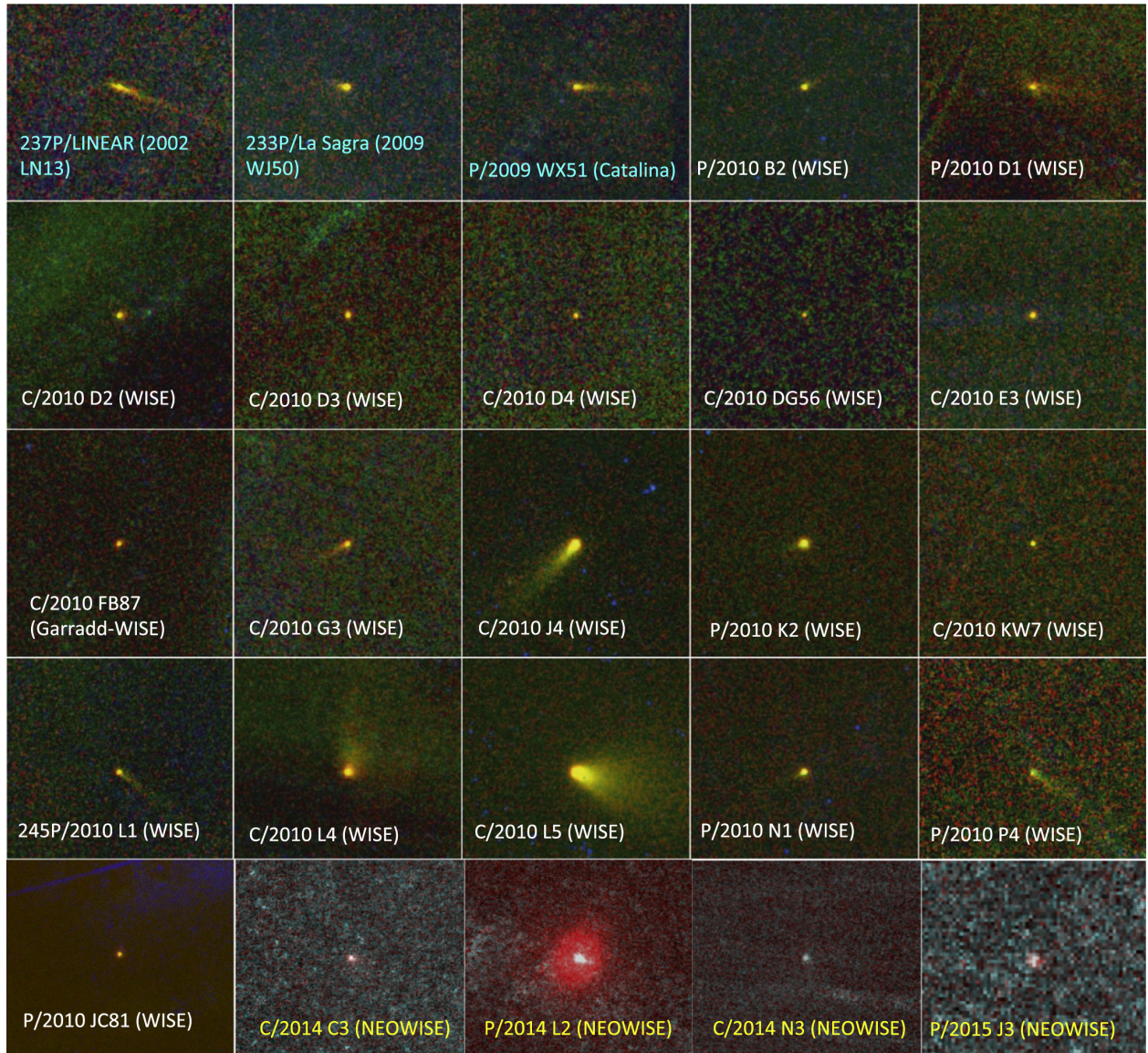


Figure 1.8: Discovery images of WISE/NEOWISE comets shown in 3-colors. The prime mission comets have the $22\ \mu\text{m}$ image mapped to red, the $12\ \mu\text{m}$ image mapped to green, and the $4.6\ \mu\text{m}$ image mapped to blue. The comets for which the activity (and not the object) were discovered by NEOWISE are shown with blue labels, in the upper left. In the case of the four comets discovered to date by the NEOWISE Reactivation (yellow text labels, on the bottom row), the $4.6\ \mu\text{m}$ image is mapped to red, and the $3.4\ \mu\text{m}$ image to both green and blue. The images are $6'$ on a side. The comets span a wide range of morphologies and activity levels; over half are LPCs. Figure taken from Bauer et al. (2015).

1.3.3 NEOWISE Observations and Data Collection

We used data taken by WISE (Wright et al. 2010) and NEOWISE (Mainzer et al. 2014). NEOWISE is in a sun-synchronous polar orbit with an orbital period of ~ 95 minutes, which completes a full mapping of the sky in the infrared twice a year. The satellite’s orbit is such that it is facing away from the Sun, usually around solar elongation angles of $\sim 90^\circ$ – 110° (due to orbital precession) and is protected with a sun-shield to prevent stray light from entering the aperture. The telescope aperture is 40 cm, it has a $47' \times 47'$ field of view, a pixel scale of $2.''75 \text{ pixel}^{-1}$, and the images have a Full-Width at Half Maximum (FWHM) of $6.''1$ and $6.''4$ in $W1$ and $W2$ respectively. Data in $W1$ and $W2$ are taken simultaneously every 11 s by use of a dichroic beamsplitter to separate the two channels. Each individual frame has an exposure time of 7.7 s in both $W1$ and $W2$. Because of its rate of motion on the sky, there are overlaps in data coverage, which means that moving objects such as solar system small bodies can be positively identified. Initial data products have instrumental and astrometric corrections applied via the WISE Science Data Center (Cutri et al. 2012). Once the calibrated images are searched for moving object detections, their positions and times are reported to the Minor Planet Center several times per week (Cutri et al. 2015). The calibrated image and source detection data are released online publicly via the Infrared Processing and Analysis Center (IPAC) Infrared Science Archive (IRSA) (see: <https://irsa.ipac.caltech.edu/>). The NEOWISE spacecraft takes data for many solar system objects over a variety of different heliocentric distances and observation epochs. Images are collected every ~ 3 hr for most moving objects. Due to the typical rate of motion of most minor planets in the inner solar system through the NEOWISE scan circle, the “visit” length usually spans ~ 36 hr. Objects are sometimes detected on multiple epochs, and we define a “visit” as a set of observations separated in time from one another by approximately a week or more (Bauer et al. 2015).

1.3.4 NEOWISE Methods and Aperture Photometry

After collecting and grouping all the available data corresponding to a particular visit for a comet, we sorted the individual single-exposure frames by the respective $W1$ and $W2$ bands. From the data collected in single frames, we then visually inspected each image to check for detection of the comet at the predicted position from the JPL HORIZONS Web Interface. Our selection criteria for removing frames from further consideration in our study were based on any frame with noticeable aberrations, such as those where there are obvious smearing effects from trailing, over-saturation from the Moon or other bright field objects, an object of interest being cut off by being located at the edge of a frame, or if a particular frame was listed in the IRSA WISE Image Search having a quality assessment of less than 5 (e.g., with the flag *qual_frame* < 5, with 0 being the lowest and 10 the highest) (Cutri et al. 2015). The frames containing useful data were then input into the Image Co-addition with Optional Resolution Enhancement package (hereafter, ICORE; Masci 2013), to co-add the single-exposure images in the moving reference frame of the object according to predicted positions by JPL HORIZONS. ICORE is an image co-addition package that produces final mosaicked co-adds that matches backgrounds, contains pixel outlier rejection, and boosts the signal-to-noise ratio (S/N) of the individual frames. The final co-added images have a resampled pixel scale of $1'' \text{ pixel}^{-1}$.

Aperture photometry was performed on individual objects using a modified version of the publicly available Astropy ‘photutils’ package. The photometry was executed for known objects with magnitudes and errors presented in the NEOWISE Reactivation Catalog Data (Cutri et al. 2012). We used magnitude zero-points that are specific for $W1$ and $W2$ (Cutri et al. 2015), and then performed the aperture photometry on the ICORE frames. Counts were converted to magnitudes, and then to flux densities with the correct band specific zero-points listed in Wright et al. (2010). Aperture photometry was also performed on point sources in the single-exposure frames that were used to make the final co-added images to

ensure that the field stars were of consistent brightness reported in the NEOWISE Single-Exposure Point Source Catalog. A variety of apertures were used and it was found that the 11'' radius aperture was the best choice because it captured nearly all of the light of the source while leaving a small amount of sky background necessary for removal in a sky annulus. Background subtraction from the median value in a sky annulus extending from 50'' to 70'' was used to remove sky background. After comparing the results of our single-exposure point source NEOWISE aperture photometry measurements with the values listed in the catalog, we found small deviations on the order of a few percent, which happens because the catalog uses point-spread function (PSF)-fit photometry. This gives us confidence in performing aperture photometry on the stacked images. Consistent with the results of Bauer et al. (2015, 2017), Stevenson et al. (2015), and Rosser et al. (2018), the 11'' aperture was also chosen because it best captures the FWHM of the PSF for NEOWISE observations and encloses most of the light for the target with little to no significant change in magnitude for various similar size apertures while avoiding nearby field objects. The aperture photometry was compared with faint solar system objects with reported PSF-fit photometry measurements in the NEOWISE Single-Exposure Point Source Catalog to validate the photometry measurements

1.3.5 NEOWISE Dust and Gas Production Rates

In order to quantify and determine how much excess signal exists in the *W2* 4.6 μm channel, the *W1* 3.4 μm channel is needed to constrain the properties of the dust. In this case, a Spectral Energy Distribution (SED) plot is needed; see Figure 1.9. As the *W1* signal is dominated by the dust, this is used to constrain the dust signal present in *W2*. Reflected light emission flux is thereby constrained in *W1* and the thermal emission flux is approximated from the *W1* band data. The dust model is used to fit the reflected light in *W1* and then a thermal emission model is built from that. The reflected component of the flux follows a G2V solar-type spectrum and the thermal flux is fit to a Planck function assuming a blackbody

temperature that scales with heliocentric distance, r_H . For computation of the blackbody temperature, the relation $T_{\text{BB}} = 286 \times r_H^{-1/2}$ is used that has been adopted from Stevenson et al. (2015) and Rosser et al. (2018). Using the $W1$ flux, we convert it to $Af\rho$ which is a proxy for dust production measurements introduced in A’Hearn et al. (1984). $Af\rho$ stands for Albedo, A , filling factor, f (e.g., how much of the aperture is populated by dust grains), and ρ which is the aperture radius in arcseconds projected at the distance of the comet in centimeters. As is the convention employed by Bauer et al. (2015), an $11''$ aperture placed on the center of the target is used. This $11''$ aperture best captures the signal for NEOWISE observed comets and the purpose of this technique is to search for the CO_2 signal that is assumed to emanate from a central, unseen nucleus. An annulus is used with inner and outer radii of $50''$ and $70''$, respectively to estimate the background signal. For consistency, this is used in all measurements. When computing the $Af\rho$ measurement, the equation is as follows:

$$Af\rho = \frac{(2r_H\Delta)^2}{\rho} \frac{F_{\text{comet}}}{F_{\odot}} \quad (1.1)$$

where r_H is the heliocentric distance of the Sun in au, Δ is the geocentric distance of the comet in cm, ρ is the projected aperture at the distance of the comet in arcseconds, and the $W2$ fluxes, F_{comet} (e.g., the comet flux) and $F_{\odot}$, (e.g., the solar flux at 1 au). We adopt values from Jarrett et al. (2011) for the solar flux at $W1$, which are also mentioned in the Explanatory Supplement to the WISE Preliminary Data Release Products (Cutri et al. 2011). Using the $W1$ flux point, we create a model of the $W2$ flux.

Using the spectral energy distribution, the predicted $W2$ flux is determined from the $W1$ reflected component. Any excess signal in $W2$ after removing reflected and thermal components is assumed to be due to CO or CO_2 gas emission. After determining if there is any excess signal in $W2$, we find the average column density along the line of sight to the comet assuming that it is due to all CO or all CO_2 emission according to:

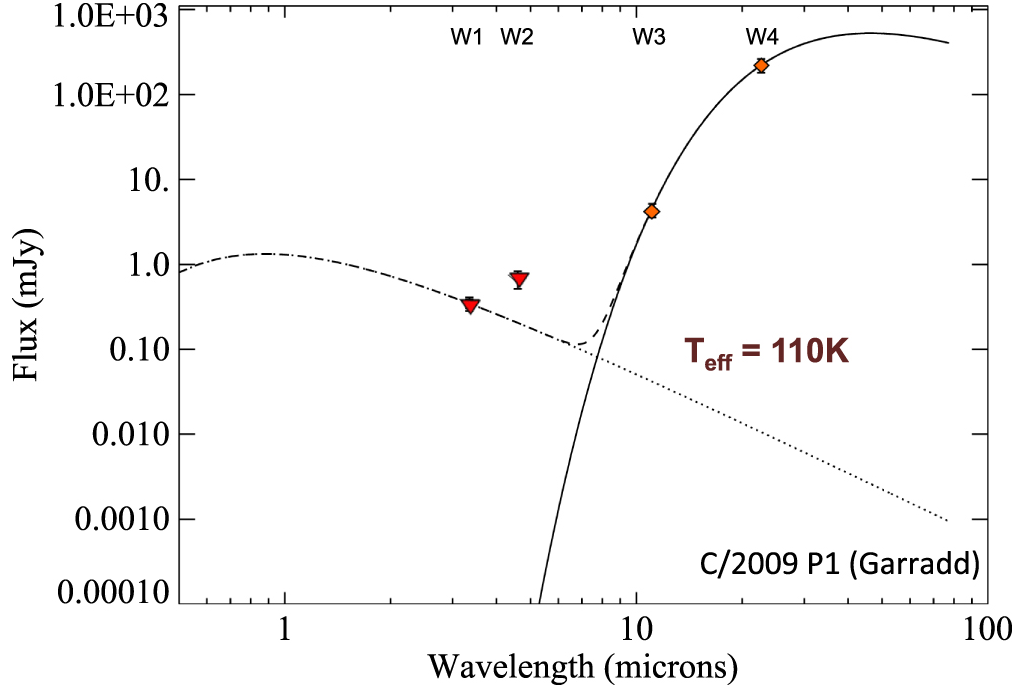


Figure 1.9: WISE 4.6 μm band (*W2*) contains CO 4.7 μm and CO₂ 4.3 μm emission lines. C/2009 P1 Garradd’s 4.6 μm band excess is not consistent with reflected or thermal contributions of coma or nucleus, but is consistent with CO₂ and CO emission. The flux from the 3.4 μm (Red Triangle, Left), 4.6 μm (Red Triangle, Right), 12 μm (Orange Diamond, Left) and 22 μm (Orange Diamond, Right) channels are shown. Also the reflected light model (black-dotted line) thermal model (solid black line) and combined signal (dashed-black line) are over-plotted. Figure taken from Bauer et al. (2015).

$$\langle N \rangle = F_{W_2} 4\pi \Delta^2 \frac{\lambda}{hc} \frac{r_H^2}{g} \frac{1}{\pi \rho^2} \quad (1.2)$$

adopted from Pittichová et al. (2008), Stevenson et al. (2015), and Rosser et al. (2018). $\langle N \rangle$ is the average column density of the gas species along the line of sight in cm^{-2} , F_{W_2} is the excess flux in *W2* after the dust contribution has been removed, λ is the wavelength of observation in μm , h is Planck’s constant in units of erg s, c is the speed of light in a vacuum in units of cm s^{-1} , and g is the fluorescence efficiency for a gas species that is taken to be $2.86 \times 10^{-3} \text{ s}^{-1}$, which is the fluorescence efficiency of CO₂ at 1 au (Crovisier & Encrenaz 1983), r_H is the heliocentric distance of the Sun in au, Δ is the geocentric distance projected

at the distance of the comet in cm, and ρ is the projected aperture radius at the distance of the comet, respectively.

Using this average column density, we determine the production rate due to CO₂:

$$Q_{CO_2} = \langle N \rangle 2\rho v \times 10^5 \quad (1.3)$$

adopted from Pittichová et al. (2008), Stevenson et al. (2015), and Rosser et al. (2018). Q_{CO_2} is the production rate of CO₂ in molecules s⁻¹, v is the expansion velocity of the gas species, which is adopted from the work of Ootsubo et al. (2012) who used $0.8 \text{ km s}^{-1} \times r_H^{-1/2}$, and $\times 10^5$ is a unit conversion factor used previously in Stevenson et al. (2015) and Rosser et al. (2018) converting from km to cm, and ρ is the scale in cm per arcsecond. Furthermore, because the CO₂ emission line is a factor of ~ 11.6 times stronger than that of CO, the equivalent production rates for CO (e.g., Q_{CO_2}) can be found by multiplying Q_{CO_2} by 11.6 (Bauer et al. 2015; Rosser et al. 2018) because it would take as much CO to produce the same emission as CO₂. This corresponds to the ratio of the fluorescence efficiencies for CO₂ and CO. It should be noted that they cannot be separated because the *W2* bandpass is so wide and because the fundamental CO $\nu = 1-0$ and CO₂ ν_3 emission lines ($4.67 \mu\text{m}$ and $4.23 \mu\text{m}$, respectively, for CO and CO₂) both fall within the *W2* channel. An assumption has to be made that the entire excess flux in this channel attributed to a gas species is due to solely CO or solely CO₂. However, some comets have already been reported to have their gas flux component attributed mainly to the presence of CO rather than CO₂, such as with 29P/Schwassmann-Wachmann 1 (Senay & Jewitt 1994), C/1995 O1 (Hale-Bopp) (Crovisier et al. 1997; DiSanti et al. 2001; Biver et al. 2002; Gunnarsson et al. 2003), and C/2016 R2 (Pan-STARRS) (Wierzchos & Womack 2018), helping to narrow down a closer value of the flux of the dominant constituent volatile species as the likely driver of cometary activity. For the cases of comets with measured CO₂ production rates, measurements performed by Ootsubo et al. (2012) and McKay et al. (2019) have led to better estimates of CO₂ inventories

in comets. In any case, the triple-bonded molecular structure of CO and the fact that it has a longer photodissociation lifetime compared to CO₂ (Huebner et al. 1992) are several key points to consider in the overall solar system volatile inventory, as well as for activity driven emission for comets at distances greater than $\gtrsim 4$ au, where it is far too cold for water-ice sublimation to occur.

1.3.6 NEOWISE Results

When the *W2* channel contains an excess in signal after a removal of the dust from *W1* and after visual inspection of the images, this excess signal is interpreted due to CO and CO₂ gaseous emission. Bauer et al. (2015) showed that for the 163 comets detected by WISE during the prime mission, 40 of those comets had an excess signal in *W2*. The simplest assumption is that the entire signal was due to CO₂ emission rather than CO, but there are cases where the opposite is true such as with 29P/SW1 and C/2009 P1 (Garradd). However, for simplicity, all gas production rate values were converted to CO₂ production rates and plotted in Figure 1.10 as a function of heliocentric distance. The conversion of CO₂ to CO production rates is simply obtained by multiplying the ratio of the CO₂ to CO fluorescence efficiencies, e.g.; 11.6 as previously described in Section 1.3.5. The results are interesting in that the LPCs and SPCs show similar scatter in the data. However, it is apparent that LPCs have greater CO₂ production rates and are active at larger heliocentric distances when compared to the SPC counterparts. Bauer et al. (2015) concluded that based on the results of this study, the appearance of more LPCs exhibiting CO+CO₂ at greater r_H suggests an evolutionary effect in the sense that LPCs more than likely retain their more volatile CO species and that LPCs and SPCs may have on average similar CO₂ abundances. This result is comparable to the conclusions found in Ootsubo et al. (2012).

Using the NEOWISE Reactivated Mission Year 1 Data taken during 2013-2014, Gicquel et al. (2023) performed similar analysis on 57 comets that were observed in this time frame.

The sample consisted of 30 SPCs (with one Centaur) and 27 LPCs. An important finding from this study is that for SPCs, the CO or CO₂ volatiles appear to be more depleted but may have potential for activity if thermal waves propagate to deeper depths. The relationship between heliocentric distance, r_H and $(Q_{\text{CO}_2}^{\text{proxy}})$ also showed little to no correlation which is again consistent with the results of Bauer et al. (2015). This is again another interesting and important result of the NEOWISE comet data that suggest the SPCs and LPCs have similar distributions given a small sampling of the data and may have implications for their formation regions. The commonly accepted notion is that the Oort cloud comets (e.g., LPCs) likely formed near Jupiter and were scattered through planetary migration and that at least some of the Kuiper belt objects originated where they reside, which is near the orbit of Neptune. (Dones, 2004). If true, this implies that the LPCs do retain their more pristine volatiles due to their infrequent passages around the Sun. It may also explain why some of the members of the Jupiter Family Comet (JFC) and LPC populations have similar compositions.

In Chapter 2, we discuss the significance of three hyperactive comets observed by the NEOWISE reactivated mission that were all found to be significantly active at large heliocentric distances, including two comets which set records at the distances where they were found to be active.

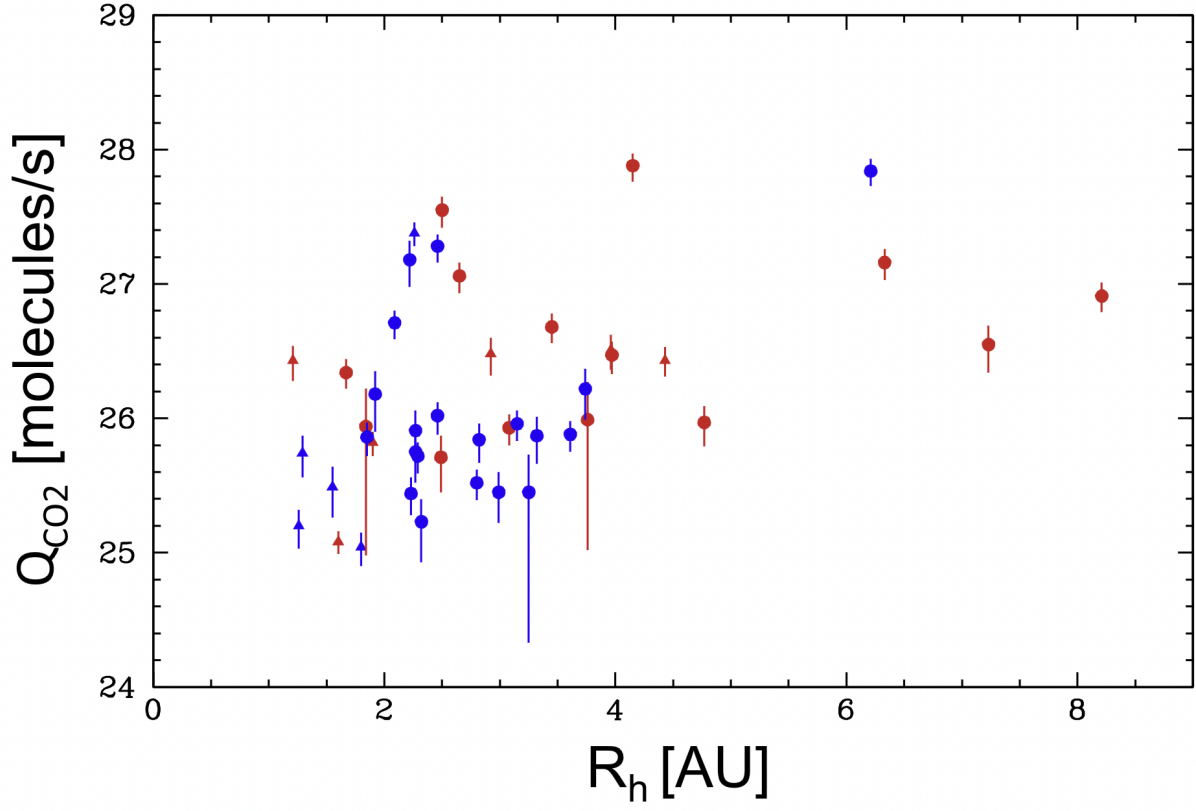


Figure 1.10: LPCs (Red) and SPCs (Blue), WISE/NEOWISE discovered comets are triangles, other objects represented by circles. Excess flux in $4.6 \mu\text{m}$ channel converted to CO_2 production plotted with respect to heliocentric distance, r_H in Astronomical Units (au). Note the distributions for LPCs and SPC are similarly scattered. Figure taken from Bauer et al. (2015).

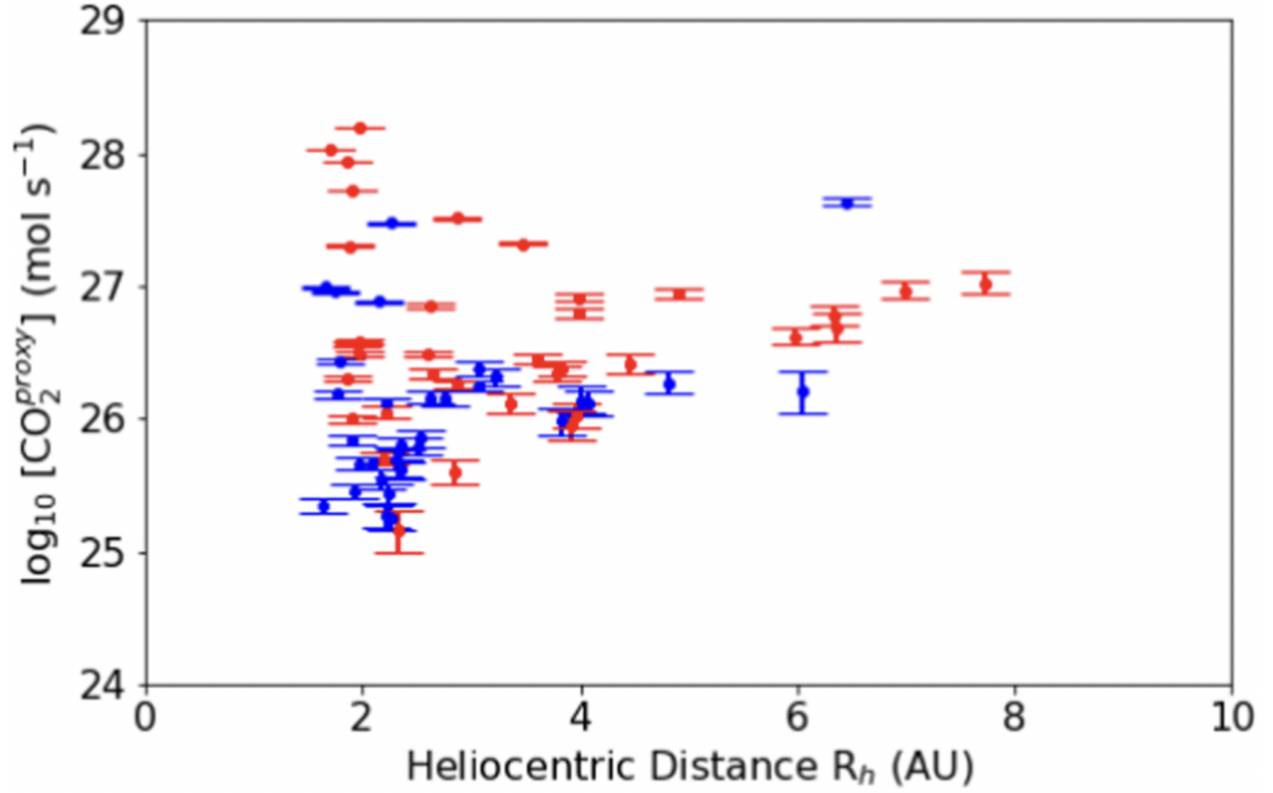


Figure 1.11: NEOWISE Year 1; e.g., 2013-2014 Observed Comets. $\log(Q_{\text{CO}_2}^{\text{proxy}})$ as a function of the heliocentric distance for LPCs (Red) and SPCs (Blue). Excess flux in $4.6 \mu\text{m}$ channel converted to CO₂ production rates and plotted with respect to heliocentric distance, r_H in Astronomical Units (au). Note the distributions for LPCs and SPC are similarly scattered. Figure taken from Gicquel et al. (2023).

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CHAPTER 2

NEOWISE Observations of Distant Active Long-period Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini)

This Chapter is adapted from the peer-reviewed publication titled "NEOWISE Observations of Distant Active Long-period Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini)", which appears in the *Astronomical Journal* Milewski, D. G. et al. 2024, *AJ*, Volume 167, Number 3, Article/Page Number 199. DOI: 10.3847/1538-3881/ad0cf4.

2.1 Overview

Hyperactive comet activity typically becomes evident beyond the frost line ($\sim 3\text{--}4$ au) where it becomes too cold for water-ice to sublimate. If carbon monoxide (CO) and carbon dioxide CO₂ are the species that drive activity at sufficiently large distances, then detailed studies on the production rates of these species are extremely valuable to examine the formation of the solar system because these two species (beyond water) are next culpable for driving cometary activity. The NEOWISE reactivated mission operates at two imaging bandpasses, *W1* and *W2* at $3.4\text{ }\mu\text{m}$ and $4.6\text{ }\mu\text{m}$, respectively, with the *W2* channel being fully capable of detecting CO and CO₂ at $4.67\text{ }\mu\text{m}$ and $4.23\text{ }\mu\text{m}$ in the same bandpass. It is extremely difficult to study CO₂ from the ground due to contamination in Earth's atmosphere. We present our *W1* and *W2* photometry, dust measurements, and findings for comets C/2014

B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini), hereafter, B1, K2, and U3, respectively. Our results assess CO and CO₂ gas production rates observed by NEOWISE. We have determined: (1) comets B1 and K2 have CO₂ and CO gas production rates of $\sim 10^{27}$ and $\sim 10^{29}$ molecules s⁻¹, respectively, if one assumes the excess emission is attributed to either all CO or all CO₂; (2) B1 and K2 are considered hyperactive in that their measured $Af\rho$ dust production values are on the order of $\gtrsim 10^3$ cm; and (3) the CO and CO₂ production rates do not always follow the expected convention of increasing with decreased heliocentric distance, while B1 and K2 exhibit noticeable dust activity on their inbound leg orbits.

2.2 Introduction

Comets are 4.6-billion-year-old surviving relics of the Sun’s protoplanetary disk and, in addition to water, contain volatile inventories of carbon monoxide (CO) and carbon dioxide (CO₂). The two major source regions for comets are thought to be the Oort Cloud (Oort 1950) and Kuiper Belt (Jewitt & Luu 1993) at temperatures of ~ 10 K and ~ 40 K, respectively. The most famous model for cometary mass loss is based on Whipple (1950), where mass loss results from the sublimation of water ice from a central nucleus. However, beyond 5 au, other processes must be responsible for cometary activity because temperatures are too low for sublimation of water ice, as seen with populations of outer solar system bodies such as the Centaurs (Wierzos et al. 2017; Womack et al. 2017; Lisse et al. 2022; Bodewits et al. 2020). CO is difficult and, in the case of CO₂ extremely difficult (given the observation technique), to study through the Earth’s CO₂-rich atmosphere. This makes space-based observatories especially useful in studies of CO and CO₂ species in comets by enabling observing outside of the Earth’s atmosphere.

Table 2.1: Orbital Elements for NEOWISE Observed Comets

Object	UT Discovery Date	a^a	e^b	i^c	Epoch	q^d	UT Perihelion Date
C/2010 U3	2010 Oct 31	−9881	1.00086	55.5	2000	8.446	2019 Feb 26
C/2014 B1	2014 Jan 28	−2973	1.00322	28.4	2000	9.557	2017 Sep 10
C/2017 K2	2017 May 21	−3830	1.00047	87.6	2000	1.798	2022 Dec 19

^a Semimajor axis, in au.

^b Eccentricity.

^c Inclination, in degrees.

^d Perihelion distance, in au.

Notes. All orbital elements taken from the JPL Small-Body Database Browser: <https://ssd.jpl.nasa.gov/sbdb.cgi>

2.2.1 Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini)

B1 was discovered on UT 2014 January 28 (Schwartz & Sato 2014) at a heliocentric distance $r_H \sim 12$ au. Optical images of B1 show a complex morphology that resembles a biconvex lens or “discus” seen edge-on, which has been explained to be due to ejection of material from its equatorial region (Jewitt et al. 2019a). Perihelion passage of B1 occurred on UT 2017 September 10 at a distance $q = 9.557$ au, just around the orbit of Saturn.

Discovered on UT 2017 May 21 (Wainscoat et al. 2017) at $r_H = 16.1$ au, K2 was the previous record holder for the furthest inbound active comet at $r_H = 23.7$ au found in optical precovery data (Hui et al. 2018). It reached perihelion on UT 2022 December 19 at $q = 1.798$ au. Numerous studies of K2, e.g., Jewitt et al. (2017, 2019b, 2021), Meech et al. (2017), Hui et al. (2018), and Yang et al. (2021), have suggested that CO is the likely driver of activity. K2 was found to be active at $r_H = 23.7$ au, only to be recently bested by the previous furthest-ever inbound active comet, U3, at $r_H = 25.8$ au. However, in this work, we explore the possibility that CO₂ may also play a role in driving the observed activity.

Finally, U3 was discovered on UT 2010 October 31 at $r_H = 18.3$ au (Boattini et al. 2010). U3 was previously the furthest inbound comet found to be exhibiting activity at distance $r_H = 25.8$ au from precovery data (Hui et al. 2019). Perihelion occurred on UT 2019 February 26 at $q = 8.446$ au. In 2021, this record was overtaken by the discovery of activity on comet C/2014 UN271 (Bernardinelli–Bernstein); (Bernardinelli et al. 2021). C/2014 UN271 was found to be active in the Dark Energy Survey data at a current record distance of $r_H = 29$ au. With regards to U3, one or a combination of CO and/or CO₂ volatiles may drive activity for this comet. However, few studies have been performed on this object because it is now outbound. A list containing orbital elements for B1, K2, and U3 can be found in Table 2.1.

All three of these comets are important to help us understand why these objects exhibit such strong activity at such large heliocentric distances. Assessing their composition for supervolatile species is important to understand how much of their primordial inventories still remain, especially for comets active at such large r_H .

2.3 Observations and Data Collection

The the NEOWISE Observations and Data Collection process have been previously described in Section (1.3.6).

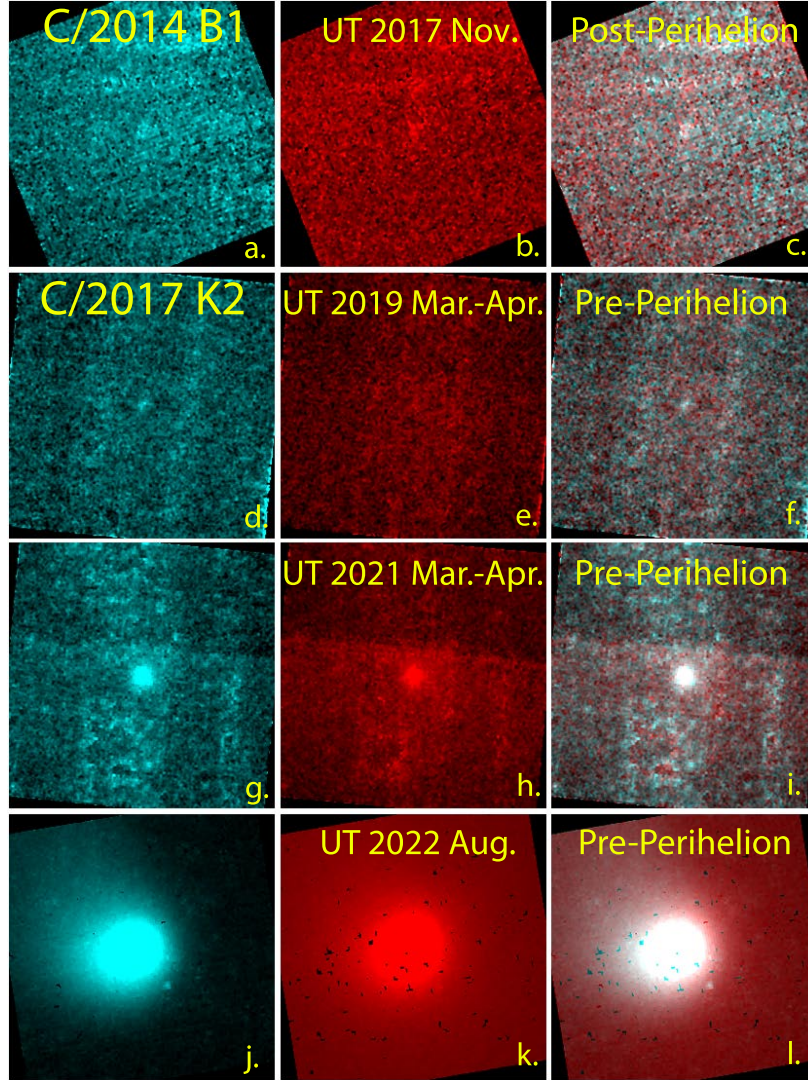


Figure 2.1: Hyperactive NEOWISE Observed Comets Shown in 3-Colors. Composite images made with ICORE (co-added in the moving reference frame of the comets and centered at its predicted ephemeris position from JPL HORIZONS) showing the comet at specific visits in $W1$ mapped to green and blue (left-hand panels), $W2$ mapped to red (center panels), and combined $W1+W2$ color-mapped composite frames (right-hand panels). For all images in Figure 2.1, the orientation (North is up, East is to the left) and image-size is consistent for all subsequent frames (e.g., $\sim 4.5' \times \sim 4.5'$) but the contrast and image stretch are not. Visible streaks are due to the slow motion of the comet, hence the background stars are not being fully suppressed in the stacking process. The name of the objects and dates of observations are labeled and applied for all panels in the rows. U3 has been excluded because its detection was ambiguous. See Table 2.2 for more information. Figure taken from Milewski et al. (2024).

Table 2.2: Observation Geometry and Summary of Photometry for NEOWISE Observed Comets

Object	UT Date ^a	# Frames W1, W2	Detection? Yes or No	r_H ^b	Δ ^c	α ^d	F_{W1} ^e	F_{W2} ^f	$Af\rho$ ^g	Q_{CO_2} ^h	Q_{CO} ⁱ
C/2014 B1	2016 Nov 13	11, 11	Y?, Y?	9.70 ↓	9.66	5.9	0.018	0.344	<277	* 8.5×10^{27}	* 9.9×10^{28}
	2017 Apr 19	8, 9	N, Y?	9.59 ↓	9.24	5.7	0.149	0.532	<2174	* 1.1×10^{28}	* 1.2×10^{29}
	2017 Nov 30	12, 12	Y, Y	9.57 ↑	9.52	5.9	0.112 ± 0.0081	0.231 ± 0.0153	1682 ± 119	$4.0 \pm 0.3 \times 10^{27}$	$4.7 \pm 0.3 \times 10^{28}$
	2018 May 2	11, 11	N?, Y	9.64 ↑	9.23	5.6	0.093	0.387	<1654	* 8.0×10^{27}	* 9.3×10^{28}
C/2017 K2	2019 Apr 1	30, 30	Y, Y	12.0 ↓	11.9	4.8	0.063 ± 0.0038	0.117 ± 0.0099	1853 ± 114	$3.4 \pm 0.3 \times 10^{27}$	$4.0 \pm 0.3 \times 10^{28}$
	2019 Jul 28	22, 22	Y, Y?	11.2 ↓	11.1	5.2	0.130 ± 0.0047	0.185 ± 0.0158	3105 ± 115	$3.9 \pm 0.3 \times 10^{27}$	$4.5 \pm 0.4 \times 10^{28}$
	2020 Mar 30	13, 13	Y, Y	9.49 ↓	9.45	6.0	0.144 ± 0.0060	0.326 ± 0.0172	2112 ± 90	$5.7 \pm 0.3 \times 10^{27}$	$6.7 \pm 0.4 \times 10^{28}$
	2020 Aug 4	16, 17	Y, Y	8.57 ↓	8.40	6.8	0.287 ± 0.0054	0.743 ± 0.0192	3042 ± 60	$1.1 \pm 0.03 \times 10^{28}$	$1.2 \pm 0.03 \times 10^{29}$
	2021 Apr 1	20, 20	Y, Y	6.72 ↓	6.65	8.6	0.799 ± 0.0063	1.370 ± 0.0165	4125 ± 35	$9.0 \pm 0.1 \times 10^{27}$	$1.0 \pm 0.01 \times 10^{29}$
	2021 Aug 1	11, 11	Y, Y	5.67 ↓	5.38	10.1	1.545 ± 0.0095	2.616 ± 0.0254	4595 ± 25	$1.1 \pm 0.01 \times 10^{28}$	$1.2 \pm 0.01 \times 10^{29}$
	2022 Apr 6	20, 20	Y, Y	3.52 ↓	3.38	16.5	5.233 ± 0.0567	12.269 ± 0.0827	3768 ± 40	$1.8 \pm 0.01 \times 10^{28}$	$2.1 \pm 0.01 \times 10^{29}$
	2022 Aug 5	8, 8	Y, Y	2.47 ↓	1.90	22.3	31.965 ± 0.1337	69.712 ± 0.2653	6370 ± 30	$3.2 \pm 0.01 \times 10^{28}$	$3.8 \pm 0.01 \times 10^{29}$
	2017 Sep 29	12, 12	N, Y?	8.97 ↓	8.92	6.4	0.052	0.277	<637	* 5.2×10^{27}	* 6.0×10^{28}
C/2010 U3	2018 Feb 23	21, 21	N, Y?	8.72 ↓	8.43	6.3	0.034	0.219	<369	* 3.8×10^{27}	* 4.4×10^{28}
	2018 Nov 3	16, 16	N, Y	8.47 ↓	8.40	6.7	0.036	0.215	<347	* 3.5×10^{27}	* 4.1×10^{28}

^a UT date at midpoint of observation.^b Heliocentric distance, in au. ↓ or ↑ correspond to inbound or outbound orbits, respectively.^c Geocentric distance, in au.^d Phase angle, in degrees.^e W1 flux, in millijanskies.^f W2 flux, in millijanskies.^g Dust production, in centimeters.^h CO₂ gas production, in molecules per second.ⁱ CO gas production, in molecules per second.

Notes. In cases where there was an ambiguous or no clear detection of the object in W1, our listed W1 fluxes and $Af\rho$ values correspond to upper limits (denoted by <). Q_{CO_2} and Q_{CO} values with an (*) are calculated using the W1 $Af\rho$ upper limit. If the actual W1 values are lower than reported, then our rates for Q_{CO_2} and Q_{CO} will be expected to be larger.

2.4 Methods and Aperture Photometry

2.4.1 Methods

The resulting frames are stacked to position the comet at the very center of each frame, as seen in the Figure 2.1 dataset showing the morphology of specific comet visits which coincide with the data listed in Table 2.2.

Figure 2.1 contains the respective $W1$ and $W2$ composite stacked frames, as well as combined $W1+W2$ color-mapped composite stacked frames for the specified visits, while Table 2.2 contains a summary of the data and measurements. Because of the slow rate of motion of the comets on the sky, in some instances there are some visible streaks and artifacts from background stars and objects not being fully suppressed in the final co-added images. The documentation in the ICORE package by Masci et al. (2013) suggests that it does its best to remove any stars bright enough to contaminate sources against moving objects, such as those from the solar system. However, there are still potential low brightness sources, such as galaxies, which may remain in the field. In this case, we refer to Mainzer et al. (2014). Systematic noise in the background may play a factor in driving up the S/N for very faint objects in the background. However, our work does show that the NEOWISE spacecraft is fully capable of detecting objects at these large distances, although it may not be fully possible to remove all sources from the background. Either way, as the object moves, using the NEOWISE data, we opt to exclude frames where very bright stars within the photometry aperture could potentially contaminate the photometry. As in previous work, we adopt the convention of Bauer et al. (2015, 2017) and Stevenson et al. (2015) with $W1$ mapped to blue and green, and $W2$ mapped to red. All frames are rotated such that the orientation always has North up, East to the left, and the size of the image was set at $\sim 4.5' \times \sim 4.5'$. The contrast and stretch are not the same in the images to suppress some of the remaining artifacts. In most cases (with the exception of some visits involving K2), the comets cannot be seen in the individual exposures but do, however, appear in the co-added images as point

sources, sometimes with extended features suggestive of dust or comae. Table 2.2 also contains a column that lists what we interpret as a comet visual detection or non-detection for the *W1* and *W2* channels from the images.

2.4.2 Aperture Photometry

Our measurement technique was validated against several distant solar system small bodies. Because of the distance and faintness of the comets that we were measuring, the major sources of photometric error are the result of the absolute calibration uncertainty and systematics, which are often due to faint inertial object residuals remaining in the final co-adds. On most visits (with the exception of K2’s passage into the frost line around ~ 3.5 au), because the phase angle was very small (see Table 2.2), we elected to ignore phase angle corrections in our measured flux densities. The dominant source of flux in *W1* at this distance appears to be the result of reflected light of dust grains in the coma which are of unknown size, porosity, and shape. Figure 2.1 shows that most objects are clearly visible, diffuse, and exhibit activity (sometimes observed in individual exposures) not typically seen for comets observed in the NEOWISE data when compared to a stellar point source. Many ‘active’ comets are typically first seen starting around ~ 5 – 6 au in NEOWISE data. However, in this work we found that for the case of K2, it was clearly visible and active as far as ~ 8 – 9 au in both the *W1* and *W2* bandpasses, hence deserving merit of future study.

2.5 Results and Discussion

2.5.1 Dust Production Rates

As previously mentioned, the $W2$ channel contains reflected sunlight and some thermal emission. However, at the distances of the times of the observations, the blackbody temperatures of these bodies are too cold to show significant thermal emission in $W2$, making the reflected light signal the dominant source of flux. Because of this, we need to extrapolate the expected $W2$ contribution using the $W1$ flux by creating a reflected light and thermal model to determine how much, if any, excess flux in $W2$ exists that is assumed to be attributed to CO and CO₂ gas emission. Next, we need to perform an $Af\rho$ calculation that has been previously described in Section 1.3.5. The aperture size, ρ . $Af\rho$ should, in theory, be independent of aperture size, but we opt to use the 11'' radius aperture for reasons previously mentioned. After the aperture photometry has been performed and $Af\rho$ analysis has been performed, an SED plot has been generated for both the reflected and thermal component for each comet visit.

For the comets analyzed in this work, the blackbody temperature at these distances are often low enough that we can largely ignore thermal contributions. This can be seen in Figure(s) 2.2, 2.5, 2.6, 2.7, 2.8, 2.9, 2.10, 2.11, and 2.12 showing the spectral energy distribution plots created for comet visits with obvious excess in the $W2$ signal thus indicating likely gaseous emission. The blue-dotted curve on the left-hand side is the reflected sunlight model, while the solid orange curve on the right-hand side is the theoretical thermal curve and the two curves are summed together with the dashed-black lines. The error bars refer to 1σ measurements. In cases where there was a non-detection, data were ambiguous or poor in $W1$ from visual inspection of the images, we were only able to determine upper limits for $Af\rho$ by measuring the flux at the predicted position of the comet and make an estimation of flux from the remaining structure. A 3σ upper limit on the flux gives a 3σ upper limit on the production rate. However, in some cases there was remaining structure, as can be seen

by visually inspecting the $W1$ and $W2$ images, where sometimes $W2$ appeared to be a point source.

2.5.2 CO and CO₂ Production Rates

Our measured Q_{CO_2} and Q_{CO} values are seen in Table 2.2 and are all between $\sim 10^{27}$ and $\sim 10^{29}$ molecules s^{-1} . For some cases where there were non-detections in $W1$ or poor quality data, such as B1's UT 2016 November visit, upper limits were made on $Af\rho$ thus setting lower limits on Q_{CO_2} as well as Q_{CO} . However, if the actual $W1$ values are lower than reported, then our rates for Q_{CO_2} and Q_{CO} will be expected to be larger. It should be stated that the gas expansion velocity is unknown at this distance but is probably in the order of $\sim 0.2 \text{ km s}^{-1}$, especially for gaseous CO and CO₂ species. This means that a difference in gas expansion velocity value would change the stated results.

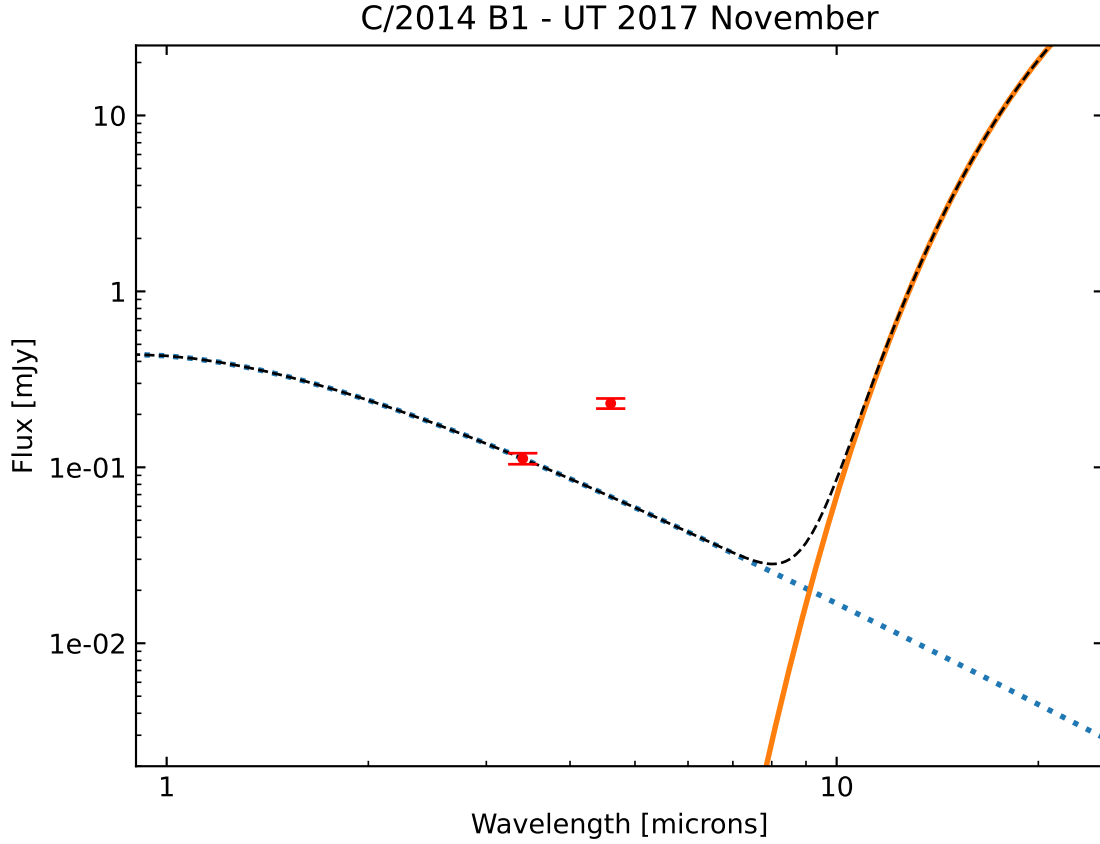


Figure 2.2: NEOWISE Spectral Energy Distribution (SED) Diagram for Hyperactive Comet C/2014 B1 (Schwartz). Spectral energy distribution plots for comets where there is an excess in $W2$ flux which is above the $W1$ signal and assumed to be due to CO and/or CO₂ gas emission. The corresponding names of the comets and visits are listed in labels. The left-hand curve (blue-dotted line) is a reflected sunlight model scaled to the $3.4\ \mu\text{m}$ $W1$ point, while the theoretical thermal curve (orange solid line) is seen on the right-hand side. The two plots are summed together by a thin dashed-black line. Figure taken from Milewski et al. (2024).

2.5.3 Simultaneous Observations of C/2017 K2 (Pan-STARRS) by the James Clerk Maxwell Telescope (JCMT) and the NEOWISE Satellite on UT 2021 April 1

On UT 2021 April 1, Yang et al. (2021) took observations of K2 using the JCMT in Maunakea, Hawaii for an integration time of ~ 8 hr. Similarly, on UT 2021 March 24, data were taken by the Hubble Space Telescope in the optical (HST GO Program, GO 16309; P.I. Jewitt). NEOWISE serendipitously scanned this region of the sky between UT 2021 March 30 to April 4 providing infrared data on morphology, as well as CO and CO₂ production rates (this work) so as to not be encumbered by the Earth’s CO₂-rich atmosphere. In addition, similar morphological features were seen in both datasets. Our results show that we obtain CO and CO₂ production rates of $9.0 \pm 0.1 \times 10^{27}$ mol s⁻¹ for Q_{CO_2} and $1.0 \pm 0.01 \times 10^{29}$ mol s⁻¹ for Q_{CO} . Yang et al. (2021) reported Q_{CO} at a production rate of $1.6 \pm 0.5 \times 10^{27}$ mol s⁻¹. Although the NEOWISE data from *W2* is potentially sensitive to both CO and CO₂, the Yang et al. (2021) measurement is only of CO. Therefore, the simplest explanation is that the NEOWISE detection was of CO₂ in comet K2, which was not seen in the JCMT data.

The results of our study, Yang et al. (2021), and the work of Jewitt et al (2019b) show results over two regimes of the electromagnetic spectrum (e.g., optical and infrared). While not fully understood in terms of sublimation and outburst mechanisms, these results show that Q_{CO_2} and/or Q_{CO} activity does increase with decreasing heliocentric distance. Similar morphology can be seen in both works (see Figure 2.1 of this work and Figure 1 of Yang et al. 2021) but there appears to be an unusual trend of dust production rising and falling over the last three years for K2, as shown in Figure 2.3 of this work. We largely suspect that at the distance where activity for K2 first began to be noticed, there was ejection of dust driven by CO and/or CO₂ sublimation. The results of Wierzbach & Womack (2020) showed that in the case of comet 29P, outbursting of CO did not always correlate with the dust outbursts. Because the surface properties of the comet are unknown, as well as its composi-

tion, this may have led to K2 switching between dust and then gas driven activity, until it moved closer inwards within the solar system where they both became dominant, as evident in the images seen in Figure 2.1, specifically, panels ((d.)–(l.)) showing its morphology with time and whether dust and/or gas were prevalent in the signal. Future studies may help to investigate this trend and also its significance with other comets. However, it may be such that either CO and/or CO₂, or both were produced and appear to be the likely culprits driving activity on distant comets such as K2 and those arriving from the Oort cloud and the outermost regions of the solar system.

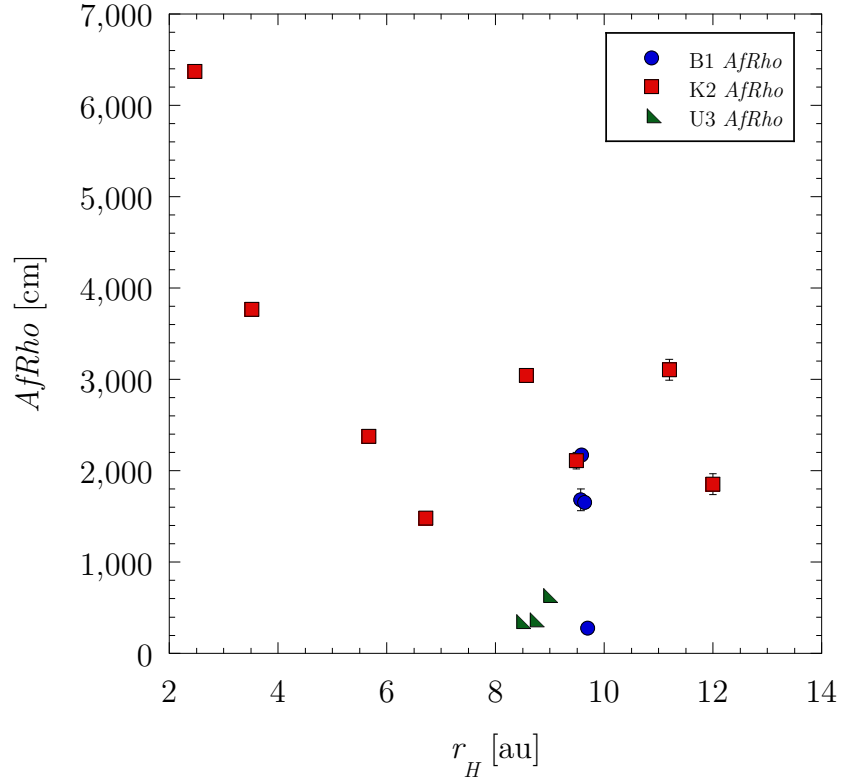


Figure 2.3: Hyperactive NEOWISE Observed Comets Dust Production ($Af\rho$) Versus Heliocentric Distance (r_H). Evolution of computed $Af\rho$ values seen over various NEOWISE visits as a function of heliocentric distance, r_H . B1, K2, and U3 $Af\rho$ values are denoted by blue circles, red squares, and green triangles for each respective comet. Note: because of some visits where there was an ambiguous or no clear $W1$ detection, these $Af\rho$ values correspond to upper limits. Figure taken from Milewski et al. (2024).

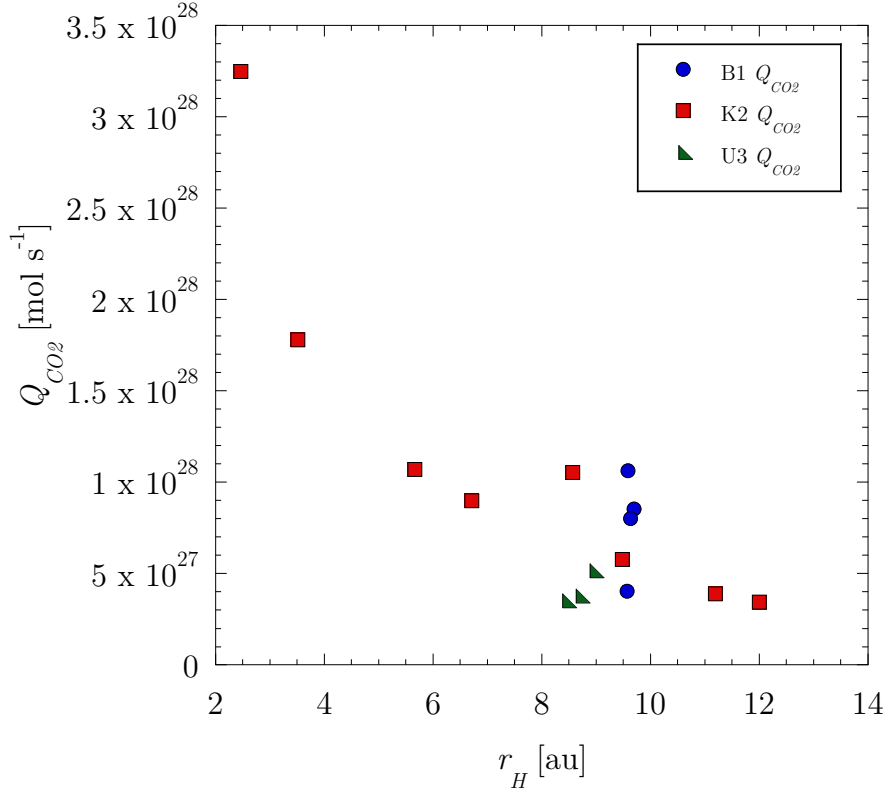


Figure 2.4: Hyperactive NEOWISE Observed Comets CO₂ Production (Q_{CO_2}) Versus Heliocentric Distance (r_H). Evolution of computed Q_{CO_2} values seen over various NEOWISE visits as a function of heliocentric distance, r_H . B1, K2, and U3 Q_{CO_2} values are denoted by blue circles, red squares, and green triangles for each respective comet. Note: because of some visits where there was an ambiguous or no clear $W1$ detection, the upper limit $Af\rho$ values determined in Figure 2.3 thus correspond to lower limits for Q_{CO_2} values. Figure taken from Milewski et al. (2024).

2.5.4 Evolution of Cometary Activity with Heliocentric Distance r_H

From our measurements, specifically in 2017 November where there is a detection in both $W1$ and $W2$, B1 appears to have an $Af\rho$ value of 1682 ± 119 cm just after perihelion passage. With regards to the measurements performed for B1 with an example in Figures 2.1 (a.)–(c.) of the B1 UT 2017 November visit. It is unknown how much of the remaining structure in the co-add may have affected the measured $Af\rho$ values. However, there is a much clearer detection in the $W2$ frames, which suggests that the detections may be real. As in previous studies of NEOWISE observed comets, detections more often occur in $W2$ compared to $W1$, which are likely to be an indicator of excess in gas flux driving activity.

We note that for all 15 epochs of coverage for these comets, there appear to be detections in $W2$ whereas only nine of our comet visits have clear noticeable features indicating activity in $W1$. We generally assume that gas emission results in dust production, but gas emission flux would be drowned out if there is too much activity, especially if the dust is optically thick. This may be what is occurring in Figures 2.1 (d.)–(f.) (e.g., UT 2019 March–April) for K2. In addition, K2 is noteworthy in that our measured $Af\rho$ values are as low as 1853 ± 114 cm and as high as 6370 ± 30 cm. Jewitt et al. (2019b) reported that K2 would likely experience a noticeable change in activity some time in early-2019 as it passes around the region of ~ 12 au, which is confirmed in our NEOWISE data and may be due to amorphous crystallization should amorphous ice exist on the comet. Amorphous crystallization refers to disordered structures, but with irregularity and the co-existence of both crystalline and amorphous water ice. These structures are also subject to irradiating sources such as the Sun and cosmic rays, which affect the organization of molecules, other volatiles, and the conditions of vapors at very cold temperatures at their initial formation (Jenniskens & Blake, 1996). In the UT 2019 July visit, the excess $W2$ flux can be seen on the spectral energy distribution plot (see Figure 2.6) which corresponds to a Q_{CO} value of $4.5 \pm 0.4 \times 10^{28}$ mol s^{−1}. Also noteworthy is an evident trend as seen in Figure 2.4 showing that Q_{CO_2} measurements

mostly increase with decreasing heliocentric distance. The gas production peaks between the UT 2020 March–April as well as UT 2020 August visits, and then falls during the UT 2021 March–April visit at about 6.72 au. However, with the $Af\rho$ measurements (e.g., dust production) specifically for K2, these seemingly rise during the satellite’s second coverage in a given year. For example, for 2019, the first coverage is from March–April and the second is July–August. This trend has been obvious from 2019 to 2021, possibly suggesting an effect of solar radiation acting on some other volatile species present in the comet, which is worthy of future investigation.

In the case of U3, it is interesting that most of its major activity (at least from visual observations; e.g., Hui et al. 2019) is suggested to have occurred much earlier than perihelion. Another result of this work is that U3 does not follow the expected convention of Q_{CO} and Q_{CO_2} increasing with decreasing distance to the Sun (unlike most of our results with B1 and K2). While U3 may be active in *W2*, it appears to be quiescing in activity in the later visits for gas production (see Figure 2.4). Because of (visual) non-detections in *W1*, we cannot comment on its dust production because we have only determined upper limits for $Af\rho$, thus setting lower limits for Q_{CO} and Q_{CO_2} .

Our work is unique in that we perform measurements of gas and dust for these three comets of interest over several visits during pre- and post-perihelion, with the latter specifically for B1. Figures 2.3 and 2.4 best summarize the activity of each comet from our measured $Af\rho$ and Q_{CO_2} values for each of the respective visits with heliocentric distance. In terms of Q_{CO_2} and/or Q_{CO} production with decreasing heliocentric distance, K2 mostly follows the expected convention of increasing with decreased heliocentric distance, U3’s activity decreases with decreasing heliocentric distance, and B1 first increases with decreasing heliocentric distance, decreases, and then increases in the last visit. All comets have some coverage during the inbound legs of their orbits. This work has also covered the entire

NEOWISE dataset while K2 was inbound from the years 2019–2022, first appearing as a point source and sometimes with extended features in the stacked images, and then in the individual frames around $\sim 8\text{--}9$ au. Because K2 was still inbound (at the time of submission of this work), it will be interesting to see the long-term evolution of gas and dust production values, as well as the morphological aspects and what role, if any, CO_2 and CO chemistry may have in what has been and what will be observed during its outbound orbit.

Previous studies have been reported for hyperactive comets near perihelion approach, such as 21P/Giacobini–Zinner (Pittichová et al. 2008) and 46P/Wirtanen (Farnham et al. 2019). Few studies have been performed in a detailed manner over a long temporal baseline on the LPCs. However, Gunnarsson et al. (2003) performed a long-term study over 17 epochs on C/1995 O1 (Hale–Bopp), though all epochs of observation are when Hale–Bopp was outbound. It is our hope that this study will provide an informative and comparative benchmark for gas and dust production for LPCs active at large heliocentric distances (especially for the case of K2) in the years to come. This work, as well as future studies, may help us understand why certain LPCs become active at large distances from the Sun. Furthermore, NEOWISE is one of the last functioning observatories offering a unique capability for a large survey of cometary CO and CO_2 , until the advent of SPHEREx (Doré et al. 2018). However, the James Webb Space Telescope can also perform targeted studies on cometary morphology, as well as CO and CO_2 production rates.

2.6 Summary

Using NEOWISE reactivated mission data, we have performed a study of CO and CO_2 production rates on remarkably active long-period comets B1, K2, and U3. This range of data over large heliocentric distances covers a large timespan during various portions of their orbits. The major results of this work are summarized as follows:

1. Our most important result is that through NEOWISE photometry, we have determined Q_{CO_2} and Q_{CO} values between $\sim 10^{27}$ and $\sim 10^{29}$ molecules s^{-1} , respectively, attributed to excess flux in the *W2* signal, for CO_2 and CO species for some of the NEOWISE observations of B1 and K2. These values are not independent Q_{CO_2} and Q_{CO} measurements, and represent the amount of CO and CO_2 being produced if one assumes that all of the gaseous emission is from CO (or CO_2). Where excess flux in *W2* exceeded that of the *W1* signal, the corresponding results presented are our measured Q_{CO_2} and Q_{CO} production rate values. For the case of U3, we investigated if there was a purported outburst by using the NEOWISE data. As this comet has receded from the Sun, it appears to be declining in activity, as evident by its low production values. Though we have determined lower limits for the reported Q_{CO_2} and Q_{CO} rates for U3, they may still be comparable with B1 and K2.
2. The range of $Af\rho$ dust production values for B1 (in all but one case) and K2 are all on the order of $\sim 10^3$ cm, suggestive of strong cometary hyperactivity (see Figure 2.3). In the case of B1, peak dust emission takes place shortly after perihelion while K2 (now moving outbound) has strong dust-driven activity, even at heliocentric distances at or greater than ~ 11 au. We correlate the rise in dust production with the onset of gaseous emission. It may be that at the onset of gas emission, dust particles may be ejected from the parent body, and there may be effects presently unknown to us (as the comet has not been visited in-situ). The fact also remains that the cometary composition of K2 is unknown, which may cause gas and/or dust production to become dominant over time. This is an interesting effect that we have noticed, but future studies will be needed on K2 to determine whether or not this may be significant. While U3 is a remarkable comet found to be active at a large heliocentric distance, its activity seems to have dropped off dramatically around ~ 9 au, even as it was still approaching perihelion, possibly suggesting an almost full depletion of volatile materials, or some

other unknown process. Because there are only three data points and this comet is faint and very far away, we can only surmise that the comet seems to be decreasing in CO and/or CO₂ activity.

3. From Figure 2.4, the three comets each have a distinct case of Q_{CO_2} and Q_{CO} production, sometimes following the expected convention of increased production rates with decreasing heliocentric distance when the comets are on the inbound leg of their orbits. Meanwhile, for the case of B1, we find that dust production was rising and peaked shortly after perihelion, and then declined with our $Af\rho$ measurements, whereas its gas production rates appear to rise in the last visit.

2.7 Additional NEOWISE Spectral Energy Distribution (SED) Diagrams

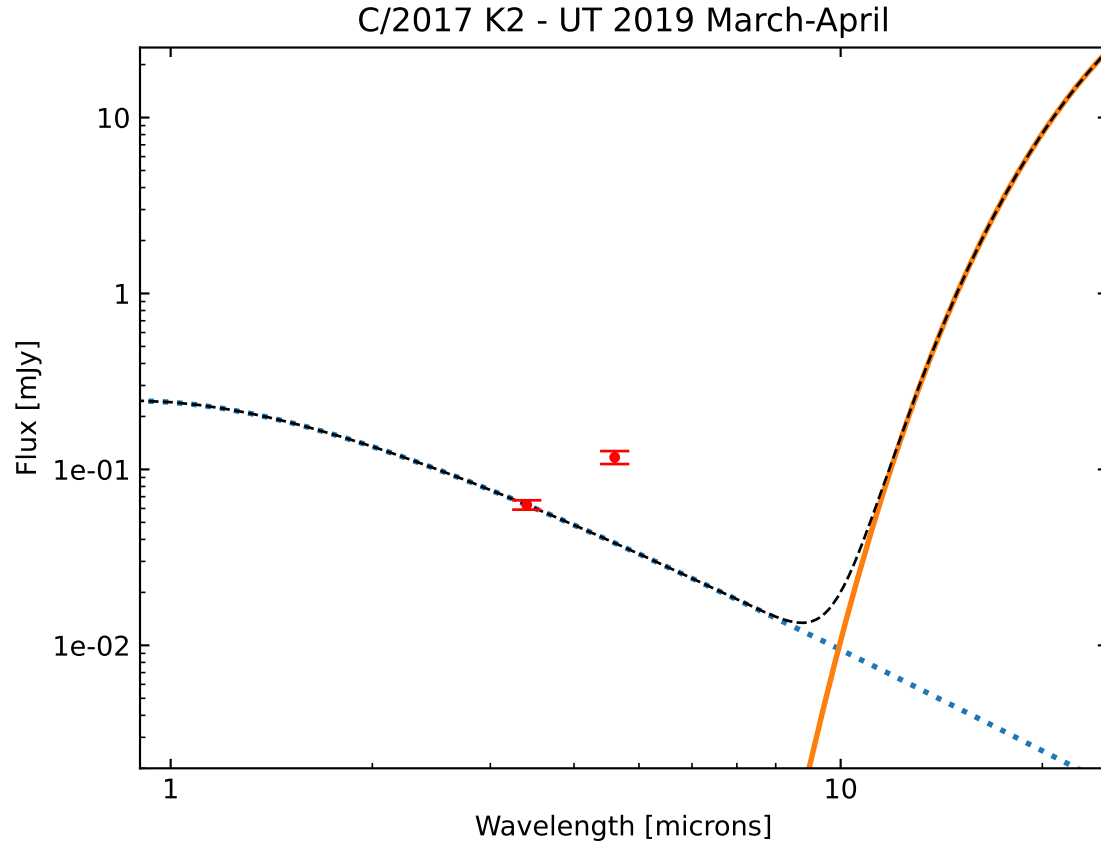


Figure 2.5: Same as Figure 2.2, but for Hyperactive Comet C/2017 K2 (Pan-STARRS). Figure taken from Milewski et al. (2024).

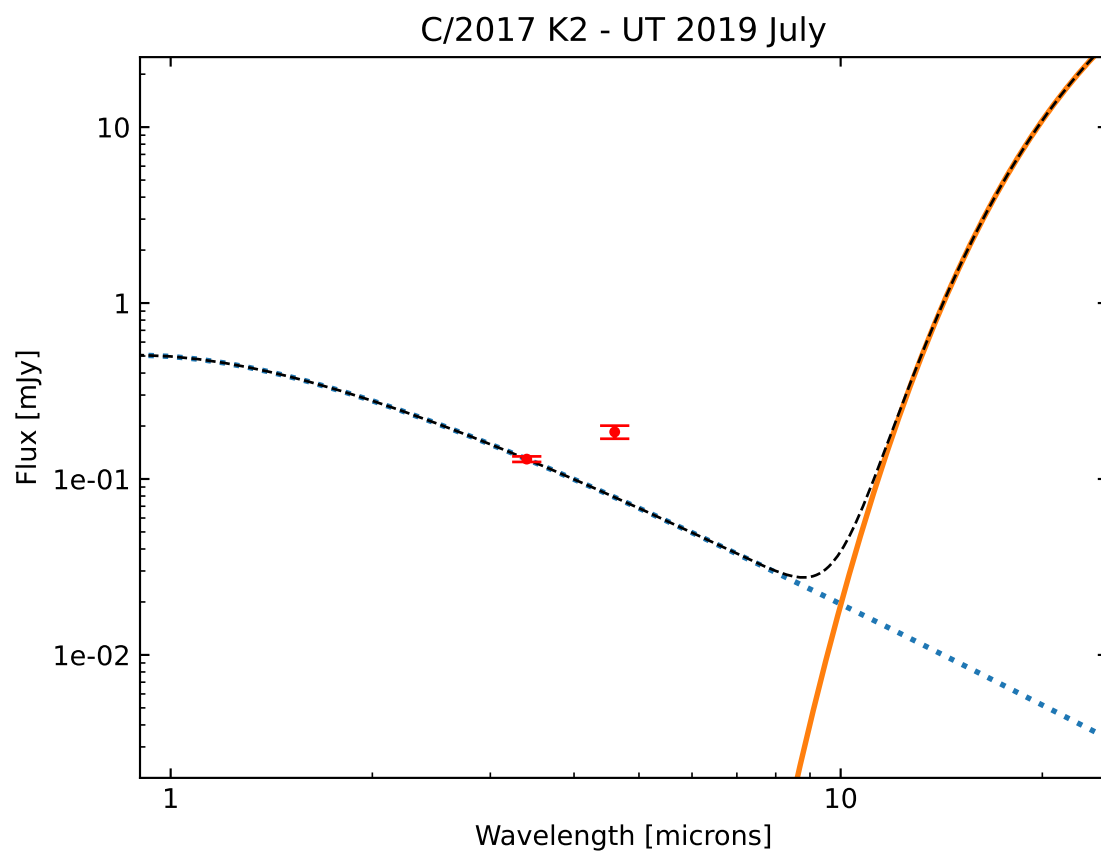


Figure 2.6: Same as Figure 2.2, but for Hyperactive Comet C/2017 K2 (Pan-STARRS). Figure taken from Milewski et al. (2024).

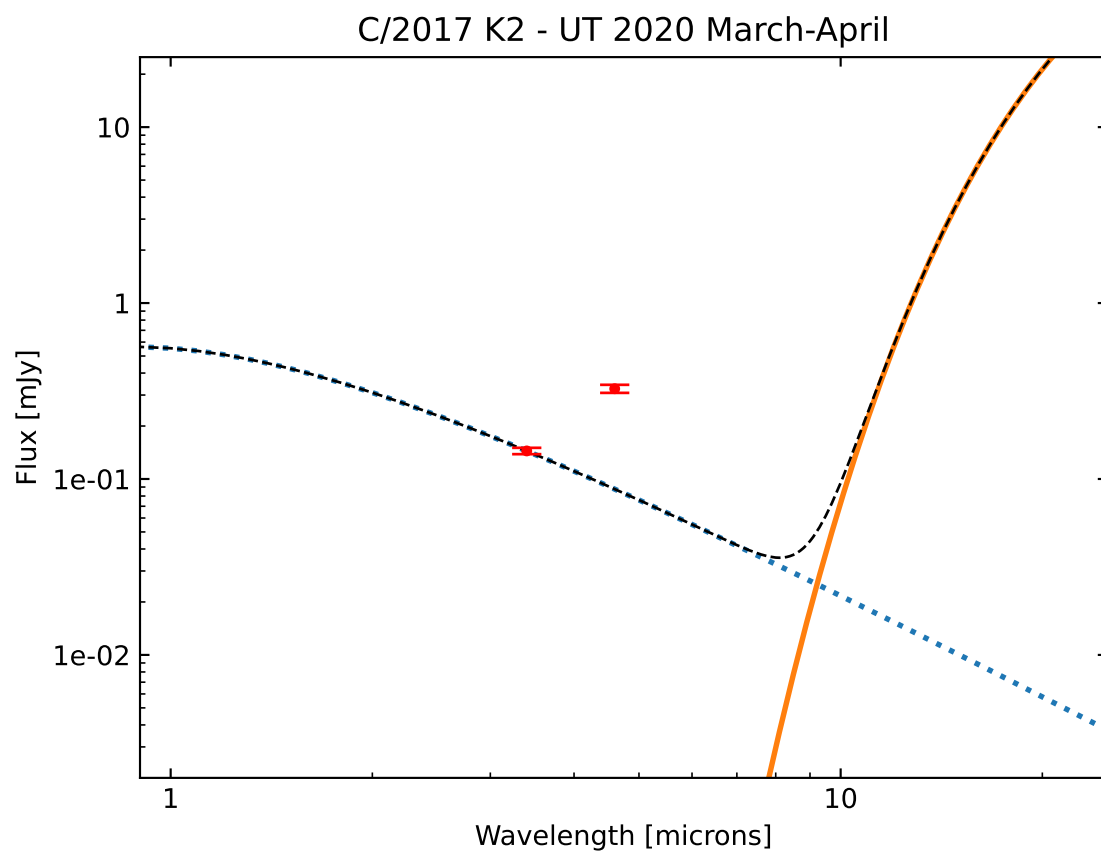


Figure 2.7: Same as Figure 2.2, but for Hyperactive Comet C/2017 K2 (Pan-STARRS). Figure taken from Milewski et al. (2024).

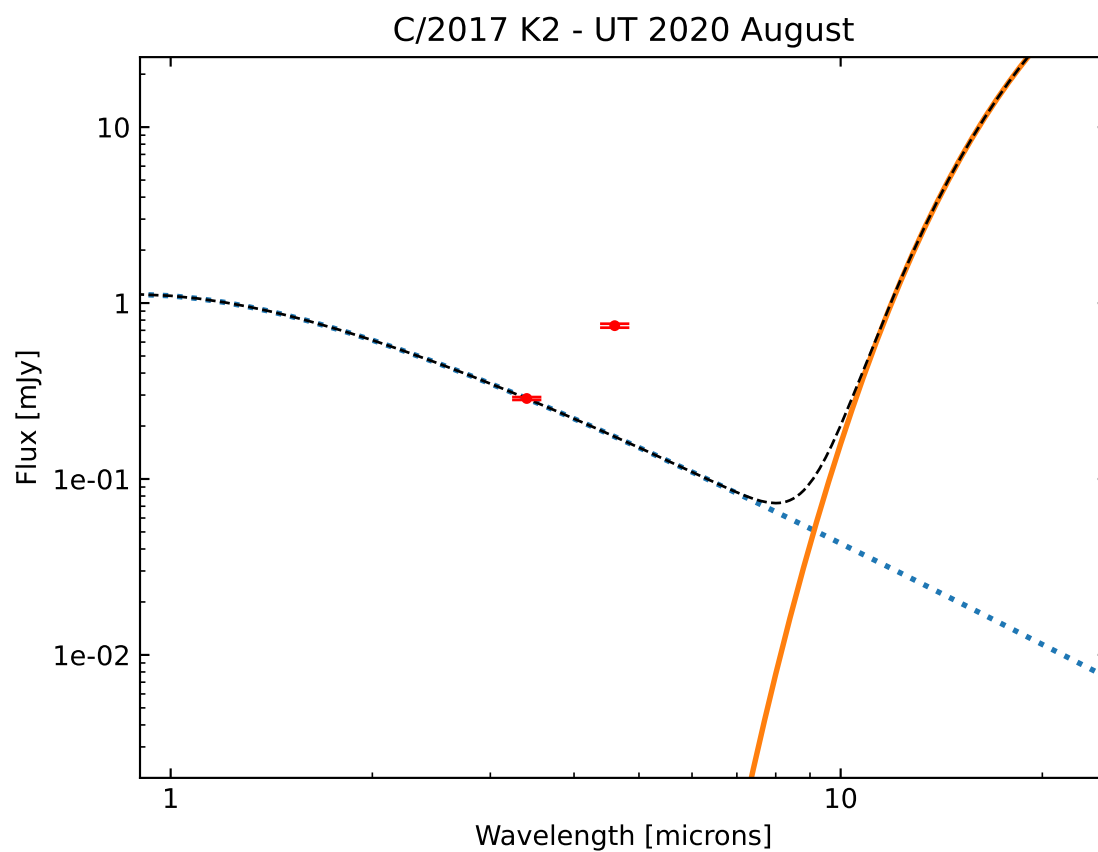


Figure 2.8: Same as Figure 2.2, but for Hyperactive Comet C/2017 K2 (Pan-STARRS). Figure taken from Milewski et al. (2024).

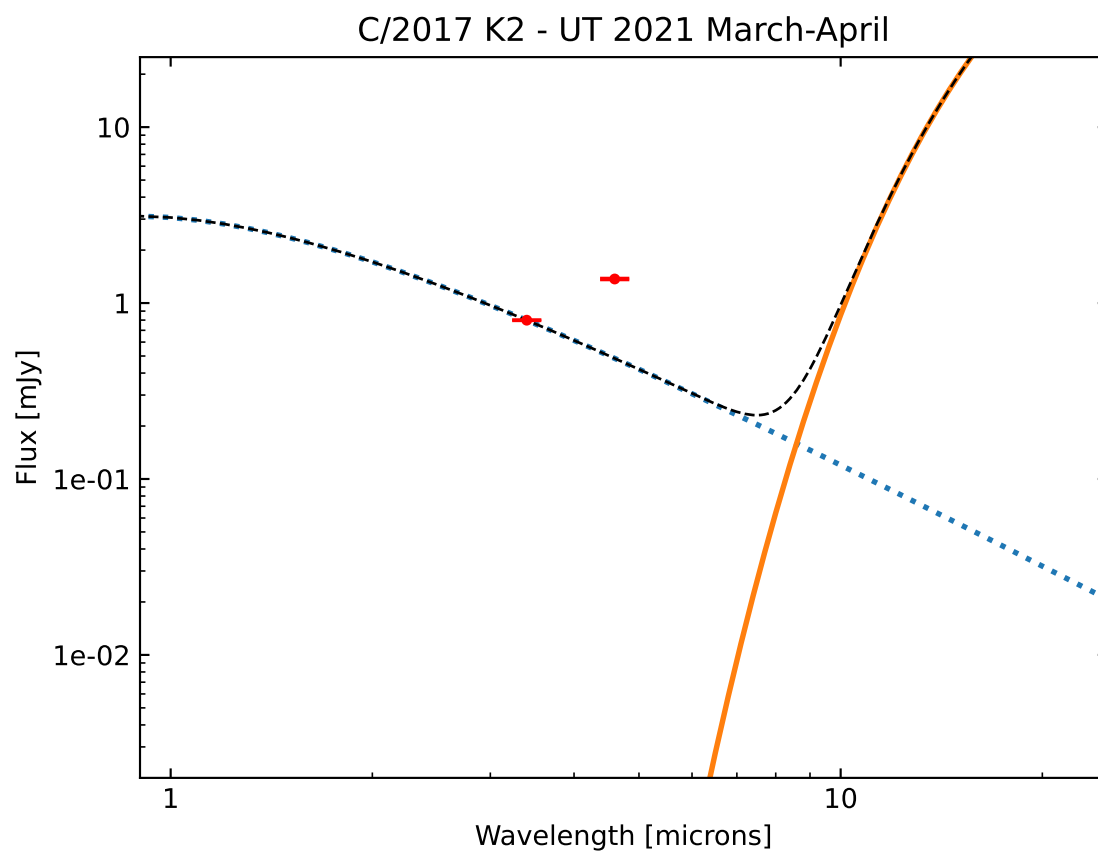


Figure 2.9: Same as Figure 2.2, but for Hyperactive Comet C/2017 K2 (Pan-STARRS). Figure taken from Milewski et al. (2024).

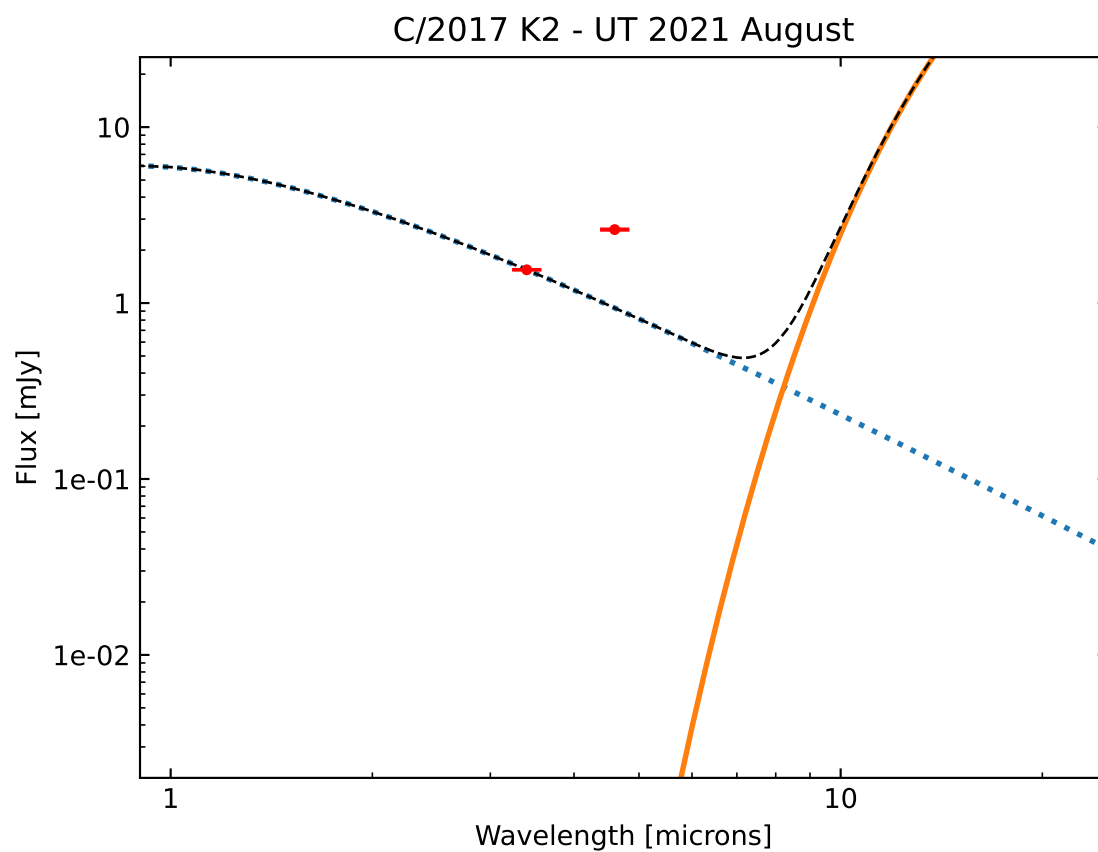


Figure 2.10: Same as Figure 2.2, but for Hyperactive Comet C/2017 K2 (Pan-STARRS). Figure taken from Milewski et al. (2024).

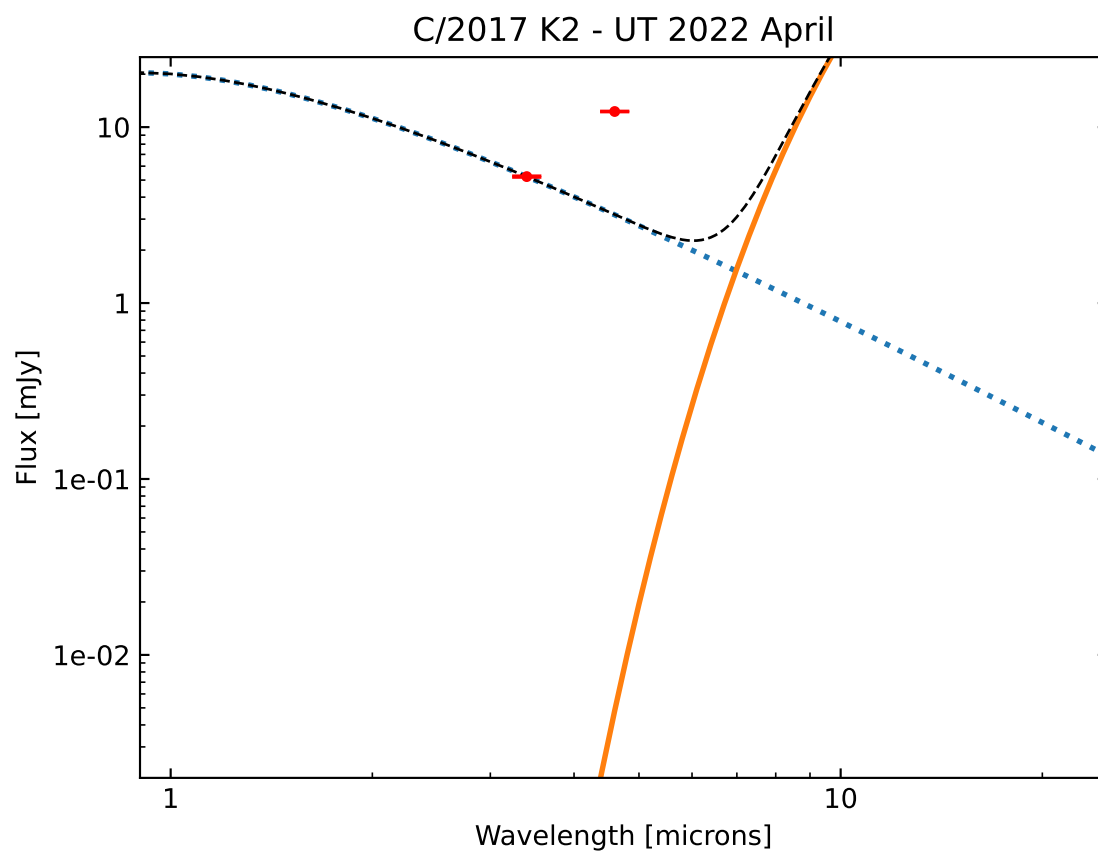


Figure 2.11: Same as Figure 2.2, but for Hyperactive Comet C/2017 K2 (Pan-STARRS). Figure taken from Milewski et al. (2024).

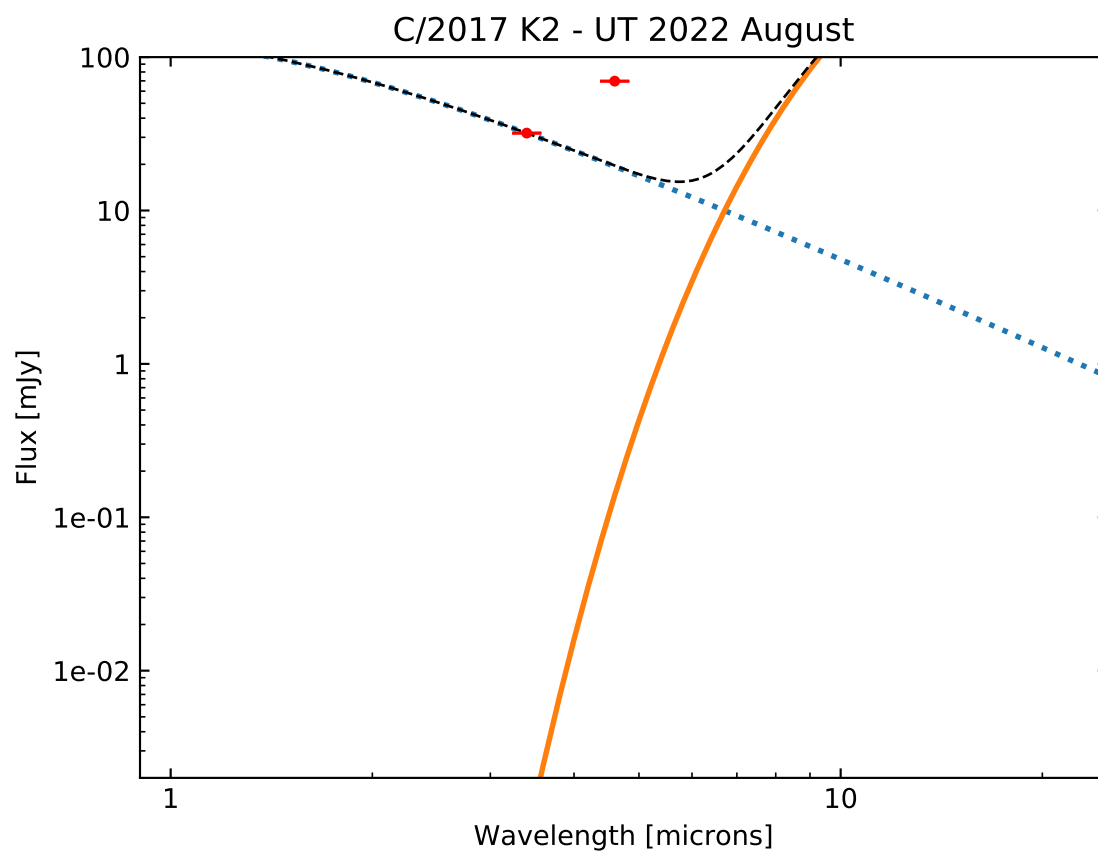


Figure 2.12: Same as Figure 2.2, but for Hyperactive Comet C/2017 K2 (Pan-STARRS). Figure taken from Milewski et al. (2024).

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CHAPTER 3

Activity of Dust and Gas Emission of Active Centaur 29P-Schwassmann-Wachmann 1 (SW1) Observed By The NEOWISE Reactivated Mission

This chapter is adapted from the paper titled "Activity of Dust and Gas Emission of Active Centaur 29P-Schwassmann-Wachmann 1 (SW1) Observed By The NEOWISE Reactivated Mission" that is in preparation to be submitted to the Astronomical Journal (AJ) (Milewski et al. (to be submitted, 2024).

3.1 Overview

We present a multiyear analysis of notoriously active Centaur 29P/Schwassmann–Wachmann 1 (29P/SW1) based on the currently available 2014-2022 NEOWISE Reactivated Mission data. Our data coverage is further augmented by simultaneous ground-based observations using the ATLAS (visual) telescope project. Dust and gas production rates are measured using NEOWISE's *W1* and *W2* channels, both sensitive to dust, while the latter, at 4.6 μm covers the fundamental bandpasses for CO+CO₂ molecular species (e.g., 4.67 μm and 4.23 μm , respectively). Though persistently in an active state, we show the gas production remains rather steady, but there have been a few episodic outburst events, quantified and seen visually (most notably UT 2017 May; dust production: $Af\rho \sim 6234.1 \pm 62$ cm, as well as plume structures) in this work. We find through 15 observation arcs (spanning ~ 8 yr) that unlike other small bodies active beyond ~ 4 au, 29P/SW1's gas activity does not always

precede dust activity events which are expected to follow thereafter, contrary to what has been primarily observed for other comets. Our infrared data monitoring dust activity at $3.4\ \mu\text{m}$ closely matches that of the visual (420–820 nm) from contemporaneous monitoring via the ATLAS telescope array spanning the years 2015–2022. Finally, we provide detailed analysis of an unusual ~ 40 -day episodic outburst event occurring during UT 2020 July–September (estimated MJD of Ejection: ~ 59042.85) measuring a (slow) dust speed of $v_{\text{dust}} = 60 \pm 2\ \text{m s}^{-1}$, at the lower end of published literature values. Our results are in good agreement with similar studies observing 29P/SW1 over various regimes of the electromagnetic spectrum.

3.2 Introduction

Comets are small solar system bodies that contain and preserve source volatile materials such as water-ice, carbon monoxide (CO) and carbon dioxide (CO₂) inventories from their initial formation (Mumma & Charnley 2011; Eistrup et al. 2019). In the formation of interstellar debris disks, CO and CO₂ are often found as common molecular species and have recently been detected in interstellar comet 2I/Borisov (Cordiner et al. 2020; Bodewits et al. 2020). Within the solar system, but beyond the water-ice sublimation region that corresponds to $\sim 3\text{--}4$ astronomical units (au), the activity observed for distant small bodies such as comets must be attributed to species other than sublimation of water-ice. Many studies (including, but not limited to): Ootsubo et al. (2012), Reach et al. (2013), Bauer et al. (2015), Womack et al. (2017), Rosser et al. (2018), Bouziani & Jewitt (2022), Gicquel et al. (2023), and Milewski et al. (2024) have shown that volatiles such as CO and CO₂ are important cometary molecular species that are capable of driving activity at large heliocentric distances. CO₂, in some cases (see A’Hearn et al. 2011; Bauer et al. 2015, 2021) appears to be the dominant volatile suspected of causing activity beyond the water-ice frost line ~ 4 au and also for the case of near-Earth comets inwards of ~ 2 au (Bauer et al. 2021). Conversely, CO has been shown to be the exception in comets famously known to be brighter and more persistent in

activity than typical Short-Period Comets as well as Long-Period Comets (hereafter, SPCs and LPCs, respectively). The distinction between cometary families and subdivisions can be classified mostly on the basis of their orbit periods with LPCs having orbits at or exceeding 200 years while the SPCs having less than this (Nesvorný et al. 2017). A further subdivision of SPCs are that of the Centaurs who occupy a region of the outer solar system with a grouping of inactive, and ‘active’ Centaurs (Jewitt 2009). Some exceptional examples of comets where CO has been suggested to be the dominant volatile include 1P/Halley and C/1995 O1 (Hale–Bopp); (Meier et al. 1993; DiSanti et al. 1999; Jewitt et al. 1996; and Bockelée–Morvan et al. 2009). For distant solar system objects coming inward from the Oort cloud, around the region of $\sim 9\text{--}20$ au, activity of small bodies appears to undergo significant, and noticeable chemical pathways ultimately resulting in ground or space-based detection of these objects. This further suggests that cometary activity begins at Kuiper belt distances (Jewitt et al. 2021) and a cohesion bottleneck (Jewitt et al. 2019) may be indeed responsible for altering these bodies as they pass within the Kuiper Belt, and into the Main Belt with some further distinctions of the members of these specific solar system populations. Nonetheless, many studies and laboratory experiments have been performed in order to assess the mechanisms, interaction, and chemistry of volatile species at specific environments where these bodies reside (Crovisier & Encrenaz 1983; Lisse et al. 2022).

However, the most famous among the members of the active Centaurs and a specific small body where CO has been shown to be a major contributor of activity is that of comet 29P/Schwassmann–Wachmann 1 (hereafter, 29P/SW1). When first discovered in 1927, 29P/SW1 was found in an active state. 29P/SW1 has since been well-known for exhibiting a near-perpetual dust coma. The orbital osculating elements of 29P/SW1 are semimajor axis (a) of 6.05 au, eccentricity (e) of 0.04475, inclination to the ecliptic (i) of 9.36° , and a perihelion distance (q) 5.78 au according to JPL’s Small-Body Database Lookup (Reference: JPL K192/80). 29P/SW1 has an atypical orbit (given its near-circular

orbit when compared to other comets), distance, brightness, frequent episodes of outburst activity causing demonstrably measurable changes in its brightness. 29P/SW1 also has been described as a crucial transitional object migrating inward from the outer solar system, thus becoming a SPC with the suggestion that it will behave much differently in the next 10^4 years. Another possibility is that during this time, 29P/SW1 may become sufficiently bright to potentially outshine any other comet in the sky. This specific transition in the evolution of 29P/SW1’s orbit has led to the nomenclature of ‘Gateway’, of which 29P/SW1 is the largest of four presently known such objects (Sarid et al. 2019; Lisse et al. 2022). Modeling performed by Guilbert-Lepoutre et al. (2023) suggests that 29P/SW1 may perhaps be even more thermally processed than other objects entering this region. Another anomaly of 29P/SW1 is its rather large nucleus currently estimated to be of radius 32.3 ± 3.1 km (Schambeau et al. 2021). A further peculiarity of 29P/SW1 is the fact that it is often bright enough (especially during a period of outburst) to be an easy target-of-interest for Earth-based observers even when it is considered ‘quiescent’ or inactive. This alone has made 29P/SW1 a very well-studied object.

3.2.1 NEOWISE (Infrared) Data

The NEOWISE spacecraft operates with a 40-cm aperture covering a $47' \times 47'$ field of view of the sky with pixel scale of $2.''75 \text{ pixel}^{-1}$ and image Full-Width at Half Maximum (FWHM) coverage of $6.''1$ and $6.''4$ in $W1$ and $W2$ respectively. Images are taken every 11 s by the spacecraft using a dichroic beamsplitter with an effective exposure time for each individual frame of 7.7 s in both $W1$ and $W2$ filters. The spacecraft does not make targeted observations but data are taken when the NEOWISE field of view sweeps over a given region of the sky where an object happens to be located. This usually occurs for solar elongation angles of $\sim 90^\circ$ – 110° due to the orbit of the satellite. Data provided from NEOWISE is simultaneously taken in specific observation arcs that we refer to as “visits” that typically span a ~ 3 day coverage. For a given set of observations, a “visit” is simply the

collection of data and images resulting from an observation arc (Bauer et al. 2015). Because of NEOWISE’s motion on the sky, moving (solar system) objects can be further separated from background objects. Data are processed, calibrated, astrometrically corrected, and then become available on the Infrared Science Archive (IRSA) that is further explained in Cutri et al. (2015). The final data products seen in Figures 3.4 and 3.5 as images of 29P/SW1 in $W1$, $W2$, and finally a composite $W1+W2$ version for each individual column are the result of individual 7.7 s frames that are coadded (see Section 3.3) and further assessed to quantify dust and gas production on a qualitative level. Table 3.1 lists the obtained fluxes as well as dust and gas production rates as a result of aperture photometry performed on the datasets. Typically, these individual exposures comprise a dataset of about ~ 10 or so individual images in both $W1$ and $W2$, within a given visit. Another unique aspect of NEOWISE is that on subsequent coverages of the sky for a particular visit, data are taken just $\sim$ hours apart providing further refined information for solar system small bodies. This allows us to further investigate whether or not the activity of gas and dust is in any way correlated, or if the plausible explanation of dust activity preceding gaseous emission by the rising of dust grains due to the onset of gaseous emission from the body.

In Table 3.1, we list the observational geometry and dates of coverage for 29P/SW1 NEOWISE data. For cases where there was more than one observation in a given year, we list the year followed by the letter ‘A’ or ‘B’ to represent subsequent observing coverage taken. As we use data from the NEOWISE Reactivated Mission spanning the years 2014–2022, we do note that in 2015, we excluded two visits having very poor-quality data, but do list the dates of observation in Table 3.1 for consistency.

3.2.2 ATLAS (Visual) Data

ATLAS consists of four 0.5-m telescopes with two assets located at Haleakala (HKO) and Mauna Loa (MLO) on the Hawai‘ian islands, providing a cadence of ~ 1 day from -50° to

+50°. At the polar regions, there is coverage spanning and ~ 2 days over a series of 4×30 s images taken about one hour apart for Near-Earth Object (NEO) coverage. The location of the telescopes, scanning pattern, and cadence assures goals of surveying the sky for planetary defense objectives and preventing false alarms. The CCD detectors on each telescope contain an STA 1600 $10,560 \times 10,560$ pixel single detector. The pixel scale is $1.''86 \text{ pixel}^{-1}$ with a roughly $5.^{\circ}4 \times 5.^{\circ}4$ field of view. Individual exposures have a 10 s overhead between subsequent shutter exposures that effectively tile the sky in an overall 29 square degree field created from 30 s exposures. The remaining two telescopes became operational in 2022 and are found in South Africa, and Chile thus now providing a full-coverage of the sky in both the Northern and Southern hemispheres via two cyan and orange (hereafter referred to ‘*c*’ and ‘*o*’) filters having bandpasses of 420–650 nm and 560–820 nm, respectively. The *o* filter can be used at twilight and is especially useful for sufficiently dim solar system objects (e.g., ~ 19.7 mag based on the AB magnitude system), and its use can be seen in Figure 3.5 of this work. It is important to point out that at the present time, there is currently no direct filter translation between the ATLAS to broadband optical filters. However, the *c* filter is most similar to composite PS1 *g* + *r* filters (e.g., 420–650 nm) and the *o* filter is most similar to composite PS1 *r* + *i* filters (e.g., 560–820 nm). Also, the HKO asset contains both the *c* and *o* filters, while the MLO asset contains only the *o* filter. Therefore, a majority of our data use mainly the *o* filter. Using the available ATLAS data, photometry can be performed on specific targets of interest. Forced photometry allows user selection of known solar system objects classified by the Minor Planet Center (hereafter, MPC) over specific input intervals. A Point-Spread Function (PSF) is calculated for sufficiently bright field stars with high Signal-to-Noise and then fit to either a target or difference image (in the case of transient objects) to determine the photometry measurements (Tonry et al. 2018; Smith et al. 2020).

3.3 Methods and Analysis

Additional information regarding the methods and analysis of the NEOWISE data have been presented in Sections 2.3 and 2.4. The moving objects are detected by the WISE Moving Object Pipeline Service (WMOPS) in accordance with Cutri et al. (2011, 2012, 2015), whereas the WISE Science Data System (WSDS) performs the necessary calibrations. WMOPS successfully identifies moving solar system objects from fixed background sources and reports these observations several times per week to the MPC. We limit our selection criteria and data usage to frames with a quality assurance factor flag (e.g., ‘qual_frame’) of 5 or greater (with 10 being the highest) and the object must be visible in both the individual and the co-added images that are made using the single-exposure frames used to make a mosaic. Data criteria can be further refined by excluding frames containing stray moonlight, the Southern-Atlantic Anomaly (SAA) being located within the vicinity of the object being imaged, and only using frames that contain near-neighbor pixels from previous frames for a particular visit. These mosaics are then centered at the object in accordance with the documentation provided in Masci (2013) for the Image Co-addition with Optional Resolution Enhancement package (hereafter, ICORE) and further described in that reference. The resultant frames are resampled to $1'' \text{ pixel}^{-1}$ that have a higher signal-to-noise ratio (S/N) with most moving or trailed objects such as galaxies, stars, and cosmic rays suppressed. This boosted S/N is dependent on the object and its position in the sky as well as incorporation of the number of useful frames. Greater S/N is the result of more useful frames being coadded for a given visit. Another advantage of the coadded data is that it reveals more features which sometimes are not always apparent in single-exposure images as well as allowing for a direct comparison between the dust-dominated *W1* channel and the gas-dominated *W2* channel. Furthermore, a comparison of potential morphology differences and specific quantification of dust and/or gas species can be made. For cases where the object is located in a crowded field, this can lead to spurious detections, results, or even contamination from other field sources. We mention this as this was the case for visits 2015 A and 2015 B (this work).

Specific NEOWISE $W1$ and $W2$ magnitude zero-points are used and explained in Cutri et al. (2015) and Wright et al. (2010).

We utilize an $11''$ aperture radius as this is the optimal choice that best measures the PSF of the FWHM and can be readily compared with values listed for PSF-fit photometry in the NEOWISE Single-Exposure Point Source Catalog. This photometry can produce results with very small formal errors, on the order of a few percent or less. Brightening of the nucleus is consistent with our aperture photometry using an $11''$ aperture while avoiding other background objects that may sometimes appear within the field. An annulus with an inner radius of $50''$ extending to an outer radius of $70''$ is used to estimate and remove background flux from the surrounding region. These measurements are used to determine the respective $W1$ and $W2$ magnitudes which are then converted into fluxes as described in Wright et al. (2010). In order to further prevent any additional discrepancies, we assume that the $W1$ flux component follows that of the solar spectrum and do not consider any color corrections which may influence the measured gas production rates. Also, we make no corrections for phase angle, α . However, the latter varied over a small range $8^\circ \leq \alpha \leq 10^\circ$ (see Table 3.1), so that corrections for the scattering phase function, while unmeasured, are likely to be negligible. Sources of photometric uncertainty are the result of calibration of the data, instrumental systematics, and we provide 1σ uncertainty measurements from pixel statistics. Our raw flux values are shown in Figure 3.1 where we show $W1$ and $W2$ fluxes as yellow and orange diamonds. For comparison between pre- and post-perihelion activity, we denote this by a dashed-red line being placed on UT 2019 March 7 (e.g., MJD 58549) when perihelion passage most recently occurred for 29P/SW1.

Table 3.1: Summary of Photometry and Flux Analysis for
Comet 29P/Schwassmann-Wachmann 1 (SW1) from NEOWISE Data

Visit ^a	r_H^b	Δ^c	α^d	F_{W1}^e	F_{W2}^f	Q_{CO}^{proxy}	$Af\rho^h$	Image Stack Mid-point ⁱ
Feb. 2014 A	6.16	6.02	9.23	0.25 ± 0.02	1.72 ± 0.03	$1.48 \pm 0.03 \times 10^{29}$	971.69 ± 82.62	56,713.90910
Aug. 2014 B	6.12	5.59	9.52	0.51 ± 0.01	2.01 ± 0.04	$1.57 \pm 0.03 \times 10^{29}$	1967.95 ± 52.47	56,885.17539
*Mar. 2015 A	6.06	5.96	9.46	—	—	—	—	57,101.65373
*Sep. 2015 B	6.01	5.79	9.56	—	—	—	—	57,270.72080
Apr. 2016 A	5.95	5.86	9.71	0.42 ± 0.01	2.16 ± 0.04	$1.65 \pm 0.03 \times 10^{29}$	1509.85 ± 43.44	57,492.69748
Sep. 2016 B	5.90	5.58	9.49	0.21 ± 0.02	1.38 ± 0.03	$1.03 \pm 0.02 \times 10^{29}$	689.33 ± 63.48	57,656.78187
May 2017 A	5.85	5.77	9.95	1.84 ± 0.02	2.97 ± 0.03	$1.54 \pm 0.01 \times 10^{29}$	6234.06 ± 61.91	57,885.12475
Oct. 2017 B	5.81	5.42	9.35	0.60 ± 0.01	2.18 ± 0.03	$1.40 \pm 0.02 \times 10^{29}$	1899.05 ± 27.62	58,045.09867
Jun. 2018 A	5.78	5.68	10.12	0.46 ± 0.01	1.63 ± 0.02	$1.09 \pm 0.02 \times 10^{29}$	1489.08 ± 30.68	58,281.73647
Nov. 2018 B	5.77	5.31	9.10	0.61 ± 0.01	2.01 ± 0.02	$1.23 \pm 0.01 \times 10^{29}$	1854.32 ± 23.04	58,433.91180
Jul. 2019 A	5.77	5.68	10.15	0.67 ± 0.01	2.55 ± 0.04	$1.72 \pm 0.02 \times 10^{29}$	2189.40 ± 33.80	58,675.81224
Dec. 2019 B	5.78	5.36	9.16	0.70 ± 0.01	2.16 ± 0.02	$1.32 \pm 0.01 \times 10^{29}$	2161.26 ± 26.37	58,829.50749
Aug. 2020 A	5.82	5.75	10.03	1.58 ± 0.01	3.06 ± 0.02	$1.73 \pm 0.01 \times 10^{29}$	5292.58 ± 39.76	59,070.20683
Jan. 2021 A	5.85	5.41	8.99	0.39 ± 0.01	2.39 ± 0.03	$1.68 \pm 0.02 \times 10^{29}$	1237.84 ± 24.95	59,221.88559
Sep. 2021 B	5.91	5.82	9.81	1.20 ± 0.02	2.93 ± 0.03	$1.87 \pm 0.02 \times 10^{29}$	4195.79 ± 57.22	59,466.11706
Feb. 2022 A	5.96	5.51	8.79	0.37 ± 0.01	2.00 ± 0.02	$1.45 \pm 0.02 \times 10^{29}$	1247.81 ± 29.02	59,613.62827
Oct. 2022 B	6.03	5.95	9.54	0.56 ± 0.01	2.40 ± 0.02	$1.86 \pm 0.02 \times 10^{29}$	2070.56 ± 31.14	59,857.51794

^a Visit, where A or B denotes the first and then subsequent visits in a given year.

^b Heliocentric distance, in astronomical units.

^c Geocentric distance, in astronomical units.

^d Phase angle, in degrees.

^e $W1$ flux, in millijanskies.

^f $W2$ flux, in millijanskies.

^g CO gas production, in molecules per second.

^h Dust production, in centimeters.

ⁱ Midpoint of the image stack, in Modified Julian Date.

Notes. *2015 NEOWISE Data Coverage is listed in Table 3.1, but excluded in this work due to poor quality data.

Notes. Perihelion occurred on approximately UT 2019 March 7 (e.g., MJD 58549).

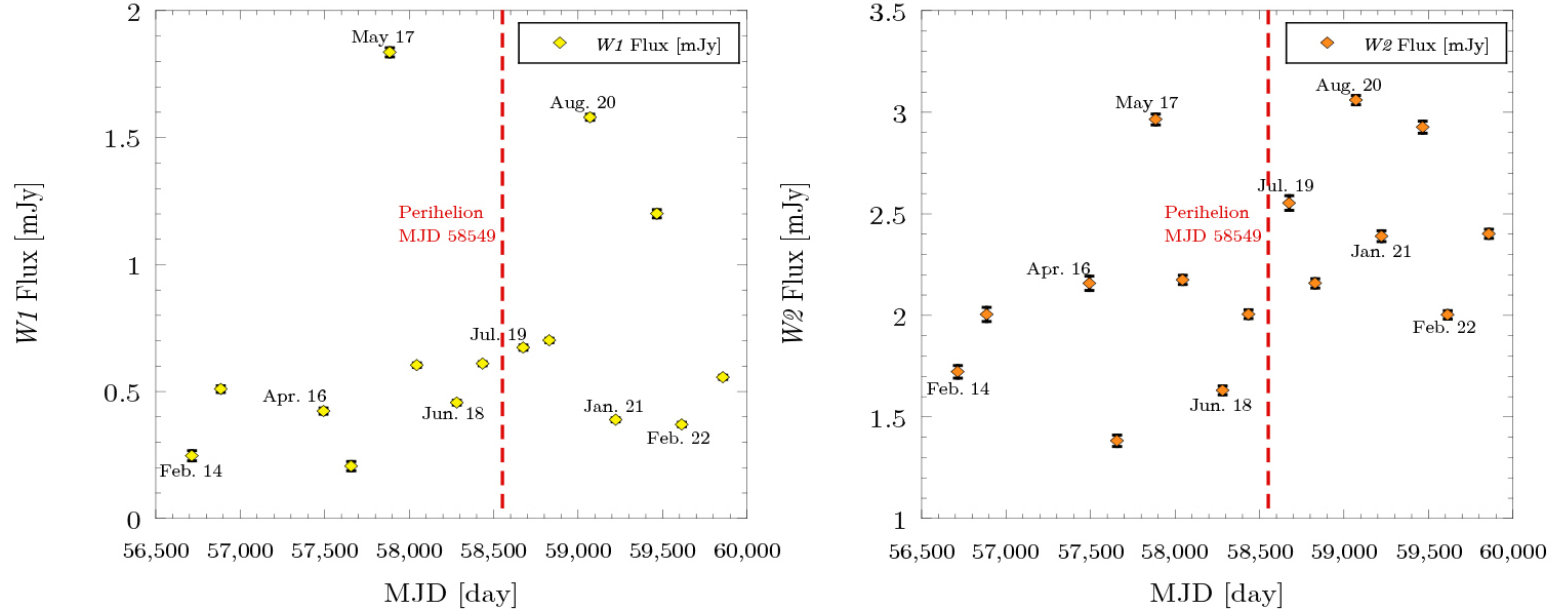


Figure 3.1: NEOWISE 29P/SW1 Measured $W1$ and $W2$ Fluxes. NEOWISE Flux measurements of 29P/SW1 with no color-corrections applied. The first visit for a given year (e.g., Visit ‘A’ listed in Table 3.1) is denoted with labels adjacent to the data point. For example, the label marker ‘Feb. 14’ corresponds to the month and year, e.g., 2014 visit ‘A’ (or appearing in the text as 2014 A) which took place during 2014 February. $W1$ (yellow) and $W2$ (orange) measurements appear as diamonds. A dashed-red line denotes 29P/SW1’s perihelion passage having occurred on UT 2019 March 7 (e.g., MJD 58549).

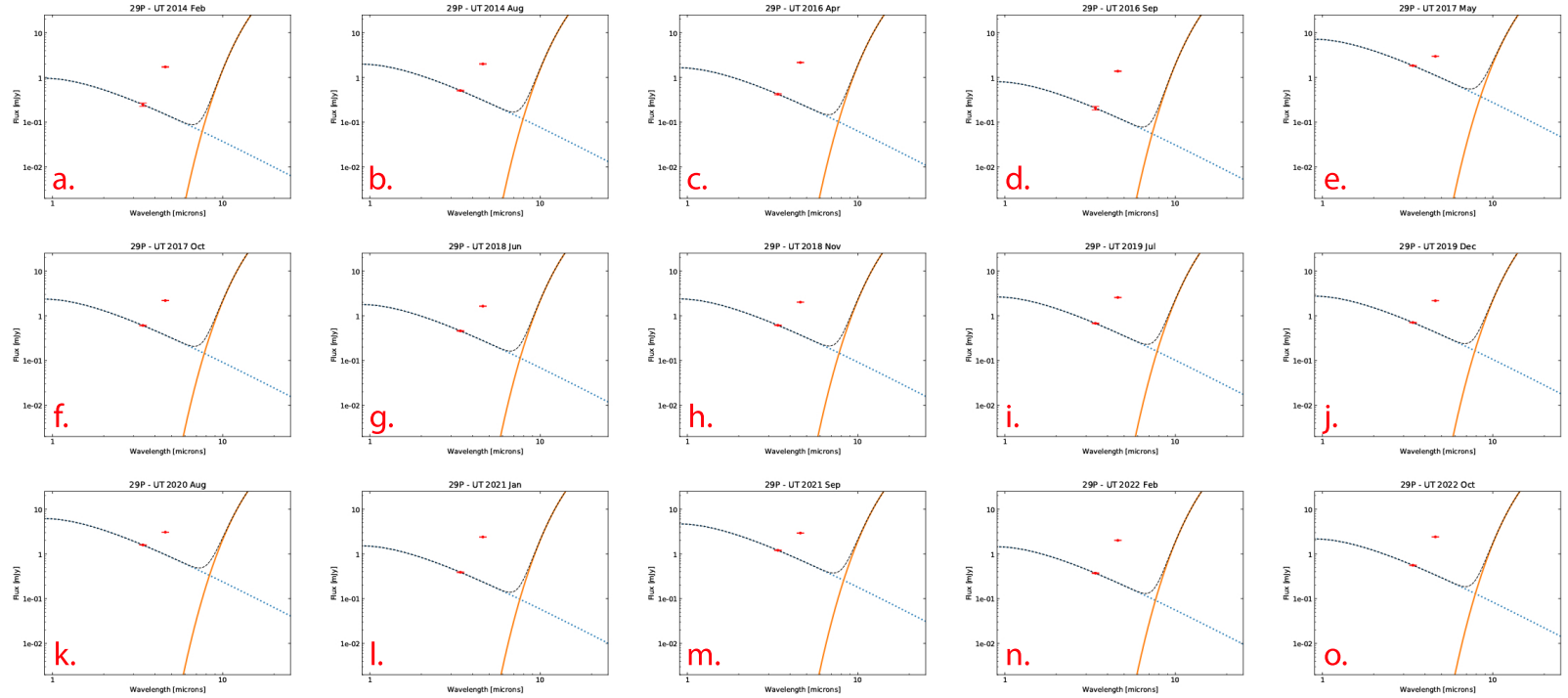


Figure 3.2: NEOWISE Spectral Energy Distribution (SED) Diagrams for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1). Spectral energy distribution plots for comet 29P/SW1 where there is an excess in $W2$ flux which is above the $W1$ signal. Given 29P/SW1's residence in the outer solar system, it is too cold for significant thermal effects at these distances. Henceforth, this excess flux is assumed to be due to CO gas emission. The corresponding visits are listed in the labels. The left-hand curve (blue-dotted line) is a reflected sunlight model scaled to the $3.4 \mu\text{m}$ $W1$ point, while the theoretical thermal curve (orange solid line) is seen on the right-hand side. The two plots are summed together by a thin dashed-black line. Larger versions of the individual panels can also be found in Section 3.6 of this work.

Figure 3.1 presents the measured fluxes as a function of observation date. Figure 3.2 plots the computed SEDs for the 15 NEOWISE visits for which we determined dust and gas production rates for 29P/SW1. In all cases, there is excess signal in $W2$ above the dust signal constrained by $W1$ and confirmed visually in the images suggesting that this excess is due to the presence of molecular species, presumably the emission from the $4.67\ \mu\text{m}$ CO rovibronic fundamental band. Larger versions of the individual panels in Figure 3.2 can be found in Section 3.6; e.g. Figure(s): 3.8, 3.9, 3.10, 3.11, 3.12, 3.13, 3.14, 3.15, 3.16, 3.17, 3.18, 3.19, 3.20, 3.21, and 3.22.

We use the ATLAS forced photometry routine on data acquired from 2015–2022. A majority of the observations were taken in the o filter. We removed any data that contained obvious aberrations or spurious signals (e.g., negative fluxes, which are possible with the ATLAS tphot routine, see Sonnett et al. (2013)). Only data values with very small errors in magnitude were used to construct a plot of magnitude versus Modified Julian Date (MJD) shown in Figure 3.6 of this work. When compared to NEOWISE $W1$ fluxes, the $W1$ fluxes used to determine $Af\rho$ were then converted to proxy magnitudes according to $m_{scaled} = -2.5 \log_{10} f + C$, where C is a scalar offset. We refer to these as ‘scaled magnitudes’. We connect these scaled magnitudes over the visual and infrared wavelengths by adjusting and overplotting the o and c filter ATLAS photometry with the $W1$ aperture photometry and measured fluxes. For reference, the MJD is located on the x -axis to provide information for simultaneous and periods of activity and quiescence over the full interval of the available data that has been investigated. When performing this analysis, we expected the mostly-optical ground-based data provided by the ATLAS c and o filters to generally follow the NEOWISE $W1$ data, as was the case. This suggests that the NEOWISE $W1$ channel is an effective tracer of the dust activity of 29P/SW1 observed in the infrared as in the optical data provided from ATLAS and a possible indicator of the very nature of dust itself must be sensitive to both the visual and infrared wavelengths.

3.4 Discussion

3.4.1 Dust and Gas Activity and Comparison With Previous Studies

For a comprehensive overview of comet activity mechanisms we refer the reader to Lisse et al. (2022) and references therein. The results of Ootsubo et al. (2012) provided seminal work on 29P/SW1 by providing high-resolution spectral data from the AKARI spacecraft showing that the presence of CO exceeds that of the CO₂ molecule and even other volatile species that have been observed from other published work. Accordingly, we assume the line strength of CO, being 4.67 μm is the dominant species and used in our investigation of gaseous driven activity. Crovisier & Encrenaz (1983) list fluorescence efficiencies of CO and CO₂ species as the g factors where the CO molecule is ~ 11.6 times weaker than that of CO₂, meaning that in order to produce an equivalent amount of emission for CO₂, the presence of as much CO would be needed even though other comets show the opposite, being CO₂ is the species similarly responsible for observed distant cometary activity. However, as it is impossible to separate the contribution of the CO and CO₂ species due to the wide bandpass of the NEOWISE $W2$ channel, we simply refer to the overall excess flux in $W2$ after the removal of the dust as $Q_{\text{CO}}^{\text{proxy}}$ which may include CO+CO₂ species. Figure 3.2 shows the individual contribution of both the dust in the 3.4 μm $W1$ channel as a reflected light curve on the left-hand (blue-dotted line) as a reflected sunlight model and a theoretical thermal curve using the blackbody temperature of dust that scales with r_H appearing as an orange solid line. The contribution of both the reflected light and thermal curves are summed together with a thin dashed-black line and the individual fluxes from $W1$ and $W2$ can be seen on these curves as red data points with the $W1$ data point always falling on the reflected sunlight curve. If we see that there is an excess in $W2$ above that of the dust signal found in $W1$ after removing the contribution of the dust, we interpret this ‘excess’ as due to the presence of CO+CO₂ species. In all 15 useful observing visits by NEOWISE for this work, the $W2$ signal exceeded that of the $W1$ signal that was assumed to be due to dust shown in

Figures 3.2 (a.)–(o.)

Figures 3.4–3.5 (this work) in the left-hand (*W1*) and center (*W2*) columns show the dust and gas, respectively in the coadded frames, while the right-hand column shows the combined effect of gas and dust in a composite *W1+W2* frame created from several 7.7 s individual exposures for each respective channel. Also for reference, we show examples profiling very active and quiescent phases over our pre- and post-perihelion coverage of 29P/SW1 combined with our measured gas and dust quantities listed in Table 3.1 of this work to give the reader a sense of what has been measured and observed over the duration of this study. In addition, as NEOWISE is an unbiased all-sky survey incapable of pointing at specific targets, we provide highlights of very specific states of activity or quiescence over our 2014–2022 coverage of 29P/SW1. It remains to be seen what the short and long-term evolution of 29P/SW1 will be like, or if there will be a shift in morphology or activity with time. For this work, in cases where gas is the dominant component, this can be seen with red emanations and protrusions extending from a presumed central cometary nucleus. At the distance of 29P/SW1, the flux contribution from the nucleus can be ignored due to its large heliocentric distance that is unlikely to contribute significantly to the flux measurements as the blackbody temperature here is too low. Thereby, we assume that the measured fluxes are due to the contribution from the coma. Figure 3.4 shows representative examples sometimes when dust is evident and other cases where gas is evident, as well as cases on different parts of the nucleus where dust appears in the southern hemisphere, but gas in the northern hemisphere; e.g., Figures 3.4 ((a.)–(c.)) for visit 2017 A. Remarkably, in the case of visit 2020 A, there is a clear difference in the observed morphology between the two NEOWISE filters, presumably related to the presence of gas emission in *W2*. We also trace the dust using the $\sim$ optical-infrared filter bandpasses from ATLAS. As ATLAS datasets consist of four separate 30 s exposures, taken 1 hour apart, with an assumed cadence of $\sim$ 1 day, this short term variability is useful for monitoring gas outbursts. The dust seems to be more prevalent in causing activity than the gas

and an increase in dust production does not necessarily imply that there will be an increase in gas production. In fact, from Figure 3.3, our measured gas production has remained relatively steady. Figure 3.6 shows expanded coverage of simultaneous coverage by NEOWISE and ATLAS but with very narrow coverage windows from NEOWISE in terms of where the gas activity factors into the measured dust in both the optical and infrared. Most often, in these periods of heavy activity, 29P/SW1 seems to return back to ‘baseline’ after periods of hours, or days. However when comparing the simultaneous $W1$ and $W2$ data taken by NEOWISE, it is interesting to sometimes see what appear to be strange (mostly-symmetric) dust outbursts and cases where the gas does follow. And for a few specific cases, the gas and the dust appear distinct from one another in terms of morphology. We can interpret this as a possible mixture of differing sizes of dust grains due to an asymmetric coma or differing gas expansion speeds possibly due to a mixture of species. Another important study of 29P/SW1 towards the tail-end of its most recent perihelion passage by Wierzechos & Womack (2020) also utilized multi-wavelength regimes of the EM spectrum and provided an overview of past work that had been done to investigate the dust and gas environment. Wierzechos & Womack (2020) mentioned that only two well-studied (but rare) CO outbursts documented, lasted 2–5 days in Biver (1997) and Wierzechos & Womack (2020), but concluded that there was no compelling evidence that there was a link between the gas and the dust activity of 29P/SW1.

To further investigate whether or not the gas or dust are correlated, we overplotted the production rates of gas, $Q_{\text{CO}}^{\text{proxy}}$, and the log of dust, $Af\rho$, production as green circles and blue squares, respectively in Figure 3.3. A dashed-red line denotes the perihelion passage of 29P/SW1 (MJD 58549 or UT 2019 March 7). In our 15 observing visits, we can see no overall correlation between gas and dust production, which remains steady from 2015–2022. Similarly observation arcs by Wierzechos & Womack (2020) include our NEOWISE visits 2016 A and 2018 B. The data coverage reported in Wierzechos & Womack (2020) spans two separate observing campaigns taking place from 2016 Feb.–May, (hereafter, Campaign 1)

and 2018 Nov.–2019 Jan. (Campaign 2). NEOWISE coverage for a visit roughly spans ~ 36 hr, and individual exposures are sometimes taken between as little as ~ 2 –3 hr to sometimes 10 hr.

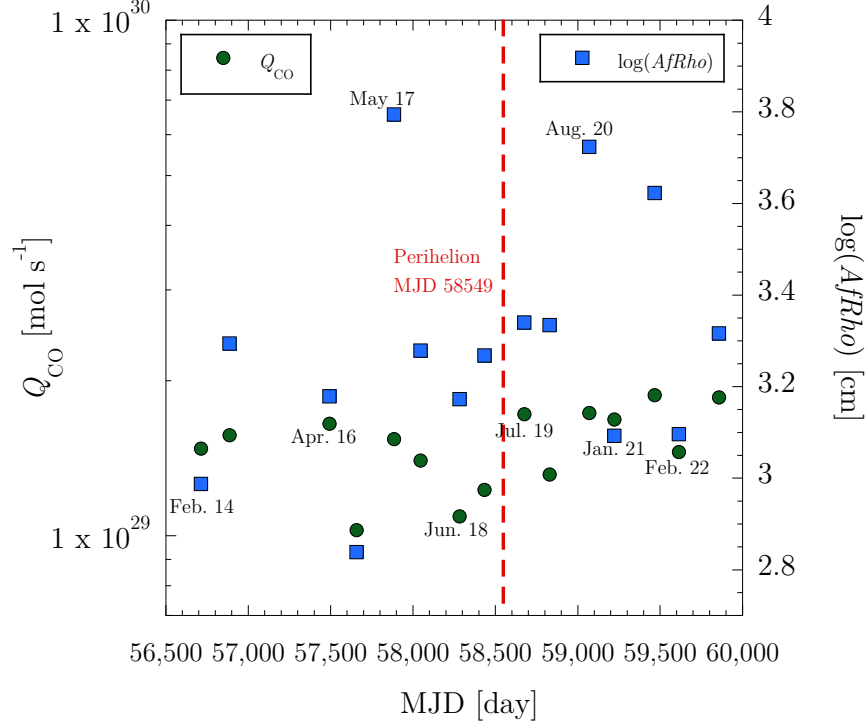


Figure 3.3: Evolution of computed gas and dust production rates seen over various NEOWISE visits as a function of Modified Julian Date (MJD) for SW1. Q_{CO} values (e.g., gaseous CO emission rates) appear as green circles and dust production values (e.g., $\log Af\rho$) appear as blue squares. These values have been shifted to show the specific influence of gas and/or dust for a given visit. For comparison, see the uncorrected flux measurements in Figure 3.1 as well as Table 3.1. Likewise in Figure 3.1, the label marker ‘Feb. 14’ corresponds to the month and year, e.g., 2014 visit ‘A’ which took place during 2014 February. A dashed-red line denotes 29P/SW1’s perihelion passage having occurred on UT 2019 March 7 (e.g., MJD 58549).

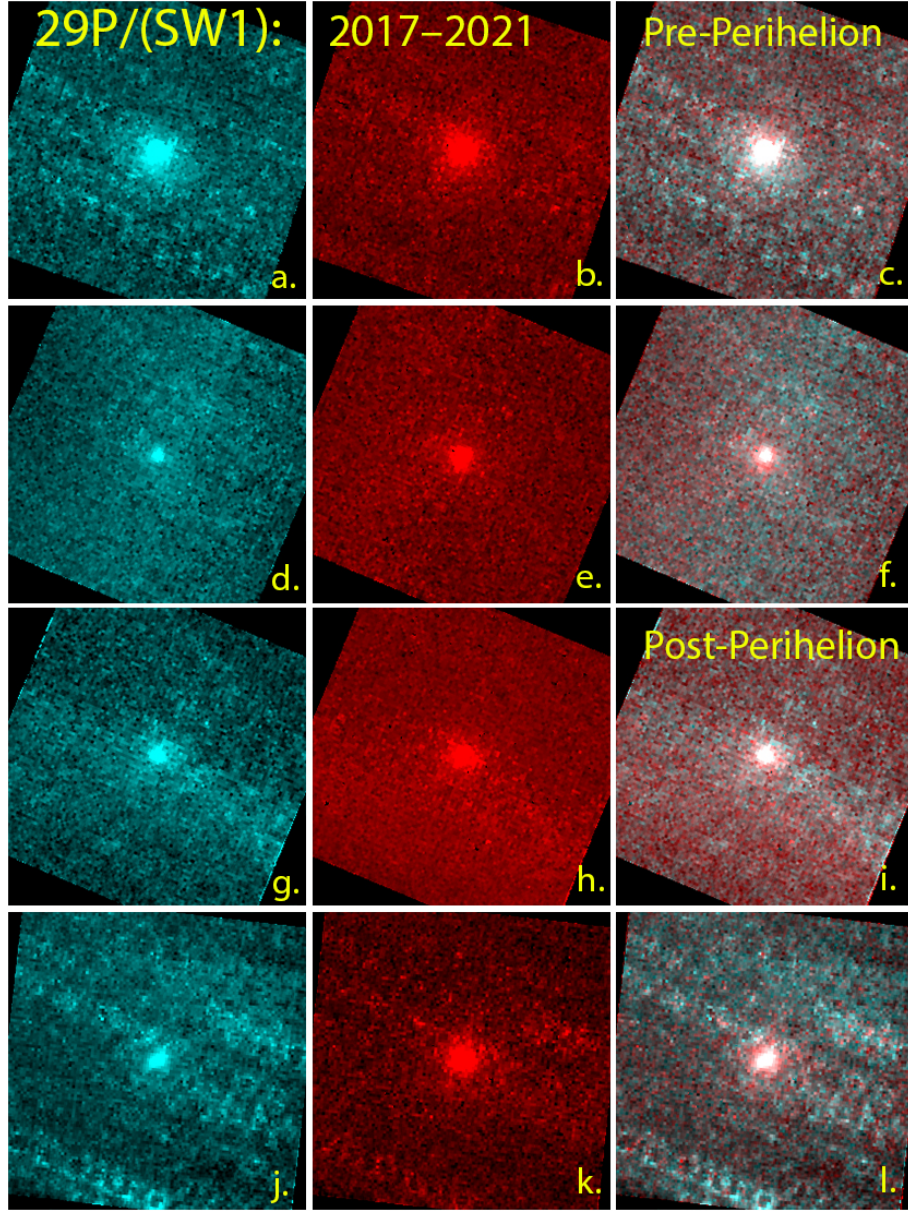


Figure 3.4: Composite images made with ICORE (co-added in the moving reference frame of the 29P/SW1 and centered at its predicted ephemeris position from JPL HORIZONS) showing the comet at specific visits in *W1* mapped to green and blue (left-hand panels), *W2* mapped to red (center panels), and combined *W1*+*W2* color-mapped composite frames (right-hand panels). For all images in Figure 3.4, the orientation (North is up, East is to the left) and image-size is consistent for all subsequent frames (e.g., $\sim 4.''6 \times \sim 4.''6$) but the contrast and image stretch are not. Visible streaks are due to the slow motion of the comet, hence the background stars are not being fully suppressed in the stacking process. Panels ((a.)–(c.)): 2017 May during a big outburst event, ((d.)–(f.)): 2018 June a quiescent, but more active appearance in *W2*, ((g.)–(i.)): 2019 July more gas than dust seen visually, ((j.)–(l.)): 2021 September elongated dust plume seen in *W1* before a major-reported outburst event.

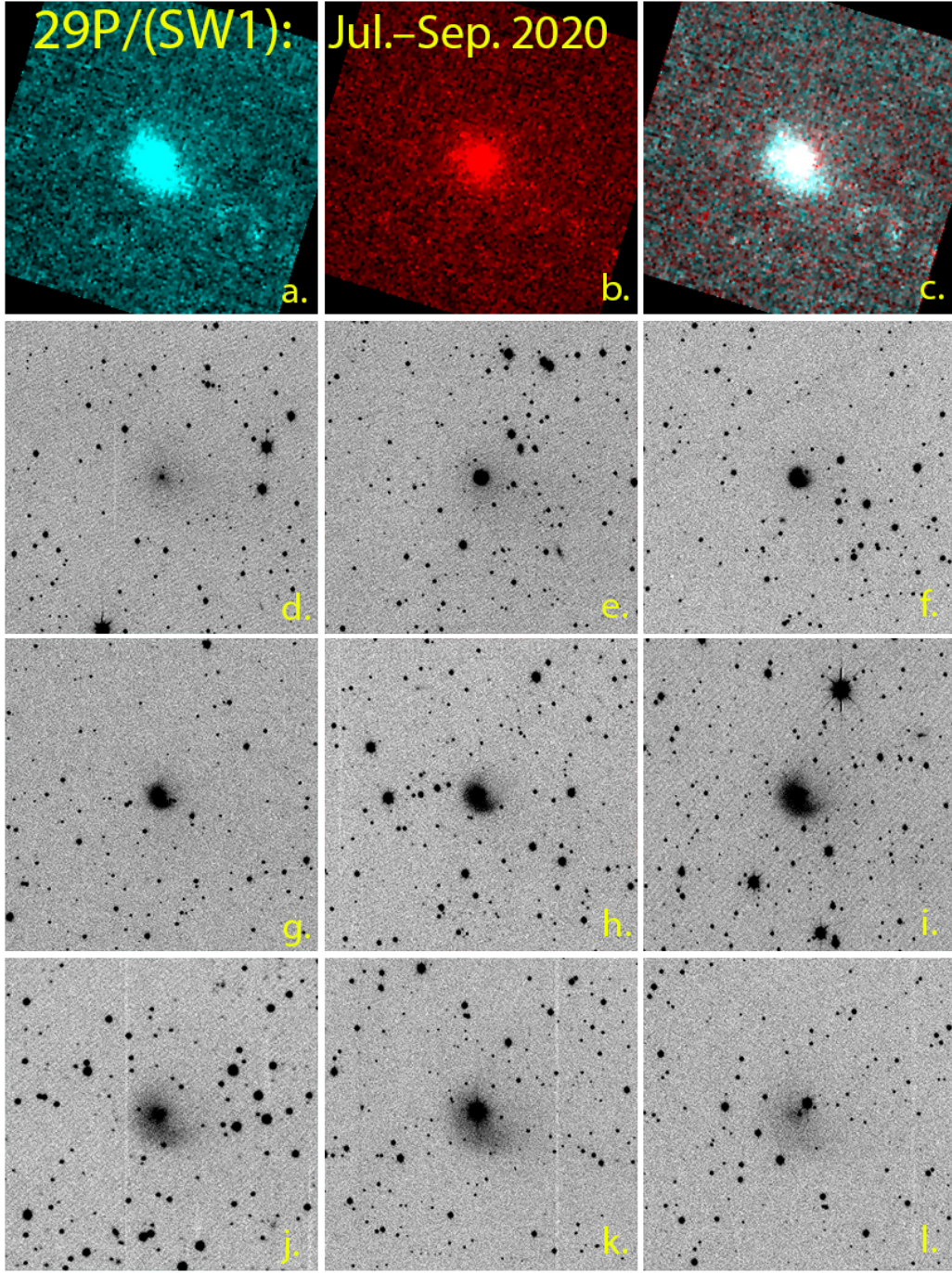


Figure 3.5: Infrared (NEOWISE) and Visual (ATLAS) coverage of 29P/SW1. See Figure 3.4 for information on NEOWISE. Composite panels ((a.)–(c.)) are NEOWISE coverage from UT 2020 August 8–9 while ATLAS coverage (single 30 s exposure time reduced images in α -filter) are from UT 2020 July 23 (MJD: 59053.58) in image (d.) to UT 2020 September 1 (MJD: 59093.49) in image (l.) In all panels, North is up and East to the left. ATLAS image panels are $\sim 12.''4 \times \sim 12.''4$.

While there is no universally accepted definition of what an ‘outburst’ is, it is commonly accepted as a sudden increase in brightness by $\gtrsim 1$ magnitude. Wierzechos & Womack (2020) emphasize a difference in between what they define as a ‘quiescent’ versus an ‘outbursting’ period. The baseline production rates are the average of all provided ground-based optical magnitudes that trace the dust as reported by multiple observers and telescopes. The gas ‘outburst’ itself is defined over that average and having gas measurements taken with the ARO SMT 10-m telescope with the peak having a corresponding production rate, Q_{CO} , of $6 \times 10^{28} \text{ mol s}^{-1}$. The results of the two observing campaigns taken by Wierzechos & Womack (2020) suggest that during Campaign 1, there were some observed outbursts (above the defined baseline Q_{CO} production rate) with some possible correlation with activity of the dust and gas. Campaign 2 showed that there was no compelling evidence of elevated CO and dust production. For both Campaigns, there were 4 noticeable dust outbursts seen in Figure 2 of that work, with only one reported outburst of gas due to higher-than-normal CO detection over the baseline. Data points in Campaign 2 corresponding specifically to dust outbursts, e.g., B and C, suggested that the outburst in dust did not imply a rise in the gas. However, a rare and quantifiable outburst in gas was detected during Campaign 1 and occurred on UT 2016 February 28 which did not coincide with a dust outburst. The nearest outburst from that available data came on UT 2016 March 14, or about 2 weeks later labelled as data point ‘A’ in Figure 2 of Wierzechos & Womack (2020). Also of interest is that this gas outburst returned back to quiescent levels of activity just ~ 1 – 2 days after being observed. In our study, while we have similar time-sensitive data for Campaign 1 compared to NEOWISE visit 2016 A, our data (taken UT 2016 April 14–15) show an elevated amount of gas production when compared to our other values. However, the dust production (via $Af\rho$ measurements) are significantly lower when compared to all our other measurements taken during the duration of this study. This slight inconsistency and our higher gas values may be due to overestimation of gas in our simplified model and code as well as assumptions and systematics used by Wierzechos & Womack (2020) for their detection of the presence of

CO in the regime of radio observations compared to our infrared study. For Campaign 2 compared to NEOWISE visit 2018 B (e.g., UT 2018 November 11–12), we do corroborate an elevated presence of dust in our $Af\rho$ measurements which take place 1 day after a data point falling in Campaign 2, e.g., UT 2018 November 10.2. By conversion of their reported CO gas production into dust production as equivalent mass loss rates, assuming a 1:1 mixture of gas and dust, these results are consistent with our $Af\rho$ measurements if we use that as our sole metric to evaluate our dust production. And as before, our gas measurements are still slightly elevated when compared to theirs, again, likely due to systematics between the measurements performed in both studies.

Most significantly, our results suggest that in just 3 cases, we see the gas production is slightly higher than the dust production for NEOWISE visits 2014 A, 2016 B, and 2021 A. For the majority of the cases, we see that the dust production far exceeds that of the gas, and especially with the 2017 A, 2020 A, and 2021 B visits. While NEOWISE does perform simultaneous measurements of gas and dust, we can use the ATLAS telescope project to provide contemporaneous monitoring in some cases. However, we comment that for some results e.g., UT May 2017 (a.k.a., visit 2017 A) where there were reports of an outburst happening on 29P/SW1, there is a small deviation from the NEOWISE to ATLAS photometry seen in Figure 3.6 of this work. This can simply be explained because of a gap in coverage from the available ATLAS data for 29P/SW1 and that the ATLAS telescope project was not fully operational. The rest of the data fit the points and connected lines and can be seen where there are simultaneous data coverage and that no available data exists specifically for this time period. For the case of simultaneous data and contemporaneous monitoring, we comment on the NEOWISE August 2020 visit (a.k.a., 2020 A) from 8–9 August 2020, or MJD 59069–59070 at $r_H \sim 5.82$ au in the next Section (3.4.2) of this work. Our data presents the opportunity for a rare occurrence seen by both NEOWISE and ATLAS of a fairly impulsive event. We were able to make a determination of the speed of the expanding

dust shell and quantify the gas and dust production rates. Assuming this was a single event and having occurred around the midpoint of this outburst, coverage of this event still has remained unpublished in the scientific community.

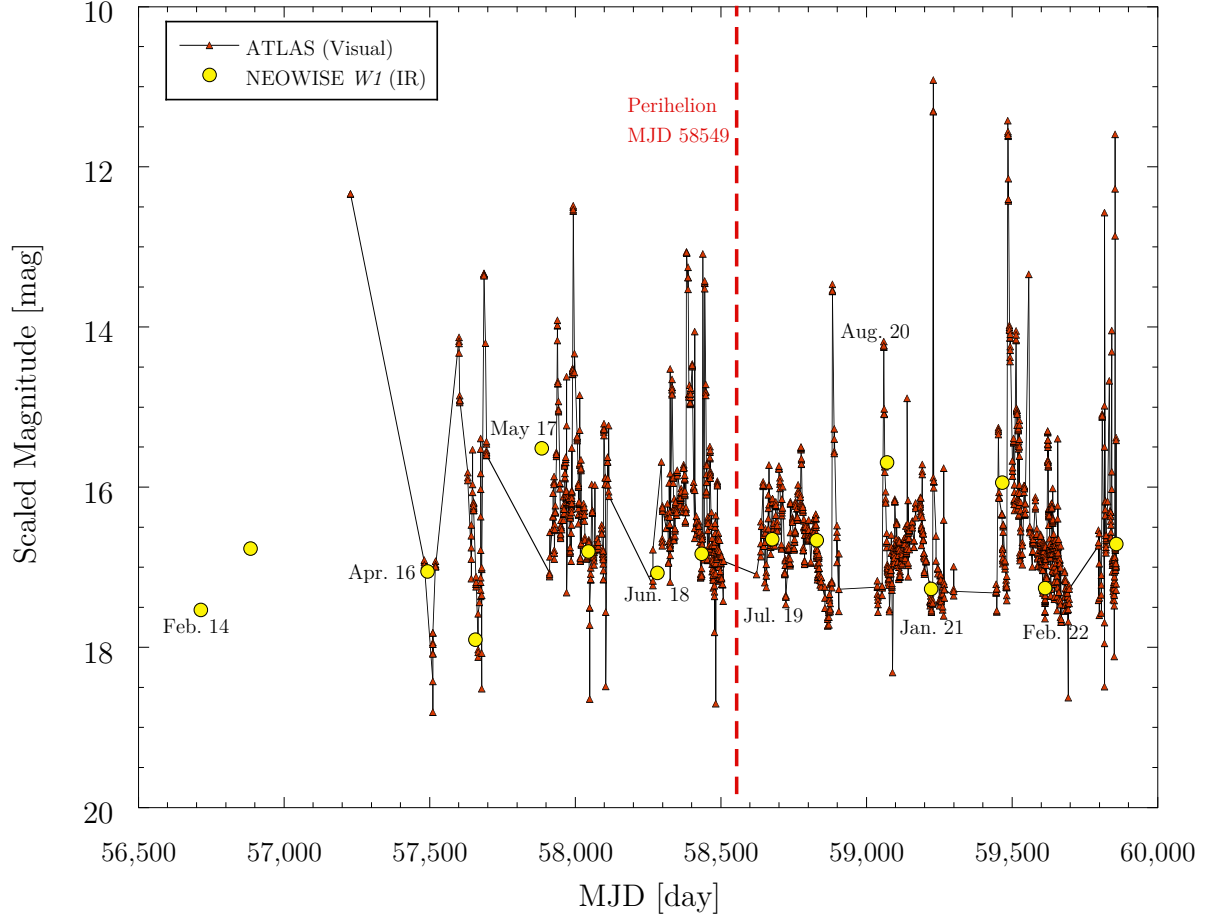


Figure 3.6: Infrared (NEOWISE) and Visual (ATLAS) contemporaneous monitoring of 29P/SW1. NEOWISE *W1* (yellow circles) and ATLAS (red triangles) secular light curves vs. MJD. The *W1* magnitudes closely follow the visual ATLAS magnitudes thus showing close agreement between the infrared and visual regimes of the EM spectrum. For NEOWISE observations, field objects in the background have mostly been suppressed using ICORE, further suggesting these outbursts (e.g., spikes in the data) are indeed real. A vertical dashed-red line marks 29P/SW1’s perihelion passage on UT 2019 Mar. 7 (e.g., MJD 58549).

3.4.2 The Speed of the Dust

We determined the dust expansion speed using the ATLAS data. Figures 3.5. (d.)–(l.) all have a plate scale of $1.86'' \text{ pixel}^{-1}$, field of view $\sim 12.'4 \times \sim 12.'4$, and usual cardinal directions of North facing up and East being to the left. The forced photometry routine allows for MPC queries of solar system objects with known designations to be extracted from the available ATLAS data with the object centered in the frame based on its ephemeris data that is provided from the MPC. For consistency, we set the image scaling to be the same for all data to be analyzed and inverted the color scheme to produce the resultant individual frames seen in the bottom ATLAS panels. Using the reduced images provided by the forced photometry routine, we also use the specific location of 29P/SW1 in its orbit, e.g., r_H and Δ as well as the pixel scale as necessary parameters to determine the speed of the expanding dust shell over this outburst period where we use the data from Figures 3.5 (d.)–(l.). We counted the pixels in the negative-color images offset from the center of the frame (e.g., where the MPC has placed the expected position of the nucleus) to the leading front of the expansion shell all the way to point of where the dust shell expands to become more or less indistinguishable with the background continuum.

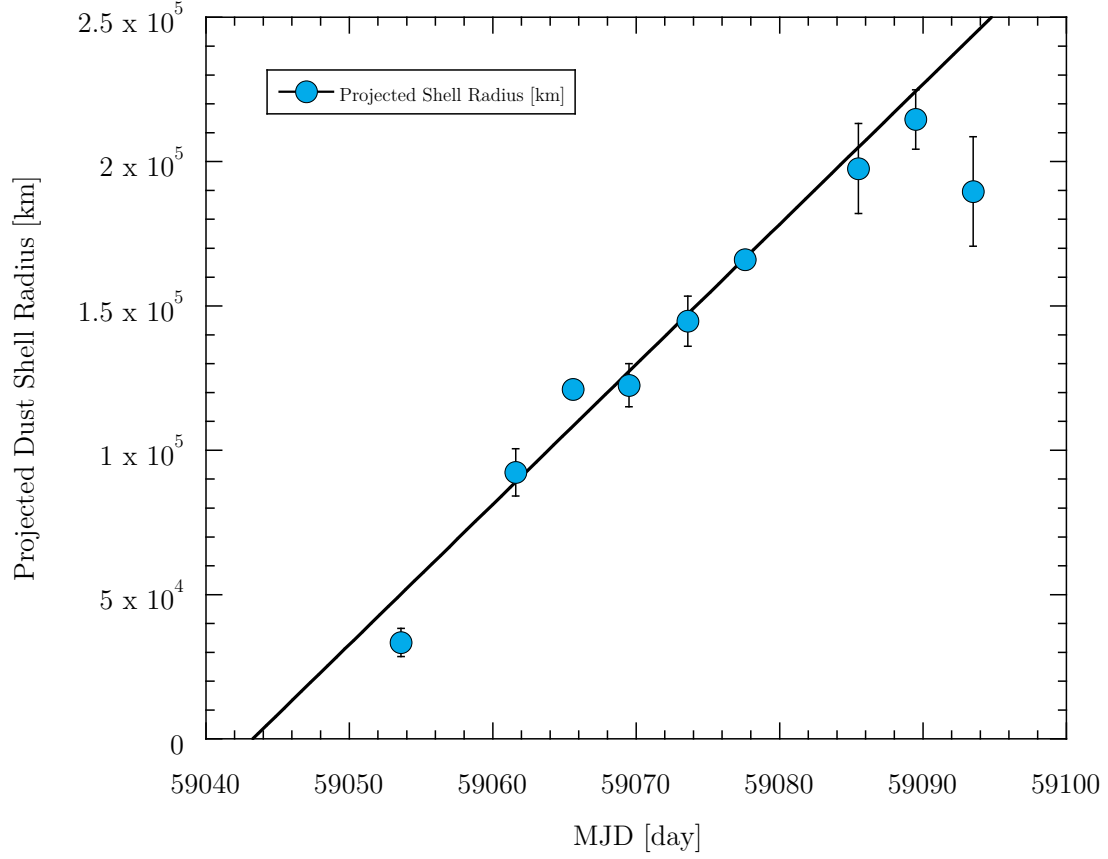


Figure 3.7: Projected dust shell radius versus time used to determine the speed of the expanding dust shell for the outburst event of 29P/SW1 occurring between UT 2020 July–September. The intercept of the fitted line gives the most probable date of ejection on MJD 59042.85, corresponding to UT 2020 July 12. The slope of the line gives the dust speed $v_{dust} = 0.060 \pm 0.002 \text{ km s}^{-1}$ consistent with, but at the lower end of, previously reported measurements in literature.

Figure 3.7 of this work shows the projected size of the expanding shell in kilometers versus the MJD. We determined a weighted-fit line from which extrapolated zero radius gives the Date of Ejection (DOE). We find $\text{DOE} = \text{MJD } 59042.85$ (UT 2020 July 12). In addition, the gradient of the best-fit line gives the dust shell expansion speed $v_{\text{dust}} = 0.060 \pm 0.002 \text{ km s}^{-1}$. Our measured dust expansion velocity is at the lower-end of previously reported results which range from $0.05\text{--}0.15 \text{ km s}^{-1}$ from Wierzechos & Womack (2020). The gas expansion velocity, on the other hand is $\sim 0.3 \text{ km s}^{-1}$ based on radio and submillimeter observations. The slower speed of the dust presumably reflects its poor coupling to the gas flow, itself an indicator of larger particle size.

Schambeau et al. (2021) has used data from the Spitzer MIPS $24 \mu\text{m}$ channel to model dust grain radii $10\text{--}100 \mu\text{m}$ and reports a range dust ejection speeds of $10\text{--}50 \text{ m s}^{-1}$ when 29P/SW1 is considered to be quiescent. In the model, slow, staggered large emitted dust grains on the order of $10 \mu\text{m}$ in radius produce an outflow velocity of 60 m s^{-1} . This matches our measured dust expansion speed of 0.06 km s^{-1} (see Figure 3.7) and is just above the regime where 29P/SW1 is considered quiescent. However, if we correct our results slightly based on amateur reports and assume that the ejection date started on UT 2017 July 27, then we would arrive at a dust ejection speed of 0.08 km s^{-1} which suggests a mixed-population of dust grains on the order of $\sim 10 \mu\text{m}$ in radius. This better matches the range of ejection speeds by Schambeau et al. (2021) whether 29P/SW1 is considered quiescent or outbursting. For the range of expansion velocities when 29P/SW1 is in a period of impulsive release of dust due to outbursts, this dust expansion speed can range from $100\text{--}300 \text{ m s}^{-1}$. Our stated results would suggest that 29P/SW1 is found closer towards the range of a quiescent period that follow the observations likely due to solar radiation pressure dispersing the lingering grains.

3.5 Summary

We present a study in Chapter 3 of frequently active Centaur 29P/SW1 over an 8 year period using observations by the NEOWISE Reactivated (NEOWISE-R) Mission. Our study has the advantage of using a single telescope, instrument and observing strategy and thus should be relatively free from systematic effects of measurement. We compare the NEOWISE data with optical measurements from the ATLAS survey telescope in order to quantify and compare the gas and dust production rates.

The major results and summary of our work are as follows:

1. Instantaneous gas and dust rates are not correlated in the period 2014–2022, consistent with the results of Wierzbach & Womack (2020).
2. $W1$ and $W2$ filter images are morphologically different. Images from an outburst in UT 2020 August 8–9 show clear morphological differences between the $W1$ (pure dust) and $W2$ (dust + gas) channels. An asymmetric, radiation-pressure swept dust structure evident in $W1$ is swamped by spherically symmetric emission from gas in $W2$.
3. Optical photometry from ATLAS follows the temporal variations in the NEOWISE $W1$ dust channel and shows much more rapid changes than can be assessed given NEOWISE observational sampling.
4. The expansion of a dust shell in 2020 July–September was measured at $v_{dust} = 60 \pm 2 \text{ m s}^{-1}$, which is our best estimate of the dust ejection speed.

3.6 Additional NEOWISE Spectral Energy Distribution (SED) Diagrams

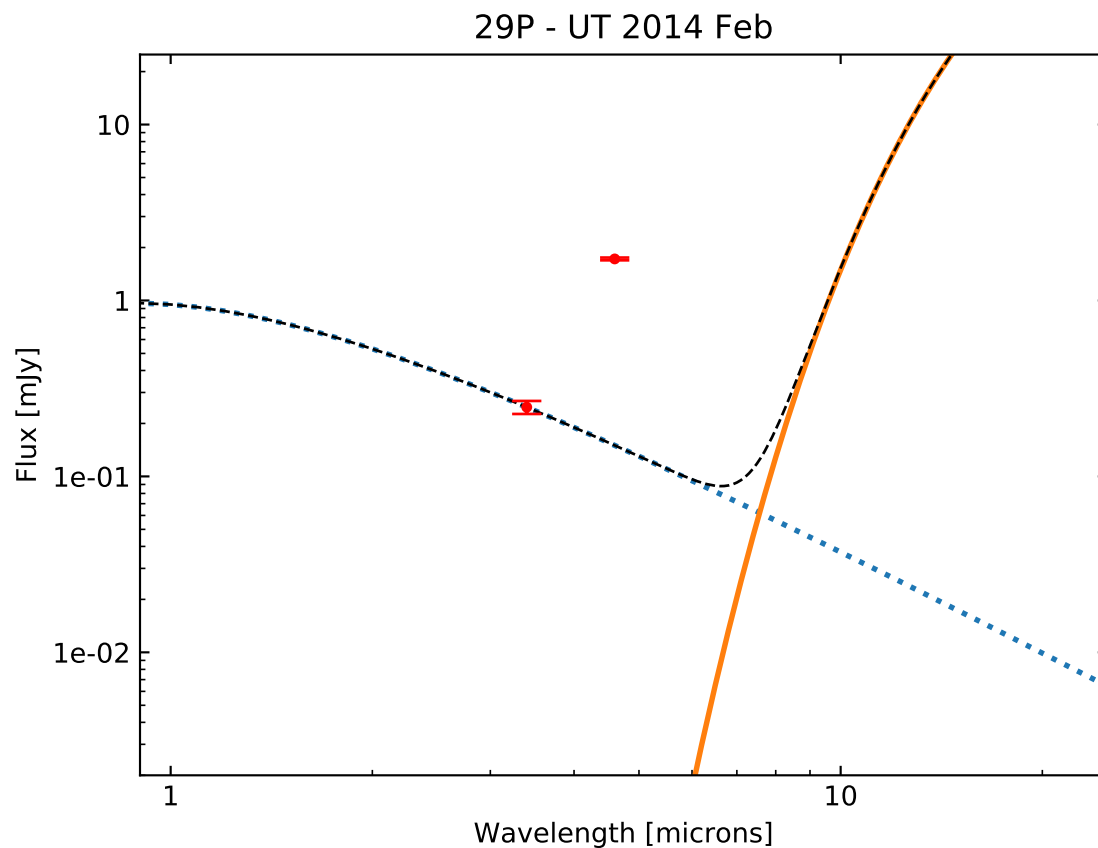


Figure 3.8: NEOWISE Spectral Energy Distribution (SED) Diagram for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1). The information is the same as in Figure 3.2, however the year and date of this NEOWISE Visit is listed in the figure title at the top of the plot; e.g., the 2014 Feb. NEOWISE Visit.

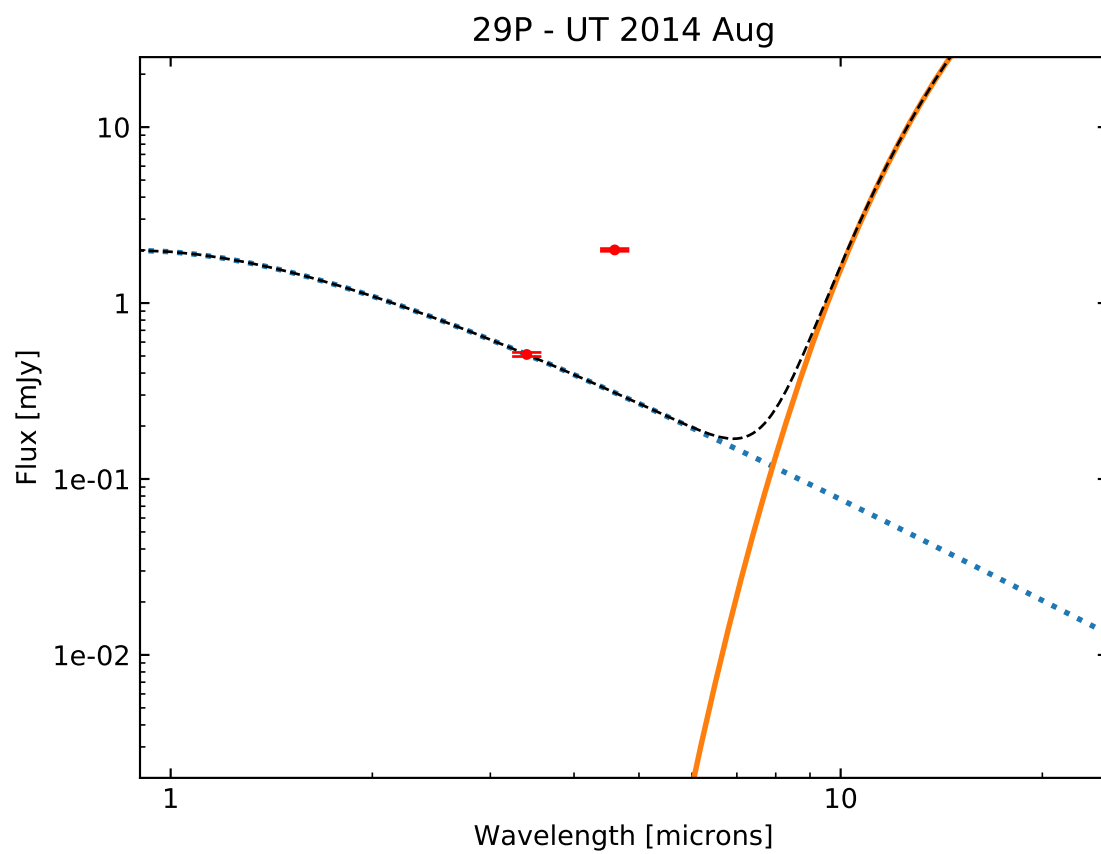


Figure 3.9: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2014 Aug. NEOWISE Visit.

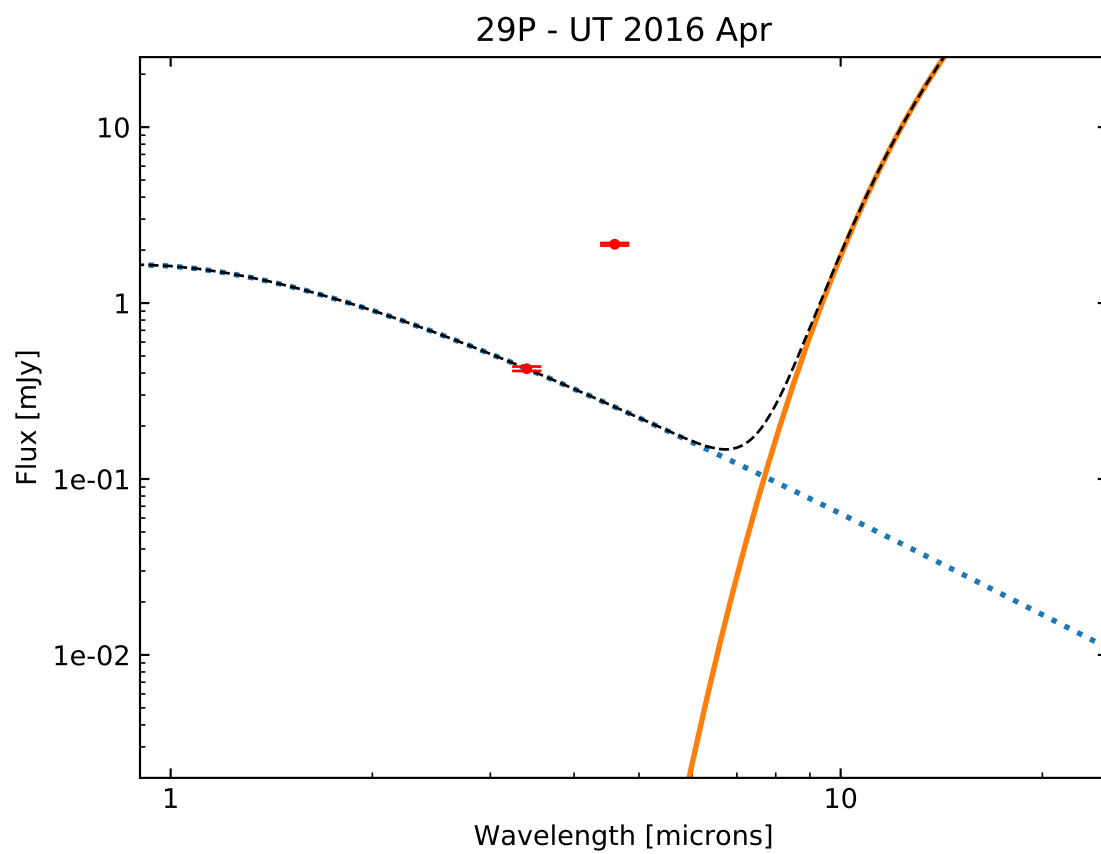


Figure 3.10: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2016 Apr. NEOWISE Visit.

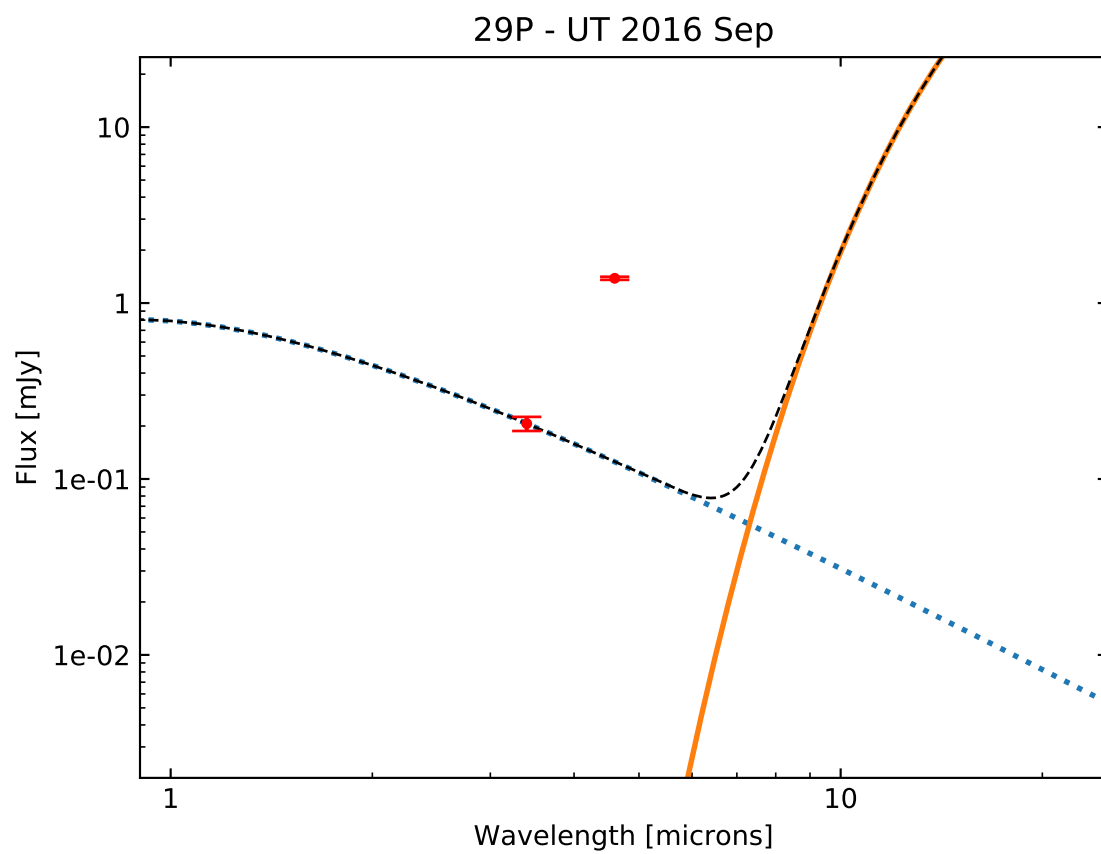


Figure 3.11: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2016 Sep. NEOWISE Visit.

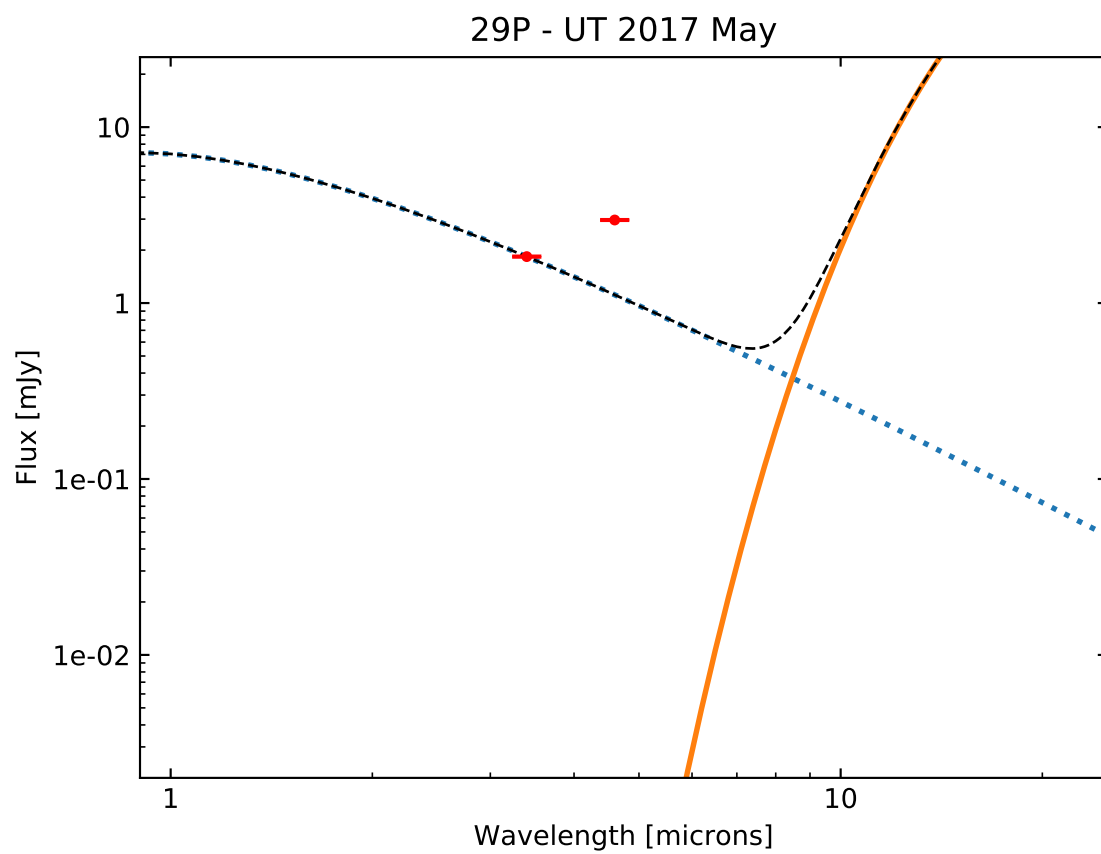


Figure 3.12: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2017 May NEOWISE Visit.

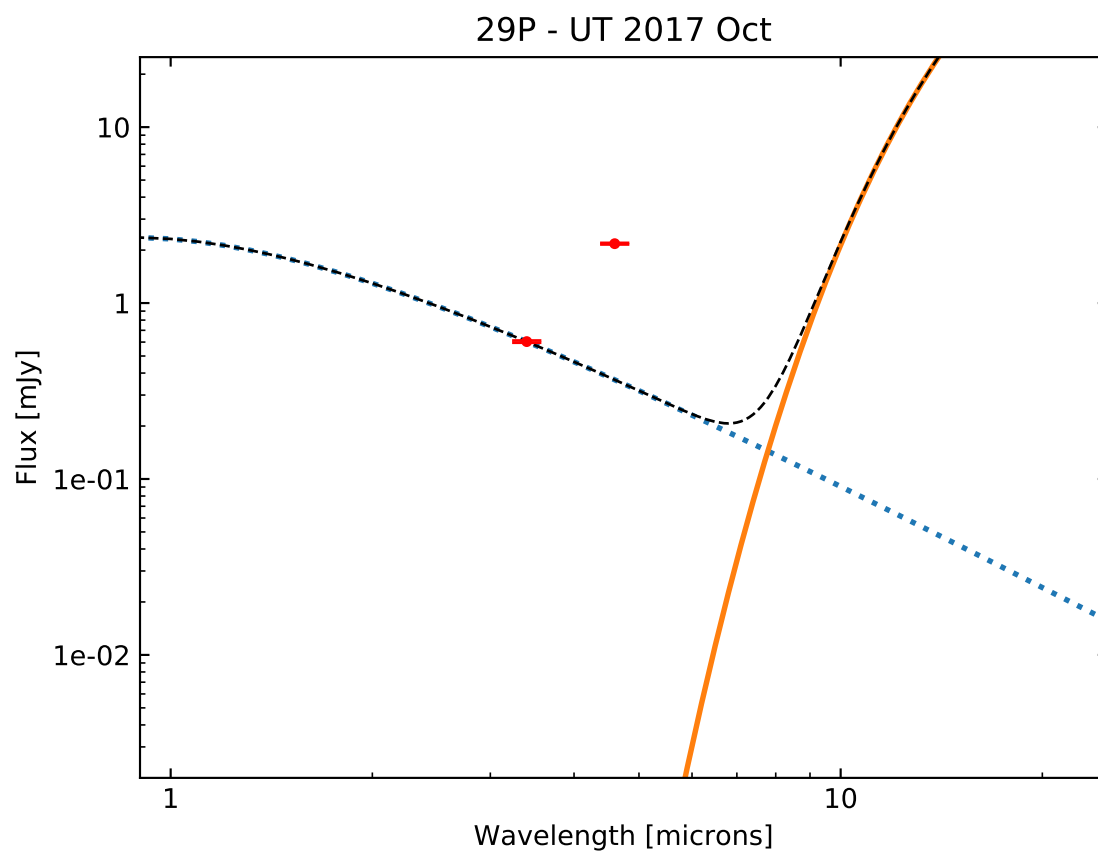


Figure 3.13: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2017 Oct. NEOWISE Visit.

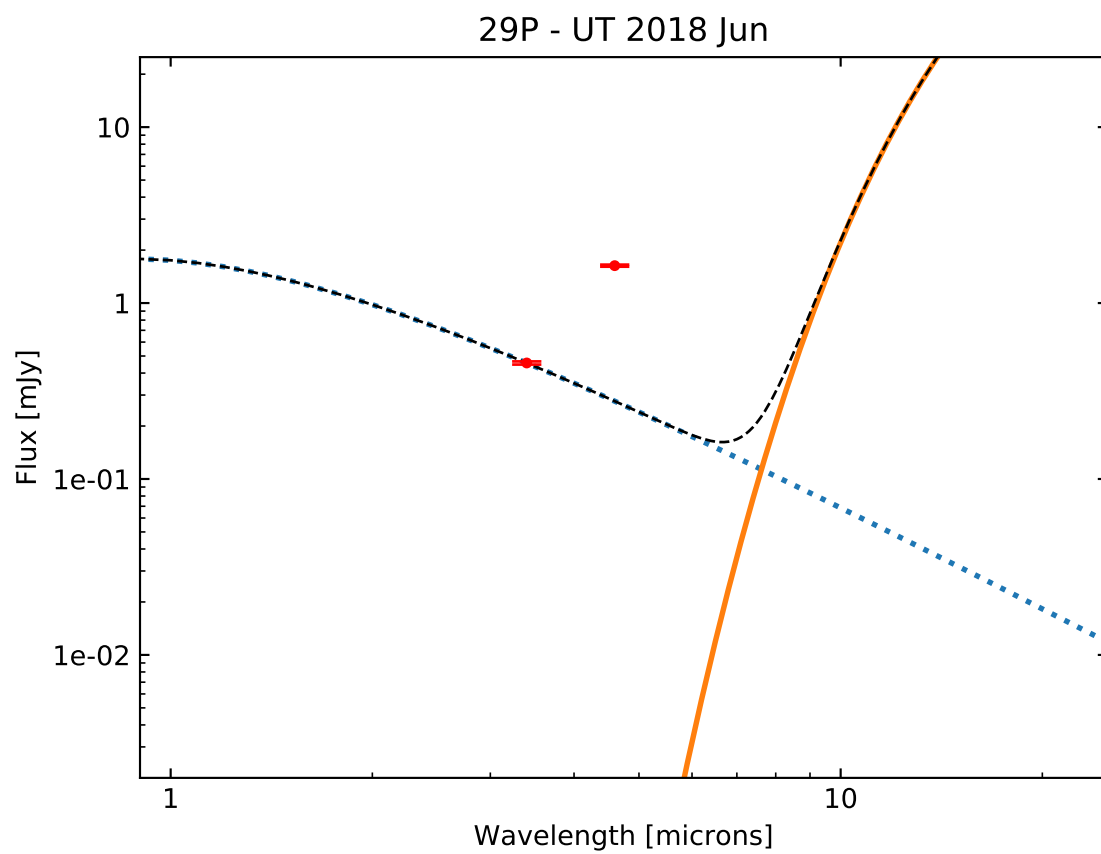


Figure 3.14: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2018 Jun. NEOWISE Visit.

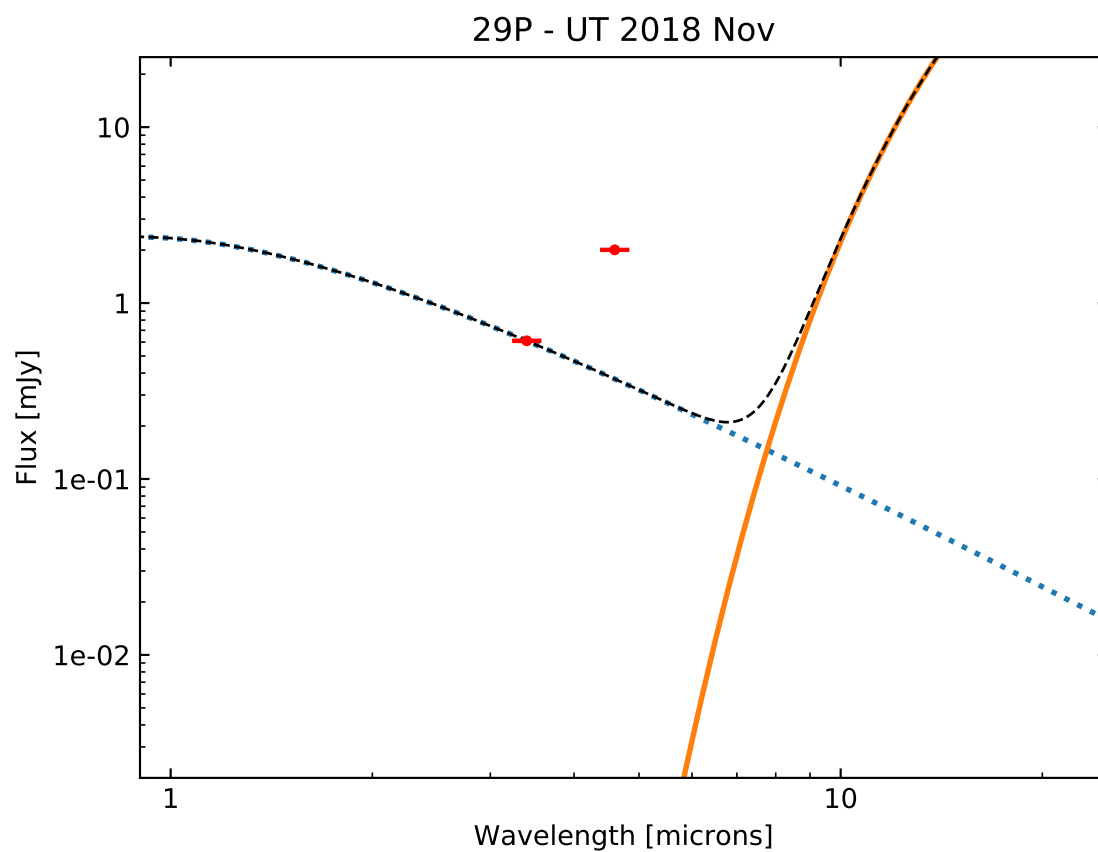


Figure 3.15: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2018 Nov. NEOWISE Visit.

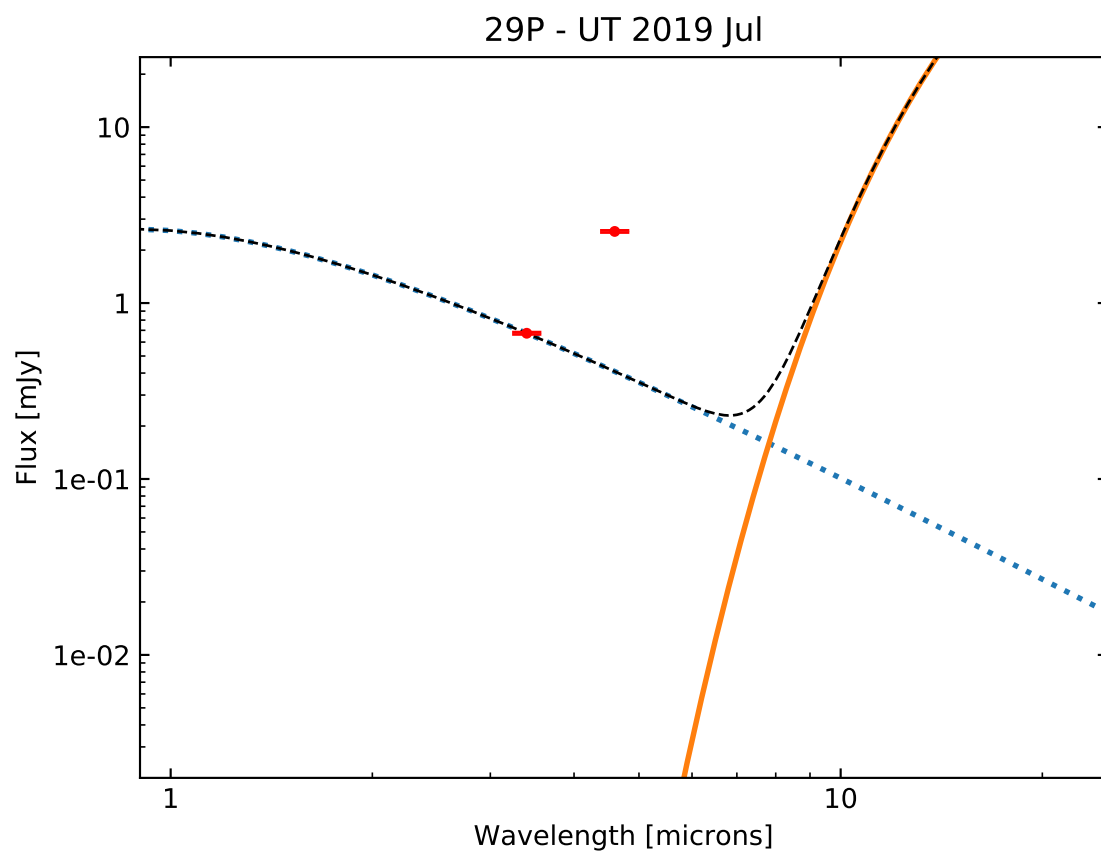


Figure 3.16: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2019 Jul. NEOWISE Visit.

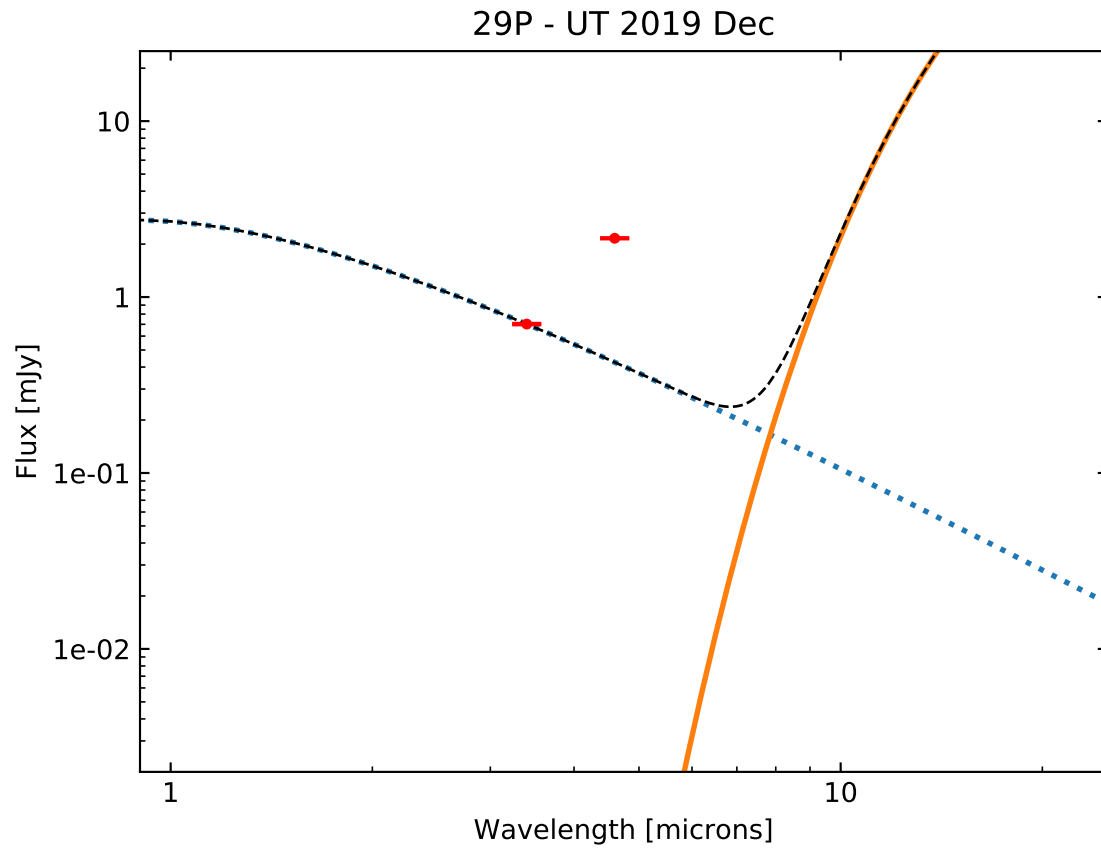


Figure 3.17: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2019 Dec. NEOWISE Visit.

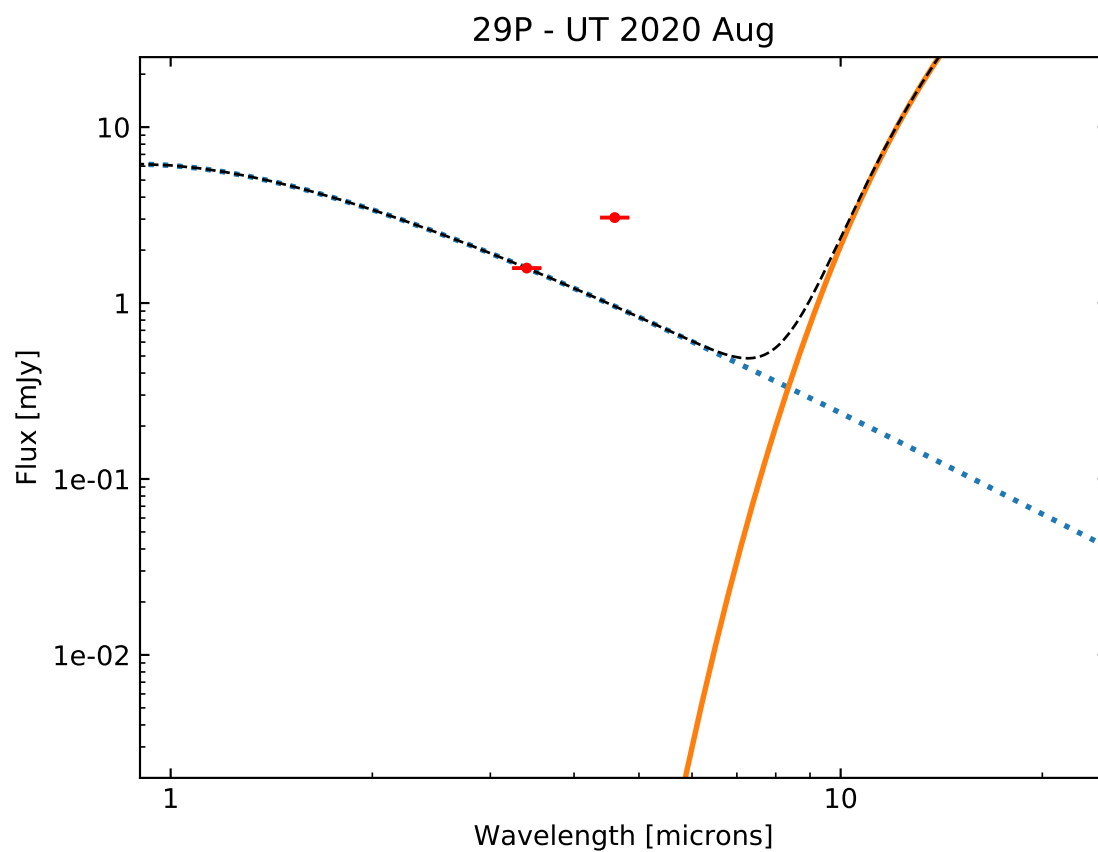


Figure 3.18: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2020 Aug. NEOWISE Visit.

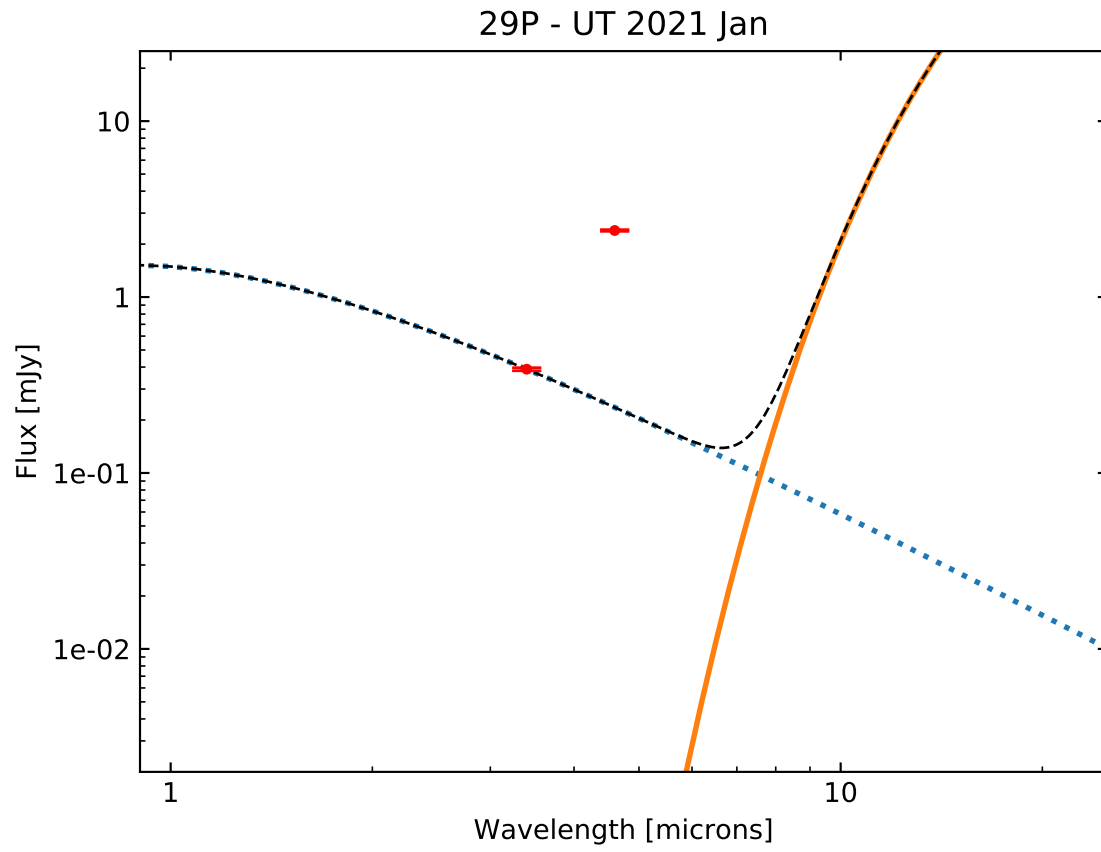


Figure 3.19: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2021 Jan. NEOWISE Visit.

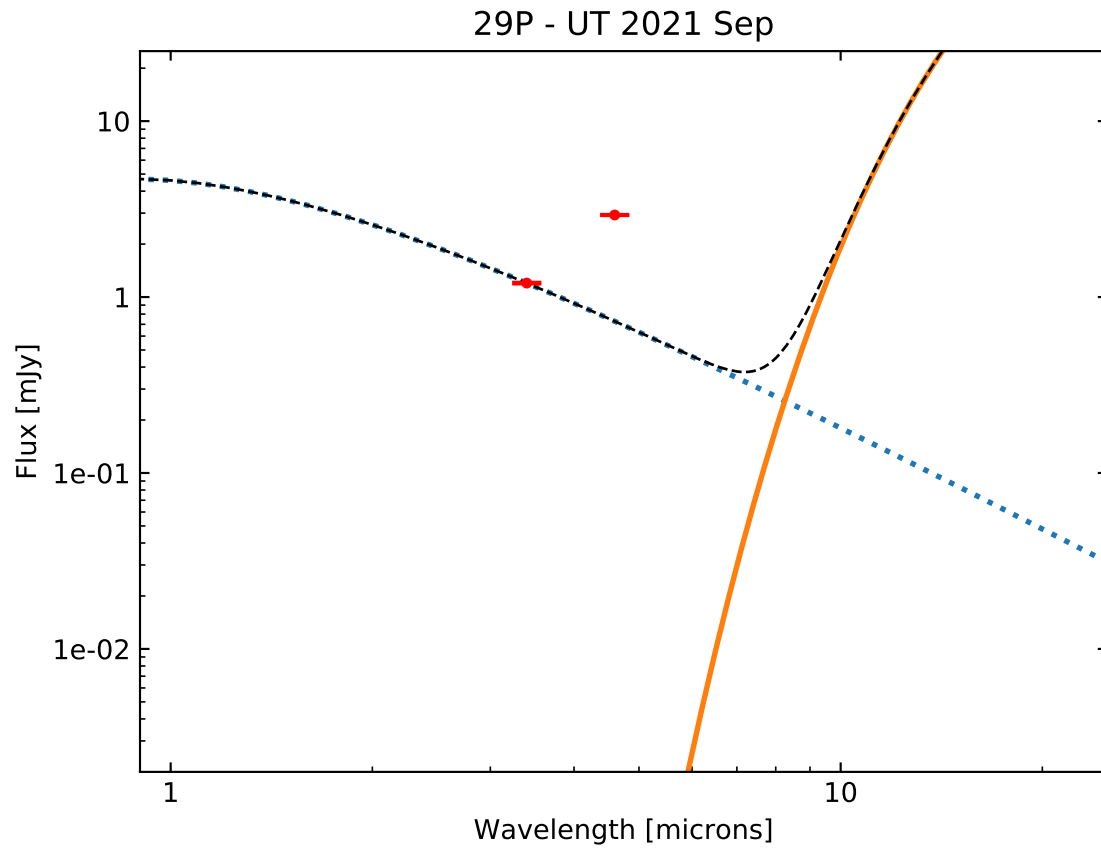


Figure 3.20: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2021 Sep. NEOWISE Visit.

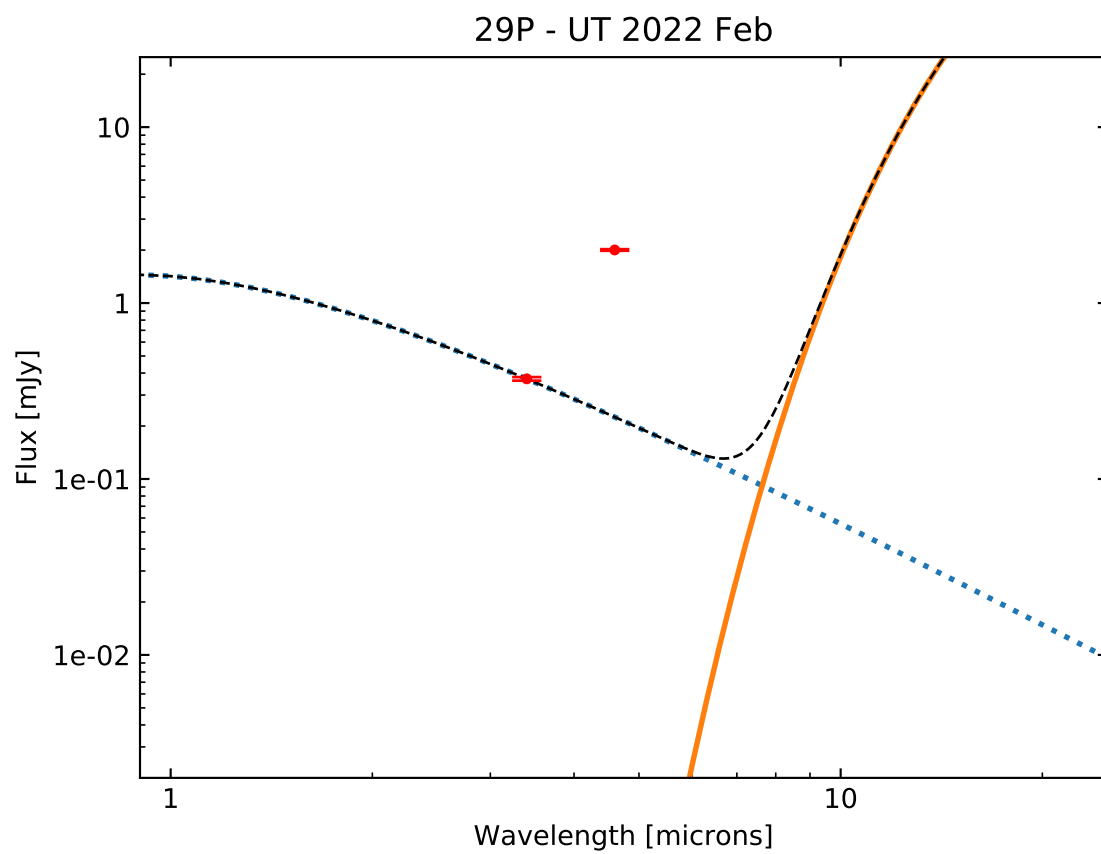


Figure 3.21: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2022 Feb. NEOWISE Visit.

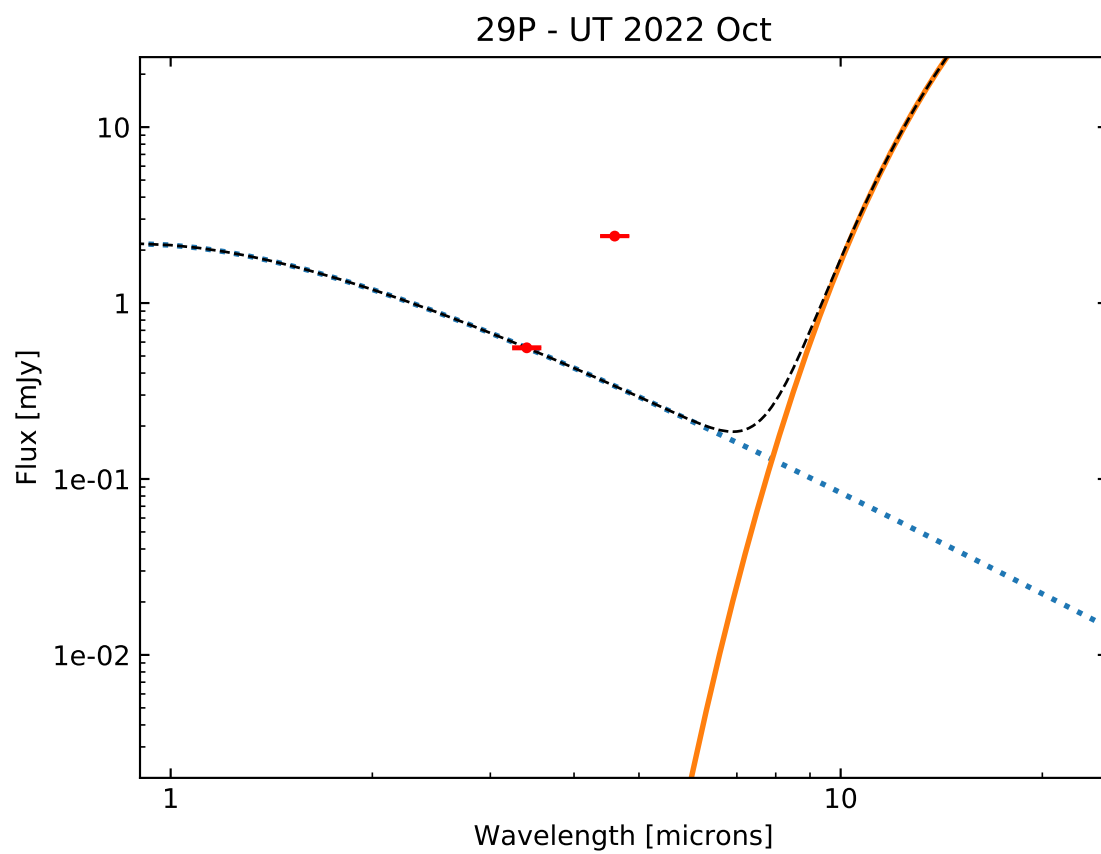


Figure 3.22: Same as Figure 3.8 for Short-Period Comet (SPC) 29P/Schwassmann-Wachmann 1 (SW1), but for the 2022 Oct. NEOWISE Visit.

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CHAPTER 4

Concluding Remarks

4.1 NEOWISE Observations of Comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS) and C/2010 U3 (Boattini)

4.1.1 Hyperactive Comets Summary

The study of hyperactive comets described in Chapter 2 by Milewski et al. (2024) provided crucial information on the gas and dust activity of the three hyperactive comets C/2014 B1 (Schwartz), C/2017 K2 (Pan-STARRS), and C/2010 U3 (Boattini). All were found to be active beyond the water-ice sublimation region of the solar system. A half-sample bootstrap method (Wright, personal communication) was employed in preliminary data reduction stages, especially for faint comets barely visible in the NEOWISE single-exposure data. This was used to test for spurious detections caused by residual galaxies, stars, or background noise and to boost confidence that the sources were indeed real. In using ICORE (Masci 2013), we opted to use an algorithm where near-neighboring pixels would be included in the final images and this was such that a minimum of three single exposures were needed in order to build up a final mosaicked frame. Background matching was applied and the images were co-added in the moving reference frame of the comet. Objects that are ~ 16 in $W1$ magnitude often have background noise that dominate the images leading to poor quality data. This is explained further in Mainzer et al. (2014). The B1 and U3 visits are an example of this, except when B1 was near perihelion and a point source could be seen in the $W1$ and $W2$ data with enough signal-to-noise to confirm that the detection was indeed

real. Similarly, K2 acted in a likewise fashion as it first became measurable in *W1*, and later in *W2* as it entered the region of the inner solar system. This may imply that for the LPCs, the presence of a coma is likely due to the sublimation of gaseous species lifting the dust grains in addition to an often symmetric (spherical) coma emanating from the unseen nucleus, especially at or beyond the CO and CO₂ crystallization zone. Comet K2 did appear (albeit faintly) in some single-exposure data, which is quite remarkable as most NEOWISE observed comets are commonly first detected at $\sim 5\text{--}6$ au in the WMOPS processing.

This has significance especially since two of those comets, K2 and U3, were found to be active at such great heliocentric distances (r_H) of 23.7 au for K2 (Hui et al. 2018) and U3 at 25.8 au (Hui et al. 2019). Milewski et al. (2024) provided some crucial measurements of gas and dust in the infrared wavelengths. Further, of the currently available datasets for measurements of cometary dust and gas, few measurements exist in the literature for LPCs, especially when at large heliocentric distances. Ootsubo et al. (2012) focused on 18 comets, including some Oort cloud comets, and provided at least two measurements for every comet observed, sometimes at different r_H . Our data show that K2’s gaseous inventories of CO and/or CO₂ are comparable to those of the most active comets reported by Ootsubo et al. (2012). As the research of Milewski et al. (2024) was conducted, only the inbound leg of K2’s orbit was able to be studied as it reached perihelion on UT 2022 December 19. K2 reached a perihelion distance (q) of 1.798 au where temperatures were high enough to trigger water-ice sublimation activity. As K2 may now be more thermally processed compared to other Oort cloud comets, its outbound trajectory and evolution will be important to provide comparisons with other Oort cloud comets that have been studied both inbound and outbound. While Yang et al. (2021) suggested that K2’s activity was likely due to substantial amounts of CO when measured with the JCMT, Cambianica et al. (2023) had reported that through spectral analysis, K2 revealed the presence of forbidden oxygen emission lines. Forbidden oxygen lines might suggest that CO₂ is the driver of activity for both K2 and other exceptionally active comets such as C/2016 R2 (Pan-STARRS) (Raghuram et al. 2020), e.g., ‘R2’. This is because

the CO molecule is tightly bound compared to CO₂, and the timescale for photodissociation is very long (Huebner et al. 1992). For K2, even at 2.8 au from the Sun and interior to the solar system water-ice sublimation line, Raghuram et al. (2020) argued that CO₂ must be the parent source of oxygen in the observed activity and that CO₂ is dissociated and produced with large excess velocity. If true, this would imply that even with our assumptions that the activity and quantification of Q_{CO_2} and Q_{CO} species could be better explained given the discrepancies of Milewski et al. (2024) and Yang et al. (2021). Unfortunately, excess activity in the NEOWISE *W2* channel is contributed by an inseparable mixture of CO and CO₂, and we cannot decide which, if either, is dominant. Fougere et al. (2016) found that a mixture of CO and CO₂ species is indeed possible for comets.

4.1.2 Future Investigations of Hyperactive Comets

Understanding the nature of cometary activity, both pre- and post-perihelion, holds scientific importance for determining the role of short-term evolution of the outgassing surface. Comet C/1995 (O1) (Hale-Bopp) well studied both before and after perihelion and found to have a rather large nucleus and to produce substantial production rates in carbon monoxide (CO) (c.f. Chapter 1). Szabó et al. (2011) detected Hale-Bopp at 30.7 au (outbound) and suggested that it was still significantly active even as far as 25.7 au, providing the furthest ever detection of activity in a comet that was outbound. As Hale-Bopp did indeed cross into the water-ice sublimation region of the solar system, a question that can be asked is what is the significance of thermal modification and even possible aqueous alteration in present and future cometary activity? The LPCs are returning comets, allowing the possibility of chemical modification at previous perihelia. Another area of focus can be placed on the size of the nucleus of these cometary bodies in the significance of their retention of volatiles when these comets become active at significant distances from the Sun. Szabó et al. (2011) suggested that the nucleus of Hale-Bopp was ~ 35 km in diameter (about half of previous estimates of 60-65 km) which is scientifically interesting. Most recently, Kelley et al. (2022)

observed Hale-Bopp with JWST at a distance of 46 au and suggested that its activity had ceased at around ~ 27 -28 au, based on both infrared and optical observations. As K2 is now outbound, measurements of its nucleus as well as quantification of its gas and dust species will be especially important for future studies of evolving cometary activity. Bouziani & Jewitt (2022) have even suggested the importance of CO and CO₂ hypervolatile species that are capable of driving cometary activity beyond the planetary region, perhaps even as far as ~ 100 au. If true, this would place great interest on future observations of comets at extreme distances, as well as on their orbital evolution. In most cases, the presence of a dust coma (in LPCs) seems to suggest that dust and gas are closely linked. This has been the notion historically attributed for LPCs. However, in the case of 29P/SW1, the gas and dust, are not necessarily closely coupled, as discussed in Chapter 3.

4.1.3 Future Observational Facilities

Future optical surveys by the Vera C. Rubin Observatory (previously referred to as the Large Synoptic Survey Telescope; LSST) will provide new observations and discoveries of numerous comets, as well as the capability to study cometary activity at large heliocentric distances. Hui et al. (2024) have suggested that K2 and U3 may belong to a new subclass of comets that are active at distances greater than ~ 20 au. While only four such objects are known at the present time, it is likely that many other members of this cometary family exist and will be discovered by the planned Rubin sky survey. In 2024, NEOWISE, used for the infrared observations in this Dissertation, will cease operations. The upcoming Near-Earth Object Surveyor (NEOS) telescope (scheduled to be launched in late 2027) will provide new and refined measurements of small bodies in its role as a successor to the NEOWISE Mission. However, the next major space-based asset working in conjunction with measurements provided from JWST is that of the Spectral-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer (SPHEREx) (Doré et al. 2018). This all-sky spectral survey will provide information for astrophysical objects such as stars and galaxies, in ad-

dition to instrumentation sensitive enough for the measurement and separation of volatile species in comets and asteroids. These, and future missions will all be necessary assets for our understanding of nature of activity in comets.

While no comet rendezvous missions are currently planned, C/2017 K2 (Pan-STARRS) remains a target of interest for the joint ESA-JAXA Comet Interceptor Mission that is scheduled for launch sometime in 2029. Ideally, a sample return mission could provide revolutionary new information regarding the composition of comets, as could a spacecraft carrying a mass spectrometer into the cometary coma. Pristine cometary dust sample material was returned from the NASA Stardust mission that collected dust samples from 81P/Wild-2, but more information from future dust sample return missions, especially if 29P/SW1 is chosen as a potential target for the Comet Interceptor Mission could prove invaluable. Such missions could characterize the relative importance of CO and CO₂ species as well as a host of other species unobservable from the ground.

4.2 Distant Active Centaur 29P/SW1

4.2.1 Activity of 29P/SW1 Summary

We present a study in Chapter 3 of frequently active Centaur 29P/SW1 over the ~ 8 years of coverage (including both pre- and post-perihelion observations) observed by the NEOWISE Reactivated (NEOWISE-R) Mission. This utilizes a single instrument in the infrared regime to quantify the gas and dust production over a long temporal baseline, specifically NEOWISE-R years 2014–2022. The gas production measurements are also unhampered by the residence of CO₂ in the Earth’s atmosphere or telluric CO contamination which has presented substantial observation challenges for ground-based observers in the past. The latter specifically is of importance as the activity associated for distantly active comets has been shown to be due to these crucial volatile species. Furthermore, submillimeter and radio studies lack the morphology that can be obtained via simultaneous NEOWISE multi-channel

measurements enhanced by imagery and morphology, giving a more complete profile of the gas and dust activity covered by the infrared regime of the electromagnetic spectrum. We then augment and trace reported activity events on 29P/SW1 using the ATLAS ground-based telescope project as well as determination of the dust and gas species. In addition, follow-up analysis of an impulsive 2020 July–September outburst event was performed in order to make a determination of the speed of an expanding dust shell, $v_{dust} = 60 \pm 2 \text{ m s}^{-1}$, which is at the lower end of published literature values. However only minimal coverage of this event exists based mostly on reports and limited data from ground-based amateur astronomers.

The UT 2020 July–September outburst (assuming this is a single event) lasted ~ 40 days and continued as late as what we suspect UT 2020 September 1 (MJD 59093.49). This is the date at which the comet returns to a quiescent state as shown in the ATLAS imagery. We present the first-such scientific study greatly documenting a rare outburst event with a long and unusual period of persistent dust lingering in the vicinity of the nucleus. 29P/SW1 represents an interesting and enigmatic object entering a potential transition region of the outer solar system with CO-driven activity very well likely to be the source species dominant for its observed activity. How the gas and dust events factor into the activity, still do remain unexplained. The results of our study mostly follow and corroborate previous work, but especially the recent analysis of documented more-recent outburst events such as those by Wierzechos & Womack (2020). This suggests that the behavior of gas and dust with the onset of activity is, is not always linked or may not necessarily be correlated. Given the fact we present our results covering the infrared regime (via NEOWISE) with simultaneous dust and gas measurements, we can further refine whether or not such events are coupled or correlated in any way with other wavelengths of the electromagnetic spectrum such as optical, radio, and submillimeter measurements.

4.2.2 Future Observations of 29P/SW1 and Monitoring Outbursts

Commenting on the nature of dust environment, in a recent polarization study of dust for distantly active comets, Kochergin et al. (2023) suggests a possible correlation of magnesium-rich dust particles, interestingly in roughly the same region of the outer solar system around $\sim 6\text{--}7$ au from some reported measurements, suggesting that 29P/SW1 may exhibit negative polarization of dust grains as found for exceptionally active distant long-period comet C/2017 K2 (Pan-STARRS). That study also compared similar features observed in the comae of active comets at this distance and the nature of their activity. Implications of this study suggest a size of submicron to micron sized particles consisting of magnesium-rich silicates, water-ice, organics, and amorphous carbon dust with an age of up to 15 days that have emanated from the nucleus. This is especially useful as there may be a link explaining activity between 29P/SW1 and K2 at this r_H where crystallization of amorphous water ice is largely suspected to be the cause of cometary activity. Hui et al. (2024) also places K2 as a member of a small, but possibly new class of distantly active comets; whereby, we speculate the specifics of the dust grains and species at these distances may provide more greater understanding on the nature of their distant activity. Milewski et al. (2024) concluded that CO+CO₂ activity is prevalent and a major contributor for rather exceptional cometary bodies where K2 did have an elevated CO₂ production rate and was most-recently suggested to be the parent source of atomic oxygen in Cambianica et al. (2023). Figures 2.1 (d.)–(i.) of this Dissertation show the similar features and cases with observed differences in the morphology of gas and dust for K2 at or just beyond ~ 6 au also at similar low phase angles ($\sim 5\text{--}10^\circ$ for K2; c.f. Figure 2.1, and $\sim 9\text{--}10^\circ$ for 29P/SW1; c.f. Figure 3.4) as well as high dust and gas production measurements also using NEOWISE.

With a small number of important studies such as Biver (1997) and Wierzechos & Womack (2020) characterizing the sudden spike in gas production for 29P/SW1 only return to ‘nominal’ levels in just a few hours or days, this could imply that the gas and dust nature of activity are slightly entrained but for such a small timescale that is otherwise extremely

difficult to know when this occurs. This, unfortunately remains well outside the capability of most ground or even space-based surveys to monitor continuously at the present time. If the nature of dust species for both these objects are similar, further investigations involving laboratory experiments or monitoring these grains would be well-warranted and strongly encouraged. In addition, as 29P/SW1 did seemingly increase in gaseous activity after its 2004 perihelion passage, Moreno (2009) performed detailed dust modeling. That study concluded that if dust emission is assumed to be produced by a single active-area driven by insolation, this source must be located on the southern hemisphere near -35° in latitude and shown in Figure 5 of that work for a variety of latitudes using CCD imagery to construct a model of the post-perihelion dust ejection. This occurred after perihelion and is remarkably similar to what is seen in our work after the 2019 perihelion passage in our infrared (Figures 3.5 (a.) & (c.)) and optical (Figures 3.5 (f.)–(l.)) images. Future monitoring whether this seemingly upward trend in gaseous activity will continue (c.f. Figure 3.3).

4.3 Conclusions

Originally presented in Section 1.1.2, the focus of this Dissertation addresses and seeks to answer several fundamental scientific questions. The major results of this Dissertation are as follows:

- K2 and 29P/SW1 both produce similar peak dust production values (quantified by $Af\rho$) despite differences in heliocentric distance, r_H , at peak production, respectively. However, both have steadily produced a substantial amount of CO and CO₂ also despite their r_H . With K2, its peak dust production occurred in the last NEOWISE Visit at $r_H = 2.47$ au just before perihelion which is expected. However 29P/SW1 produces comparable dust at larger r_H , (5.85 au), which is unusual (c.f. Tables 2.2 & 3.1). This addresses Scientific Questions 1, 2, and 3.

- For K2, the paradigm of the emergence of a dust coma likely due to lifting of dust grains by unseen gas which soon follows thereafter is the model that best explains activity seen in distant active comets, especially for the LPCs. Despite this, for 29P/SW1 being an SPC, there is no strong evidence of correlation between dust and gas in observed activity; Chapter 3 from this Dissertation as well as Wierzechos & Womack (2020). This addresses Scientific Questions 1, 3, and 4
- K2 and U3 are two of four currently known comets found to be active (on inbound orbits) as far as at least 20 au in r_H and a potentially new subclass of comets (Hui et al. 2024). The emergence of these four comets presents serious challenges to previous models for explaining cometary activity. Nonetheless, this Dissertation provides crucial information of their gas and dust inventories over various stages of their orbits for K2 and U3. For U3, a limited number of studies (which includes Milewski et al. (2024)) have been performed on this object and it is outbound, well outside the capability of detection of most telescopes. This addresses Scientific Questions 1, 3, and 4.
- Future observations of K2 may constrain the size of the bare nucleus to be compared with Hale-Bopp. Gas and/or dust activity may be subsiding but only future observations will be able to show if, when, and at what r_H this may eventually terminate for distant active comets on the outbound legs of their orbits. This addresses Scientific Questions 1, 3, and 4.
- K2 will provide a comparison to Hale-Bopp as it is now outbound. Hale-Bopp was well studied both pre- and post- perihelion. With JWST online, SPHEREx and NEOS coming, more information on this comet as well as further separation of the contribution of CO and/or CO₂ may be attained. This addresses Scientific Questions 1 and 4. Further, the model proposed by Bouziani & Jewitt (2022) can be tested.
- While the Whipple Model (1950, 1951) has sufficiently explained activity for comets due to the sublimation of water-ice as comets make close approaches to the Sun, the

importance of CO and CO₂ volatiles posit a refinement of Whipple’s ‘dirty-snowball’ model. Bouziani and Jewitt (2022) suggest CO and CO₂ are hypervolatiles that can drive activity out to ~ 100 au. Again, this addresses Scientific Question 4.

- 29P/SW1 still retains a significant portion of its pristine volatiles (e.g. CO) despite its close distance to the Sun over millions of years and produces gaseous emission comparable to that of the few rare measurements that exists for the most active comets seen Ootsubo et al. (2012). As such, this result for 29P/SW1 is unusual. This addresses Scientific Questions 1 and 2.
- The long-term evolution of 29P/SW1 during its 2019 perihelion passage in terms of its gas and dust activity as well as morphology remains to be seen. If it behaves as it did just after the 2004 perihelion passage, gaseous activity was seen to increase just after perihelion. This Dissertation provides some data points about 4 years since it has reached perihelion in 2019 and current data shows the gas production appears to be trending upwards (c.f. Figure 3.3). This addresses Scientific Questions 1 and 3.
- The importance of spectral observations of comets containing forbidden oxygen lines needed to disentangle CO₂ in especially active comets like R2 and K2 will be especially useful for future studies and to investigate a possible link between water and CO₂ as CO₂ has been found for active comets inward of the solar system frost line, whereas beyond this, it is due to CO as suggested by Ootsubo et al. (2012). This addresses Scientific Questions 1, 2, and 4.
- The arrival of inbound interstellar objects, especially those which are active such as 2I/Borisov that had a substantially high amount of CO compared to solar system comets (Bodewits et al. 2020) can provide a comparison of solar system comets to those coming from elsewhere and their CO and/or CO₂ inventories. As such, more observations and measurements of CO and CO₂ in comets will be crucial for comparison as more interstellar comets will become detectable with especially sensitive instrumen-

tation coming online capable of detecting them. This addresses Scientific Questions 1 and 4.

- Future investigations at 1P/Halley's 2061 approach along with future instruments providing improved sensitivity to CO and CO₂ will allow comparison with volatile production from 1986. The orbit period of 1P/Halley is comparable to the average human lifetime. Unfortunately, the orbital periods of most LPCs greatly exceed the human lifetime. This makes all potential measurements of cometary gas and dust inventories as well as characterization of their activity absolutely essential for furthering cometary science. This addresses Scientific Questions 1, 2, 3, and 4.

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