

UC Berkeley

UC Berkeley Electronic Theses and Dissertations

Title

Unveiling the Secrets Beneath Jupiter's Clouds with Radio Observations

Permalink

<https://escholarship.org/uc/item/4wj4k6wb>

Author

Moeckel, Chris

Publication Date

2024

Peer reviewed|Thesis/dissertation

Unveiling the Secrets Beneath Jupiter's Clouds with Radio Observations

by

Chris Mario Moeckel

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Earth and Planetary Science

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Imke de Pater, Chair

Professor Stuart Bale

Associate Professor William Boos

Spring 2024

Unveiling the Secrets Beneath Jupiter's Clouds with Radio Observations

Copyright 2024
by
Chris Mario Moeckel

Abstract

Unveiling the Secrets Beneath Jupiter's Clouds with Radio Observations

by

Chris Mario Moeckel

Doctor of Philosophy in Earth and Planetary Science

University of California, Berkeley

Professor Imke de Pater, Chair

Giant planets are characterized by their predominant gaseous composition, with hydrogen and helium as the major constituents. The presence of trace gases in the atmosphere has two effects. Condensible trace gases form clouds, restricting visible and near-infrared observations to mostly explore the top-most cloud layer. This severely limits our understanding of atmospheric composition and global circulation, both of which are concealed below the clouds. However, the interaction of certain trace gases with radiation also provides a window through the clouds. We can use spectroscopy to retrieve the distribution of these gases below the clouds and investigate their three-dimensional structure with mid-infrared and radio observations.

One of the key trace gases in the atmospheres of giant planets is ammonia (NH_3). Ammonia constitutes a small fraction of the atmosphere (approximately 300 parts per million), but it serves as a valuable tracer for atmospheric circulation. In the radio regime, the spectral absorption features of ammonia are highly pressure-broadened, allowing us to explore the atmosphere ranging from tenths of a bar to thousands of bars; essentially from the ammonia cloud tops to several hundred kilometers below. Through comparisons of radio observations with model atmospheres, where we can manipulate the distribution of trace gases and temperature profiles, we can constrain the atmospheric properties and the processes that shape the atmosphere.

Prior to the arrival of the Juno mission, radio observations had already indicated that Jupiter's atmosphere is neither latitudinally nor vertically well-mixed below the cloud deck. Based on these earlier observations, it was believed that the water condensation layer around 6 bars acted as a barrier for atmospheric circulation, below which the atmosphere was considered fully convective and well-mixed. However, the presence of synchrotron radiation, the dominant source of radiation at lower frequencies, limited our understanding to altitudes above the water condensation layer.

The arrival of the Juno mission at Jupiter has enabled us to overcome this limitation by descending below the synchrotron radiation belts (peaking at 1.5 jovian radii). Throughout my Ph.D. research, I have developed tools to independently calibrate and process instrument data from radio observatories, focusing primarily on NASA’s Juno Microwave Radiometer (MWR) and NRAO’s Very Large Array (VLA). The open-source pipelines I developed retrieve relevant observational quantities (brightness temperature and its dependence on the emission angle) along with their uncertainties. Subsequently, I developed and compared models with observations, which allowed me to study the distribution of ammonia on Jupiter. The enhancement in nitrogen ($2.66^{+0.27}_{-0.17}$ solar) in Jupiter’s deep atmosphere was found to be lower than previously estimated.

A more surprising discovery was the depth to which the atmosphere appears to be depleted (20-30 bar), much deeper than can be explained by dynamics or conventional microphysics. This finding highlights that Jupiter might have a stably stratified troposphere much deeper than previously thought. The distribution of ammonia revealed that zones and belts on Jupiter can be traced below the cloud deck; in the tropical regions extending down to 20 bars, while the subtropics and mid-latitudes are confined to the upper few bars. Deeper in the atmosphere, around 30 bars, the signal reverses, showing enhanced belts compared to the depleted zones. This distribution could be explained by a stacked circulation cell model, where the middle and lower troposphere cells have opposite circulation directions.

By examining the longitudinal structure of the atmosphere using data from both VLA and MWR, I was able to analyze the weather on Jupiter. The majority of the variability in Jupiter’s atmosphere is confined to the upper few bars, affirming earlier theories and observations that weather is a shallow phenomenon on the gas giant. Even in the most dynamically active region (the North Equatorial Belt), the weather extends only to approximately the water condensation layer. The only three features I identified capable of affecting the lower troposphere were an anticyclone, an ammonia plume as part of the trapped equatorial Rossby wave, and the signature of precipitation, which appeared to deposit ammonia below the water condensation layer.

The breakthrough in understanding came from studying the impact of a giant outbreak in the South Equatorial Belt. By comparing the MWR observations of the outbreak with orbit-averaged observations, I demonstrated that the storm affected the deep troposphere down to approximately 20 bars. These are the first observations showing that storms deplete the upper atmosphere in ammonia, while cooling and enhancing the lower troposphere at much greater depths than previously anticipated on Jupiter. The mechanism through which the atmosphere is depleted favors supercooled water, rapidly updrafted in storms, absorbing ammonia to form water-ammonia hail, which is subsequently deposited around 15-25 bars. This process shows how small- and large-scale processes interact to shape the atmosphere of Jupiter. In conclusion, my work has shown that the gas giant atmospheres are not as convective as previously thought, and are controlled by the interaction of both local microphysics and the background large-scale circulation.

Contents

Contents	i
List of Figures	iii
List of Tables	xiii
1 Introduction	1
1.1 Atmospheric Circulation on Earth	1
1.2 Definition for Jupiter	2
1.3 Canonical shallow view of Jupiter's circulation	13
1.4 Challenges to the canonical view of Jupiter's circulation	16
1.5 Big questions	18
2 Measuring Ammonia with Radio Telescopes	20
2.1 Introduction	21
2.2 Data	22
2.3 Methods	32
2.4 Radiative Transfer Model	36
2.5 Results	40
2.6 Discussion	49
2.7 Conclusions	61
3 Effect of Storms	68
3.1 Introduction	68
3.2 Results	69
3.3 Discussion	75
3.4 Methods	78
4 Effect of the Weather	89
4.1 Introduction	89
4.2 Data	91
4.3 Methodology	96
4.4 Modeling Results	104

4.5	Discussion	108
4.6	Conclusion	110
5	Conclusions	118
	Bibliography	121

List of Figures

1.1	Overview of the cloud structure in Jupiter's convective atmosphere. The left hand side shows the approximate pressures at which the clouds form, while the center shows the various processes involved during a convective upwelling event. Reproduced from (de Pater et al. 2023) and (Fletcher et al. 2020b).	7
1.2	Classical circulation model with rising motion in the zones and subsidence in the belts. The warm and cold indications show infrared observations above the green arrows representing horizontal momentum flux responsible for shaping the jets at the interfaces between these regions. Reproduced from (de Pater et al. 2023) and (Fletcher et al. 2020b).	13
1.3	Including recent radio observations into the circulation models shows that some of the observations could be reconciled with stacked circulation cell model. Reproduced from (de Pater et al. 2023) and (Fletcher et al. 2020b).	17
2.1	PJ3 flyby during December 2016. The map shows X-band (8-10 GHz) VLA observations taken concurrently with the flyby to show the longitudinal structure of the planet (Moeckel et al. 2019, These VLA data will be fully published in a subsequent paper). The red footprints correspond to MWR's Channel 5 observation, where we have plotted the highest resolution (i.e. smallest emission angle), while the blue footprints correspond to the VLA resolution (Note: In December 2016 the VLA was in the most extended A-configuration). Inset a) is a zoom-in for the indicated region and shows all the 60 individual observations colorized by their beam-convolved emission angle that are centered around the equator. These 60 observations are the basis for fitting the nadir brightness temperature and the limb-darkening at 0° . Inset b) is a zoom-in to illustrate how the emission angle varies across the beam, where the red central dot corresponds to the boresight center and the black dot indicate the position of the spacecraft. The dashed ellipses correspond to the beams' extent projected onto the planet with the contours showing how the emission angle varies across the beam. The final beam-convolved emission angle is 59.2° when integrating over the $2.5 \theta_{HPBW}$ contour that corresponds to 99% of the emission.	26

2.2	Brightness temperature at 12° deg north latitude for the 6 different channels, plotted against the beam-convolved emission angle. The closed circles correspond to the observations considered in the fit, and the open circles to the observations that were removed. Open circles inwards of the cut-off are observations with high susceptibility to synchrotron radiation (spatial filter – see Section 2.2), while open circle outwards are measurements where part of the beam is off the planet. The cut-off is determined such that all beam elements interior 2.5 HPBW are on the planet. The impact of the synchrotron radiation leaking in through the side lobes can be seen in Channel 1 and 2, where the brightness temperature increases beyond 60 deg, while the drop in brightness temperature at higher frequencies is due the cold sky leaking in. The solid line with shading corresponds to the fitted model according to Equation 2.3 and three uncertainty fidelities ($n=1,3,10$). The intersect at an emission angle of zero is the nadir brightness temperature, and the limb-darkening parameter defines the shape of the curve.	29
2.3	Verification of the fit uncertainty derived from the weighted least squares approach (see Equation 2.5) by comparing the results to an Markov-Chain Monte-Carlo (MCMC) method using the same underlying model to fit the data (see Equation 2.3). The solid black lines corresponds to the 16%, 50% and 84% quantiles, while the dotted red lines indicate the errors retrieved from the weighted least square approach. The best-fit quantities for both methods agree well within their uncertainties. The largest difference is found in the uncertainty of the fitted limb-darkening parameter, where the weighted least square errors are smaller than the MCMC results.	30
2.4	Nadir brightness temperature for the 6 channels between -60 and 60 deg, where the thick lines indicate the orbit averaged values, and the dashed thin lines correspond to the individual PJs. The dotted line represents the orbit averaged value based upon a deconvolution algorithm (Oyafuso et al. 2020) and shows a good agreement between the two methods, validating both our approaches.	32
2.5	Same as Figure 2.4 but for the limb-darkening parameter.	33
2.6	Compilation of the relevant temperature profiles which we assume for our retrieval. The temperature profiles are anchored at the 1 bar level to the radio occultation measurements of Voyager (Lindal et al. 1981) and to the Galileo probe measurements (Seiff et al. 1996). Above the 0.7 bar level we use profiles obtained via infrared measurements (Fletcher et al. 2009). Below the 1.0 bar level we use the expected wet and dry adiabatic lapse rate until the two profiles merge at the height of the water cloud. The little cutout shows the anchor points at the 1 bar level, with the corresponding uncertainties.	38

2.7	Weigthing functions visualize the pressure levels from which radiation is received. We plot the functions for both end members on the planet, a highly enriched part in the atmosphere (solid line corresponding to the EZ), and a highly depleted part (dashed line corresponding to the NEB) showing the depth and range from which we receive the signal. The abundance profile for which we compute the weighting functions are taken from our fit to the orbit-averaged MWR data (see Figure 2.9). The left hand side shows the relevant functions for the Juno spacecraft, and the right hand side shows the function for the VLA.	39
2.8	Globally averaged $[-45^\circ, 45^\circ]$ ammonia profile as a function of depth. The red profiles corresponds to our thermo-chemical equilibrium model, and the blue line corresponds to our stochastic model with the shading corresponding to $n = 1, 10$. The blue dashed curve is based on the results of Li et al. (2017a), and the green curve is based on the VLA data from de Pater et al. (2019b). The radio attenuation (Folkner et al. 1998) and Galileo Probe Mass Spectrometer (GPMS)(Wong et al. 2004) are superimposed.	42
2.9	Ammonia abundance map based on Juno's orbit average brightness temperature and limb-darkening with a $3\text{-}\sigma$ fit uncertainty level. The map shows familiar features such as the column of enriched ammonia in the EZ and the depletion of ammonia in NEB, with smaller scale features at the mid-latitudes. Plotted on the same color scale is the original VLA map based on observations between 2013 and 2014 (de Pater et al. 2016; de Pater et al. 2019b). The overall structure is very similar between the two maps, with the Juno data allowing to resolve more structure at depth and the transitions in the atmosphere due to its low frequency observations. The dotted lines indicate the latitude at which the zonal wind speed peaks, and with that denotes the difference between the zones and belts. The vertical gray lines correspond to locations of the atmospheric cross sections in Figure 2.10.	44
2.10	Comparison of the atmospheric structure at the locations indicated in Figure 2.9. The two models developed for this work agree well on the overall structure of the atmosphere despite different modeling frameworks. The biggest difference in the ammonia distribution between our results and VLA results (dashed lines) (de Pater et al. 2016; de Pater et al. 2019b) is that we add more information about the fine-scale vertical structure. Compared to the PJ1 results (Li et al. 2017a), we find no strong evidence for the inversion at midlatitudes.	45

2.11	Forward modeling results based on the best fit distribution of ammonia trace gases compared to the Juno observations, plotted against latitude. The Juno nadir brightness temperatures are the solid black lines and with their uncertainties represented by the shading. The red and blue lines correspond to temperatures based on the ammonia distributions as shown in Figure 2.9. The shading of the red and blue lines indicates the sensitivity of the results to the uncertainties ($n=1,10$). The green line is the forward model based on the VLA data (de Pater et al. 2019b). Overall, our forward models fit the brightness temperature well within the uncertainties.	47
2.12	Same as Figure 2.11 but for the limb-darkening coefficient. While we can fit the overall structure of the atmosphere within the uncertainties, the solutions for Channel 2 all result in less limb-darkening compared to the observations. The solution closest to the observations (upper end of the shaded area) corresponds to the retrieval that creates a larger mismatch for the brightness temperature. The results that best fit the brightness temperature ($10\text{-}\sigma$) have the largest misfit for the Channel 2 limb-darkening, and the $1\text{-}\sigma$ results fit the limb-darkening best. .	48
2.13	Comparison of ammonia abundance map for PJ1, based on the preliminary retrieval (Li et al. 2017a) and the best-fit model in this paper. The overall structure looks very similar, with the biggest difference that we do not find evidence for the ammonia inversion centered around 6 bars in the earlier retrieval as obtained by Li et al. (2017a).	49
2.14	Same as Figure 2.11 but for the PJ1 observations. The MWR brightness temperature observations are given by the solid lines, their uncertainty is given by the shaded region. The red and blue solid lines are the brightness temperatures for the abundances as plotted in Figure 2.13. The dash-dotted line corresponds to the forward modeling results based on the ammonia distribution as published by Li et al. (2017a). We note that while model the structure of the atmosphere differently, both models are close to the uncertainty.	50
2.15	Same as Figure 2.14 but for the limb-darkening coefficient.	51
2.16	Ammonia distribution based on the combined Juno and VLA observations. The top panel shows the distribution based on the thermo-chemical equilibrium model, the middle panel is based on the stochastic model, while the lower panel shows the effect of clouds onto the radio spectrum.	52
2.17	Slices through the atmosphere at the same locations as indicated in Figure 2.9. We plot additionally here 10 draws from the MCMC results to show the spread in solutions that are consistent with the observations. The left panel shows the solutions for our perturbed thermo-chemical equilibrium model while the right hand side shows the results for our stochastic model. We can see that overall structure is reproduced well by the MCMC draws, indicating the confidence in the retrieved solutions.	53
2.18	Uncertainties for and correlations between the retrieved parameters in the Equatorial Zone.	54

2.19	Same as Figure 2.18 but for the North Equatorial Belt.	55
2.20	Retrieved atmospheric parameters as a function of latitude (with the individual zones and belts denoted by the vertical dashed lines) and for various combinations of uncertainty (different colors and linestyles). Left: a) Relative humidity of ammonia gas, b) Cloud formation efficiency, c) The reduced - χ^2 value for the retrieved atmosphere. Right: d) Bottom pressure of mixing region, e) Pressure range over which mixing occurs, f) Absolute change in ammonia abundance in the mixing region.	56
2.21	Effect of regularization constrain on the ammonia abundance profile in the EZ when fitting to the combined VLA and Juno data. The yellow lines show the results of various different retrievals (and are the same as in Figure 2.10), while the horizontal lines are the pressure nodes between which the gradient can vary. The three different panels show the effect of the vertical regularization as described in Section 2.3, where the shading corresponds to the 0.16 and 0.84 quantiles from the MCMC runs. The left panel has the regularization turned off ($\lambda = 0$ in Equation 2.20), with a mild regularization constraint in the middle and a moderate constraint on the right. While the regularization constraint changes how smooth the profile is with altitude, it changes very little about the overall structure.	59
2.22	Corner plots for the nominal model (panel b in Figure 2.23 where we show the average between the 8 mixing gradients in the atmosphere between 100 and 1 bar. The combined VLA and Juno retrieval indicates a lower humidity in the EZ compared to the pure Juno retrieval (see Figure 2.18), but the mixing gradient clearly shows a well-defined increase of ammonia abundance with altitude. . .	60
2.23	Testing the robustness of the vertical structure against various assumptions in the retrieval compared to various other retrievals (different line styles). Model 1 and Model 2 are slices through Figure 2.16, the ammonia abundance map based on the joint retrieval of the combined VLA and Juno MWR dataset. In panel a we retrieve the atmospheric structure for a wet-adiabatic temperature profile (see Figure 2.6), and show a large increase of the ammonia abundance (note the different scale for this panel). We compare this to the vertical profile of the nominal dry adiabat in the panel b. The panel c relaxes the assumption that the atmosphere approaches a globally well-mixed ammonia abundance and instead we retrieve the deep ammonia abundance simultaneously. The right most panel shows the effect of including absorption by cloud particles.	61
2.24	Corner plots for the equatorial inversion corresponding to the profiles shown in Figure 2.23. In this retrieval we relaxed the assumption that the ammonia is well-mixed and allow the deep ammonia to vary in the fit.	62
2.25	Corner plots for the equatorial inversion including the effect of radio absorption by cloud particles. The mixing gradients correspond to 1-H to mixing above 6 bar, and 2-H corresponds to mixing below.	63

2.26	Testing for the inversion signal at midlatitudes as seen by Li et al. (2017a), by retrieving an atmosphere based on both VLA and Juno data. We test the effect of vertical regularization on the mid latitude structure to show the confidence in the retrieved mid-latitude structure. The panels correspond to no (panel a), mild (panel b) and moderate vertical regularization (panel d). The various line style corresponds to the various retrievals, with the dot-dashed line and the shading indicated the 0.16 and 0.84 quantiles of the MCMC results. Panel c uses mild vertical regularization but reduces the uncertainty fidelity to $n = 1$. Regardless of chosen regularization we cannot reproduce the magnitude of the inversion as seen by the dotted line.	64
2.27	Relationship between the beam-convolved emission angle and boresight emission angle. The different colors indicate the integration region in units of the HPBW. Further away from the beam center, the beam sensitivity is dropping rapidly, and the contribution to the averaging becomes small. Therefore, the results converge for sufficiently large integration regions. Our final results are based on 2.5 HPBW, which contains 99% of the emission. This example is for Perijove 1 - Channel 2 observations just before closest approach to the planet.	65
2.28	Same as Figure 2.27 but for Channel 5.	66
2.29	Same as Figure 2.2 but for a latitude where the synchrotron contribution is noticeable. Note that there are two branches in Channel 1 and 2 that have a large difference in the temperature for the same emission angle. The increase temperature is due to the synchrotron leaking in through the side lobes. Our spatial restriction can handle the synchrotron contribution well, ignoring the upper, contaminated branch of the observations.	67
3.1	Comparison of PJ4 observables (colored dashed lines) with the mean observations (solid lines, shading corresponds to the standard deviation) based on the first 12 perijoves. The nadir brightness temperature is on the left, while the limb-darkening coefficient is shown on the right. The storm broke out in the SEB (indicated by the gray vertical dashed lines). The effect is strongest for the upper channels, with its strength decreasing at lower frequencies. We see an increase in brightness temperature at the location of the storm, indicating either a drying out of the upper atmosphere in ammonia or an increase of the physical temperature.	71
3.2	Brightness temperature anomaly maps for each channel. The contours outline the difference between the mean background atmosphere (PJ1-PJ12) and PJ4. The positive outlines indicate an atmosphere that is radio-warmer than the average atmosphere, while blue contours indicate a radio-colder atmosphere. All six maps are shown on the same color-scale showing that the signal is strongest in the upper two channels and decays with increasing depth.	72

- 3.3 Left panel: Vertical ammonia abundance profiles that compare the mean background atmosphere (dashed line) with the results from the relative retrieval assuming no changes to the physical temperature structure (solid lines). The locations of the profiles are indicated in the inset map that shows the C5 brightness temperature anomaly, while the shading corresponds to the uncertainty in the retrieved solutions. For all three profiles, we find a strong anomaly in the upper atmosphere, sitting over a smaller, but opposite sign anomaly located below the water cloud. Right panel: Retrieved temperature anomaly assuming that the ammonia abundance remains fixed at the background level. The regions adjacent to the clouds are characterized by strong atmospheric heating in conjunction with cooling deeper in the atmosphere. 74
- 3.4 Retrieved ammonia abundance results for different assumptions about the physical temperature structure in the atmosphere. The upper panel corresponds to the depleted region west of the storm plume (10.8°S on inset Fig. 3.3), while the lower panel shows results for the region that is co-located with the storm plume (11.5°S). The red lines indicate the background (dashed) and storm (solid) profile for our nominal assumptions of a dry adiabat, while the blue lines show the results including physical temperature variations, as shown on the right. We have included a super-adiabatic layer above the water cloud (dashed line), a subadiabatic region during the storm outbreak (solid line), and a Gaussian temperature anomaly that fits the data assuming that there is no ammonia variation below 10 bar (dot-dashed line). The thin gray lines show a range of temperature anomalies that we obtained from the simulation, where each location is indicated by the gray circle in the inset map on the right-hand side. 76
- 3.5 Radio signals record the opacity-weighted thermal emission by the atmosphere. Since the ammonia is the main factor controlling the opacity of the atmosphere, changes in the ammonia abundance will change the pressures from which the thermal signal is received. The dashed lines indicate the pressure from which the thermal emission is received for each frequency based upon the background ammonia profiles. The solid lines corresponds storm profile that we retrieved. The depleted upper atmosphere allows to probe slightly deeper than compared to the background atmosphere. 84
- 3.6 Comparison between the observed brightness temperature anomaly (solid lines) and the fitted brightness temperature anomaly for the three regions under consideration in Figure 3.3. The dashed line is the modeled brightness temperature difference between the background atmosphere and the storm atmosphere assuming a pure ammonia anomaly. The dotted line shows the result for keeping the ammonia abundance constant and instead showing a pure temperature anomaly. Both models, despite very different assumptions, fit the observations well. . . . 85

3.7	Example of the distribution of the available individual observations for the PJ4 flyby in the southern hemisphere, where each individual ellipse represents a single integration. For displaying purposes alone, we have converted each measurement into nadir brightness temperature, by assuming a limb-darkening coefficient. The bar on the right hand side indicates the zonally averaged brightness temperature, and the starting point for the deconvolution algorithm.	86
3.8	Example residual distribution for C5 during the PJ4 flyby. Panel shows shows the ΔT_{b0} distribution overlain on concurrent HST observations. The retrieved residuals are largest in regions where the HST observations show a localized white storm plumes next to a darker background. Panel b) is a cross cut through the ΔT_{b0} map where each line corresponds to the summed brightness residual after the number of indicated iterations, and the secondary axis indicates the number of observations for a given region of the map.	87
3.9	Convergence of the method by comparing the mismatch for PJ4 - C5 across all measurements with the theoretical measurement error approach 0.1% (Janssen et al. 2017) indicated by the horizontal line. We can see that within the first few iterations the standard deviations drops quickly until it slowly converges towards the theoretical limit. We track convergence in the tropical regions (lat < 20 deg) and globally, to look for possible contamination by synchrotron radiation. . . .	88
4.1	Weighting functions that indicate the pressure from which the thermal emission originates for a given frequencies. The Juno frequencies are presented on the left hand side, while the VLA frequencies are shown on the right hand side. The weighting functions are based on the mean tropical atmosphere of Jupiter coupled to a dry adiabat.	94
4.2	HST and VLA X- and Ku-band observations during 6th and 7th of April. The observing geometry from Earth only allowed hemispherical coverage of the planet, so that the both hemisphere are separated by 24 hours, or 2.5 Jovian rotation. The top row shows the red and blue composite of the HST observations, the middle row shows the VLA X-band observations, centered around 10 GHz with a 4 GHz bandwidth, and the lower row shows the VLA Ku-band observations centered around 15 GHz with a 6 GHz bandwidth. For the Ku-band data used a Gaussian filter to remove any non-zonal large scale structure (see Addendum B to the Chapter). The blue outline indicates where we have simultaneous coverage across all 6 Juno frequencies.	97
4.3	Same as Figure 4.2 but for the observations during 8th and 9th of April. The middle row shows the VLA K-band observations around 20GHz with a 4 GHz wide bandwidth, and the lower row shows the K-band observations around 24 GHz with a 4 GHz bandwidth. These lower panel was heavily filtered, and should be considered qualitative.	98

4.4	HST and VLA observations taken during Juno's PJ19 encounter. The top panel shows the HST observations, while the lower contains a composite made of the three frequency bands corresponding to three color channels: red and yellow (X-band/10 GHz) show warm and cold brightness temperatures deepest in the planet, green/white colors (Ku-band/15-GHz) show the structure under the ammonia ice clouds, and blue colors (K-band/20-GHz) probe the pressures around the ammonia ice clouds.	99
4.5	Deconvolved PJ19 Juno observations that map out the nadir brightness temperature distribution for the 6 channels. The channel numbers are increasing left to right. The colorbar for each panel is appended to the top of the plot. The resolution is set by the size of the individual beams and the the number of overlapping observations (Moeckel et al. 2024b). The lower frequencies cover less area due to the larger beamsize and therefore dictate the region over which have full frequency coverage. These maps were independently produced, analyzed, and published by (Bolton et al. 2021).	100
4.6	PJ19 observations compared to the mean atmosphere that we use to build up the reference atmosphere for our analysis.	101
4.7	Retrieved ammonia abundance based all zonally averaged Juno observables (see Equation 4.1). We median filtered this map for visualization purposes only to remove small scale fluctuations.	102
4.8	Longitudinal brightness temperature anomalies after subtracting the zonal atmospheric brightness temperature for a given frequencies overlayed on the concurrent HST observations. The contours lines show temperature anomalies that are larger than 2K for both cold and warm anomalies. We find the majority of the anomalies located in three distinct regions: At the locations of large scale vorticies, in the NEB, and at the locations of the jets at the zones and belts boundaries. . . .	103
4.9	Ammonia abundance anomalies that fit the brightness temperature anomalies shown in Figure 4.8. The right-most panel shows the (near) simultaneous HST observations, and the panels to the left show slices in pressure, with the pressure indicated in the upper left corner. The ammonia variability peaks just below the clouds, and decrease with depths. Most features extend down to about 6 bars, where the water is expected to condense out, with the anticyclone in the northern hemisphere and the ammonia plume at the interface between the NEB and EZ the two notable exceptions. The dynamics in the SEB and EZ appear to be mostly located at altitudes above 2 bar, while the NEB shows significant variations down to 6 bar.	106

4.10	3D rendering of the longitudinal ammonia anomaly (Figure 4.9) in the Jovian tropics, where red shades are ammonia depletion causing warm brightness temperature anomalies, while blue shades correspond to ammonia enhancements. The relative shallow atmospheric of the SEB can be found in the upper left corner, the EZ in the center, and the NEB and the vortex at its northern boundary can be found in the bottom right corner. We annotated the render to highlight processes that shape the atmosphere of Jupiter and indicated approximated pressure levels.	108
4.11	Zoom in on the cloud and sub-cloud structure captured during the flyby. Comparing Channel 5 with the VLA observations that probe the same depths we can see that Juno passed just east of an extended cold region that appears to be part of the plume-hotspot system at the northern edge of the EZ. Furthermore we can see that Juno flew over a particularly variable region in the NEB. The VLA observations also show that variability indeed peaks around 1 bar, with observations probing a bit higher in the atmosphere showing much less contrast (Ku-, and K-band).	111
4.12	The left panel displays the residuals after subtracting the mean of the PJ19 observations. We re-mapped the structure to be centered around the minimum emission angle to highlight its dependence on the emission angle and longitude. We calculated the running median over 20 degrees latitude to reveal the systematic brightening towards the limb, attributed to the increased synchrotron contribution. We chose a window size of 20 degrees to ensure it was twice as large as the typical extent of the zones and belts. In the right panel, the residual structure after removing the median is depicted. Although the majority of the atmospheric signal is attenuated, the structure at 15°N persists, indicating a deep-seated origin for this feature.	113
4.13	Same as Figure 4.12 but for Channel 2	114
4.14	Same as Figure 4.12 but for Channel 3	115
4.15	Residual structure due to misalignment during the deprojection process that was removed for the Ku-band observations with a Gaussian filter of 65 pixels.	116
4.16	Same as Figure 4.15 but for K-band observations around 20 GHz.	117
4.17	Same as Figure 4.15 but for K-band observations around 24 GHz.	117

List of Tables

2.1	Radiometer and antenna characteristics of Juno's MWR.	22
2.2	MWR Orbits used in our work	24

Acknowledgments

At the 2021 AGU conference, one of the keynote speakers remarked that planetary science has its roots in both astronomy and geology. The combination of astronomy's solitary observers gazing at the night sky, and geologists traversing vast landscapes to survey the land in teams. To this day, we have ground observers that explore the solar system remotely, and spacecraft teams that survey the planet up close. But Planetary Science also draws inspiration from astrology, the study of celestial motions, connecting the patterns in the skies to the lived experiences that have fascinated humanity for millennia. Thus, it feels apt to acknowledge those who have supported my journey through the lens of the planets.

The Sun - ☉ - represents enlightenment. I would like to express my gratitude to Imke: your dedication to science, to observing, and understanding the planets is truly beautiful. Yet, you never forget the humanity in the science that we do, and always encourage us to forge our own path. Your unwavering support, some might even call it blind, has truly allowed me to find my own path as it meanders between the worlds of science and engineering.

Mercury - ☿ - represents guidance. First and foremost, I would like to thank Imke's group members here. I always knew I could turn to you if I was stuck in my Ph.D. or if I was stuck in life. You have transcended the realm of colleagues and truly felt like family to me. Ned, thank you for always embracing my ideas and working them out with me, for going on adventures with me, and for the friendship we have. Erin, thank you have always been like a sister to me, I have learned so much from, and with, you. Josh, thank you for all the times you came to my office and told me to see the sun. Valerie, Murti, Ellie, thank you for all the time you dedicated to me when maneuvered myself into yet another rabbit hole. Peter, Cheng, and Hauzhi, the postdocs of our group, thank you for all your advice and encouragement along the way. I would also like to thank all the students that I have worked with over the years: Sam, Druv, Brandon, Adil, Joanna, and Jacob. It has been so much fun to work with you guys, and extremely fulfilling helping you on your journey.

Venus - ♀ - symbolizes appreciation, that I have for both Caro and Fatima. Caro, I started this grad school journey with you, and you were part of the reason why I ended up in California. Things don't always work out, but that doesn't mean we cannot appreciate the beauty behind them. I hope you find your path too. And Fatima, you were there through all of the mess that grad school was. Thank you for always being a role model for what it means to live a fulfilled life, for how to live your life with intent, and how to make sense of it all.

Earth - ☁ - represents the support, which I needed plenty of throughout the years. Here I would like to thank my family. Thank you for always understanding that life is a journey, for always encouraging me to chase my dreams, and for always believing in me. Danke euch allen, Mama, Papa, Fanny und natürlich Oma and Opa. Fanny, ich hoffe dass

du deinen Pfad findest! Du schaffst das schon. Thank you to all the graduate students in Earth and Planetary Science, in Astronomy, and in Physics that I have had the pleasure to interact with. I am also incredibly indebted to all my friends over the years for providing me with joy, guidance, and solace when things didn't go as planned. I have formed so many beautiful memories with guys that I will hold always close to my heart. There are too many to name them all here, but here we go: Patrick from my high school days. Mario, Ren, Gil, Alex, Robert, and Curly from my undergraduate days. Balto, Stefano, Vanessa, and Giorgio for the inspiration at JPL to go to grad school. And now the Berkeley contingent: Philipp, Sevan, Mihai, Andrew, Alex B., Tom, Alex R., Claire, Chase, Sarina, Rodrigo, Quentin and Emma, Ben, Daniel, Hector (oh Hector), Cynthia, Teddy, Andy, Phil, Dani, Kandy and Jackson, Roger, Alyssa, Maggie and Kayla, Becs and Steve, Drew, Milo, Claire, Hadar, Tamar, Trevor and Ashleigh, Phyllis and Andrew, Tyler, Lamont, and lastly all the cats: Hermes, RBG, Nas, and Coal . As Ned always points out, I collect characters, and what a beautiful collection of characters you all represent.

Mars - ♂ - represents perseverance and determination. Maybe I was naive when I started my Ph.D., but I believed that science was driven by curiosity and by the pursuit of knowledge. Over the years, I got trapped in a vortex of politics, which ended up with me being pretty much excluded from the Jupiter community, unable to collaborate due to the "rules of the road" of the Juno team. Here's to the hope that the next generation of planetary scientists will find that collaboration trumps competition.

Jupiter - ♃ - represents growth and expansion. It has been an unbelievable journey over the past three decades. Looking back at little Chris, the child that was obsessed with satellite images of the Earth, and with understanding what forces shaped our planet. He would be so happy seeing that I made a career of it! Here's to the small child inside my heart that still vicariously guides me with his curiosity to this day!

Saturn - ♄ - represents structure. Over the years, I have learned that research requires an incredible amount of creativity. Creativity can only blossom when there is structure around that reduces the stress on the individual. This goes out to the department, to the professors, the researchers, to all the staff who provide the structure to allow us students to truly thrive. You guys work in the background to make sure that we can focus on our science. Thank you to my quals and thesis committee (Bill, Michael, and Stuart) for providing me with stimulating conversations and feedback. Thank you to NRAO for building, maintaining, and operating these large radio telescopes, and of course, to all the operators helping me with my observations. In that vain, I want to acknowledge that I was funded by both NRAO and NASA funding. The radio community in general has been a beacon of hope for me: Thank you to Katherine, Bryan, Alex, Bob and Xander. This is also dedicated to my weekly commitments, our Friday morning rides up Tunnel Road with Hector, Kandy, Andy, Drew, and Roger that were always good for physical and mental health and always ended up at Abe's for a well-deserved burrito. If you read this, go and get a coffee from Abe

and say hi from me. And to Biketopia, the volunteer run community bike workshop, where I found a community that was even more obsessed with bikes than I was. Hiro, Teddy, Hector, Jesse, and Isaac, thank you for wrenching with me on bikes.

Uranus - δ - represents innovation and creativity. This is dedicated to the Space Science Lab that became my second academic home on campus. It's there where I spent most of my time in grad school, with a collection of incredible engineers and scientists that provided the framework to truly push what is possible. The dual CubeSat mission CURIE, which was a large part of my grad-school journey, didn't make it in time to space for my thesis, but I have gotten so much out of this mission. I started as a student, but I left the project as an aerospace engineer. David, thank you for showing me that I can truly do anything, if only I dedicate myself to it. Thank you to David, Will, Leandro, Robert, Sam and Roger. This also goes out to the PADRE team (Bradley, Ace, Savannah, Robert, Pascal, Patrick, Meredith) that took me on when CURIE was done and made me a system engineer despite being "just" a grad student. Thank you Juan and Chris for putting the trust in me and for hiring me after grad school.

Neptune - Ψ - represents spiritual guidance. I came to California as an extremely rational person, but California's nature has filled me with a deep sense of appreciation for nature. And I hope to carry this appreciation forward with me.

Grad school was truly a strange, strange experience. Let's see what life will take me next.

Chapter 1

Introduction

The simplicity of the questions, coupled with the surprising difficulty of finding answers, has always been the main allure of planetary science for me. It captures the essence of a "why" question — a query even a child could pose — yet the answers to these questions are surprisingly elusive. Simple inquiries such as "Why is the Great Red Spot on Jupiter red?", "How old are the rings around Saturn?", "Why is Uranus tilted over?", and "Why does Neptune have the fastest winds in the solar system?" embody this allure.

The reason we often fail to answer these questions is because our theories and models are frequently tailored for terrestrial applications, with underlying assumptions tied to terrestrial parameters. Exporting ideas, theories, and models to other planets often proves challenging when we stray too far from the conditions for which they were developed. In this vein, planetary science offers us a testbed not only to evaluate our understanding of processes but also to assess the robustness of our models to changing conditions. What happens when we double the planet's rotation speed or when we diminish the impact of solar radiation on the atmosphere? In essence, what happens when we encounter an atmosphere that is very different from our own?

1.1 Atmospheric Circulation on Earth

On Earth, three cells redistribute energy and advect tracers: the Hadley cell, the Ferrel cell, and the polar cell. Incoming solar irradiation heats the tropics, generating localized convection. At the tropopause, convection stops and horizontal divergences implies poleward motion of parcels. The combination of angular momentum conservation and thermodynamic constraints limits the extent of the Hadley circulation to approximately 20-30 degrees latitude (Vallis 2017). In Earth's mid-latitudes, a thermally indirect cell prevails, characterized by warm air sinking at the equatorward edge, a poleward motion at the surface and cold air ascending towards the pole (around 60°), driven by eddy momentum flux. From a circulation perspective, the air in the upper troposphere has a predominant equatorward direction, yet eddies primarily maintain horizontal transport of heat and tracers towards the poles. The

polar cell, a thermally direct cell complements the system, featuring rising air around 60° and subsiding air at the pole. The ocean circulation also contributes to heat transport towards the pole, albeit to a lesser extent than the atmosphere, primarily through eddies (Trenberth et al. 2001)

1.2 Definition for Jupiter

Before we generalize and compare the Earth system to Jupiter's, it is essential to define the Jovian system. The atmosphere discussed in this work spans from 0.1 bar to several hundred bars, encompassing three distinct regimes.

The upper troposphere extends from the tropopause (0.1 bar) to the pressure level where ammonia condensation begins (approximately 0.7 bar). Within the upper troposphere lies the convective-radiative boundary, i.e. heat transport mechanisms differ between the top and bottom. The top of the layer is cooled by radiation, whereas convection controls the lower end of the layer.

The middle troposphere encompasses the primary cloud formation region within the atmosphere, extending from the ammonia ice cloud to the pressure level where liquid water condenses (~ 6 bar). Often referred to as the weather layer, the exact pressure range is only loosely defined. The condensation of water significantly impacts Jupiter's atmosphere due to the substantial energy involved in this phase transition (Ingersoll et al. 2000). Additionally, it influences dynamics by inducing stable stratification in this atmospheric layer, as trace gases are heavier than the background hydrogen-helium atmosphere, which constitutes 99.8% of Jupiter's atmosphere (Guillot 1995; Sugiyama et al. 2011; Sugiyama et al. 2014; Li et al. 2019a). The middle troposphere is where we observe the most atmospheric variability based on radio and infrared observations (de Pater et al. 2016; Bjoraker et al. 2022; Hardesty et al. 2024; Moeckel et al. 2024a).

The lower troposphere links the water cloud base to the interior, although the extent of this layer is still under active research. Dry convection is likely the primary mechanism controlling the distribution of material and temperature, yet its connection to the deeper atmosphere remains unknown. Moreover, the depletion of condensible trace gases in the middle and lower troposphere (Li et al. 2017a; Moeckel et al. 2023) and the vertical extent of vortices (Bolton et al. 2021; Moeckel et al. 2024a) challenge the notion of a fully convective atmosphere.

Jupiter exhibits a distinct set of bands known as zones and belts, traditionally categorized based on their relative high- and low-albedo appearances and their color difference. At the border between the zones and belts we find the zonal wind jets, with the anticyclonic zones having a westward jet on the boundary facing the equator, while cyclonic belts exhibit an eastward jet on the equatorward side. The potential vorticity (PV) across a pair of zones and belts remains nearly constant, with sharp jumps in PV at their boundaries (Read et al. 2006). The white zones are attributed to thick ammonia ice clouds, while the cyclonic belts appear to possess a lower cloud deck.

Jupiter's tropics are characterized by the Equatorial Zone (EZ), marked by prominent cloud coverage, flanked by the North Equatorial Belt (NEB) and the South Equatorial Belt (SEB). The most significant contrast in atmospheric conditions (temperature, aerosol, and trace gas abundances) is observed between the EZ and the NEB. The atmospheric pattern in the tropics closely resembles a Hadley-like circulation. Interestingly, despite being at the same latitude as the NEB, the SEB displays a much less drastic contrast, creating a hemispherical difference independent of Jupiter's seasonal cycle. While the alternating zones and belts persist to higher latitudes in the visible spectrum, the contrast diminishes compared to the tropics, with their circulation likely resembling a Ferrel-type circulation.

Energy sources and distribution

While the terrestrial system is predominantly driven by solar insolation, generalizing this to the outer planets presents some challenges. First, the solar incident flux is greatly diminished in the outer solar system. Furthermore, the incoming flux is scattered and absorbed throughout the atmosphere, rather than being absorbed by the ground as on Earth. Additionally, as giant planets continue to contract gravitationally, potential energy is released, driving convection in the deep interior of the planets and transporting heat upwards (Jonathan et al. 2008). On Jupiter, the contribution from internal heat is on the same order as the received flux (Ingersoll et al. 1975). This means energy is injected into the atmosphere at the top (absorbed solar), throughout the middle troposphere (scattered solar), and at the lower troposphere (internal heat). While convection is the most likely method for redistributing heat vertically, very little is known about horizontal transport. The energy emitted by the planet is independent of latitude (Ingersoll et al. 1975), despite the latitudinal dependence of solar incidence. This requires efficient transport mechanisms (Pirraglia 1984), which are not yet understood. Horizontal mixing could potentially occur at the water condensation level, where a stable atmosphere provides conditions for horizontal mixing (Ge et al. 2024). Alternatively, it suggests a mechanism by which internal heat is preferentially transported to the poles to compensate for the decreased solar incidence (Jonathan et al. 2008).

Competing theories have been proposed regarding the mechanism that controls the lower troposphere. Numerical models suggest that stochastic variation in internal heat flow could drive the circulation (Thomson et al. 2016), while alternatively it has been argued that the system is maintained by eddy-momentum flux in the middle atmosphere but has deep roots (Showman et al. 2006; Lee et al. 2021).

Lack of a solid boundary

In the absence of a solid surface on the giant planets, there is no well-defined lower boundary condition capable of exchanging momentum with a solid/liquid planet through friction. Instead, the region where the atmosphere becomes conductive and thus is coupled to the magnetic field is often considered the lower boundary of the atmosphere (Liu et al. 2008). This transition region, based on the depths at which zonal winds decay, extends a few thou-

sand kilometers (Kaspi et al. 2020) and is about an order of magnitude deeper than any observed atmospheric variability (Moeckel et al. 2024a). The lower boundary may even play an active role in linking the inner dynamo region and the upper observable atmosphere, potentially providing energy for long-lived features observed in the upper atmosphere (Yadav et al. 2020). Furthermore, the role of wave breaking has been proposed to create drag forces in the atmosphere, simulating the effect of a solid boundary (Ingersoll et al. 2021).

Stacked cell circulation system

To explain the distribution of tracers and lightning on Jupiter, modelers have proposed the concept of stacked, counter-rotating circulation cells that exchange momentum and energy both horizontally and vertically (Showman et al. 2005; Fletcher et al. 2020b; Duer et al. 2021; Lee et al. 2021). There are limited observational constraints on the extent of these cells, but observations suggest a middle tropospheric cell positioned over a lower tropospheric cell.

In terms of width, Jupiter’s fast rotation rate restricts the meridional extent of the system, with each jet pair representing a single circulation cell (Duer et al. 2021). These cells limit meridional transport through jumps in potential vorticity (Read et al. 2006). However, this set of cells could be embedded in a hemispherical circulation that transports material poleward (West et al. 1992; Lee et al. 2021).

The depths of the lower circulations may extend to the region where the atmosphere becomes conductive (Liu et al. 2008; Schneider et al. 2009; Kaspi et al. 2020). The transition between upper and lower tropospheric cells has been hypothesized to occur around the water cloud layer (Showman et al. 2005) or potentially higher in the region where solar incidence energy is deposited (Ingersoll et al. 2000; Simon-Miller et al. 2006; Lee et al. 2021).

Molecular weight

The main constituents in the atmosphere of giant planets are hydrogen and helium, accompanied by several trace gases (astronomical metals) such as ammonia (NH_3), water (H_2O), and methane (CH_4). Unlike Earth, where there are small differences in molecular weight between the main constituents (N_2, O_2) and the trace gases (H_2O), the outer planets have trace gases that are heavier by about one order of magnitude. The condensation of water may create a stably stratified layer (Guillot 1995; Sugiyama et al. 2014; Leconte et al. 2017) that interfere with convection. This can lead to the accumulation of Convective Available Potential Energy (CAPE) (Emanuel et al. 1994), which may be released on intermittent time scales (Sugiyama et al. 2014; Orton et al. 2023).

This energy release occurs across various scales, from small-scale storms (Becker et al. 2020) to large outbreaks (de Pater et al. 2019a; Moeckel et al. 2024b), and even global-scale storms (Fletcher et al. 2017; Li et al. 2015; Li et al. 2023). The frequency of these storms is determined by the efficiency of convective inhibition and is proportional to the abundance of water (Sugiyama et al. 2014). However, the distribution of energy release between small thunderstorms and large outbreaks remains an open question (Ge et al. 2024).

Vertical Cloud Structure

The banding on the planet, the vortices, and storms embedded in Jupiter’s atmosphere all detail the complexity of the upper cloud and haze structure. Hazes form in the upper troposphere through the downward flux of energetic particles, which photochemically alter compounds in the atmosphere. This process enables chemical bonds to break, generating radicals that can subsequently evolve into more complex molecules. The depths to which these energetic particles can penetrate depend on their energy and the density of the atmosphere (Mironova et al. 2015, and references therein).

On Jupiter, the haze layer obscures the topmost cloud layer, making the distinction between clouds and haze challenging without spectroscopic data (Wong et al. 2023). Furthermore, the presence of photochemical haze products can alter the cloud structure below by providing cloud condensation nuclei.

Clouds, on the other hand, form through condensation of condensible gases when the partial vapor pressure (e) exceeds the saturation vapor pressure (e_s), which is determined by the Clausius–Clapeyron relation (Vallis 2017):

$$\frac{de_s}{dT} = \frac{L}{T(\alpha_v - \alpha_l)} \quad (1.1)$$

, which depends on the latent heat of evaporation (L) and the specific volumes for the condensible species (α , liquid or vapor). Under ideal conditions, condensation occurs when the relative humidity ($\mathcal{H}$), the ratio of partial vapor pressure over saturation vapor pressure exceeds unity. Cloud formation for a specific gas is therefore achieved by increasing the partial vapor pressure through vertical flux of gases or by fluctuations in the temperature field (Palotai et al. 2014). Generally speaking, for large-scale flows, condensation occurs when the relative humidity exceeds unity (100% relative humidity). However, dynamics and microphysical effects can cause significant deviations from equilibrium models (Vallis 2017)

The traditional basis for cloud formation relies on equilibrium cloud condensation models (ECCM), which assume that cloud formation is purely governed by thermo-chemical equilibrium. Most simple models include mixing length theory, with a simple parameterization scheme to explain the vertical distribution of clouds. This allows clouds to grow vertically as cloud particles are lofted upward, enabling them to reach much higher altitudes compared to what Equation 1.1 predicts.

Let’s start looking at the cloud structure as a function of depth starting inside the planet. Deep in the interior of the planet, at the pressures of a few hundred bars, alkali metals such as KCL , and Na_2S start condensing out. We only have indirect evidence of their presence (Bhattacharya et al. 2023) and these clouds are often outside of the scope of traditional cloud models. Instead, we focus on the clouds in the middle troposphere.

Moving upward, the first trace gas to condense is water, forming liquid water clouds (~ 6 - 8 bar), with ammonia potentially partially mixed into the liquid water droplets (Weiden-schilling et al. 1973; Atreya et al. 1985). Above the liquid water clouds, water freezes, leading to the formation of water ice clouds. These water ice clouds are expected to have a signifi-

cant vertical extent, with their cloud tops reaching pressures of up to 1-2 bar (Bjoraker et al. 2022; Wong et al. 2023). Between 2 - 3 bars, a chemical reaction between NH_3 and H_2S is supposed to form the NH_4SH cloud. While there is no direct evidence for this cloud, there is also no detection of H_2S in the middle and upper troposphere, with the NH_4SH cloud being the most likely process to remove H_2S from the atmosphere. Further evidence for this cloud comes from the ice giant atmosphere, where we find the opposite behavior. The detection of H_2S in the upper troposphere in Neptune in conjunction with radio-observations, requires NH_3 to be preferentially removed (Gulkis et al. 1978; de Pater et al. 1991; Irwin et al. 2019; Tollefson et al. 2021; Molter et al. 2021).

The uppermost cloud layer on Jupiter is the ammonia ice cloud, with its base around 0.7 bars, situated approximately 10 km above the 1 bar level. Cloud models predict these clouds to extend just below the tropopause on Jupiter, around 0.1 bar. In contrast, for the ice giants, the uppermost layer of the atmosphere is the methane cloud deck. However, the atmosphere of Jupiter never reaches temperatures low enough for methane to condense out.

In general, the color of the cloud tops has been attributed to the age of the clouds (Carlson et al. 2016; Dahl et al. 2021). Fresh cloud material, whether in the zones of the planet or in the form of localized cumulonimbus clouds, typically appears very white, while older or deeper clouds tend to exhibit a more reddish-brownish appearance (Dahl et al. 2021). This change in color likely results from the mixing of cloud material with haze products. The overlaying hazes and their interaction with the cloud particles alter the observed spectra, rendering spectroscopic retrievals unreliable. The exact compound responsible for giving Jupiter and the Great Red Spot its characteristic red hue is still a subject of debate (Strycker et al. 2011; Carlson et al. 2016; Braude et al. 2020; Wong et al. 2023).

While ECCMs are commonly used as starting models, spectroscopic confirmation of the clouds is very limited due to contamination of hazes, which makes detection challenging. For the ammonia cloud, which covers most of the planet, we only have positive detections in select, highly-convective areas that produce fresh cloud material (Baines et al. 2002).

Instead, our evidence of the haze and cloud layers comes from matching overall characteristics such as height, optical depths, and scattering characteristics. This is achieved by comparing observed spectra of the planet in particularly from radio, but also infrared, visible, and ultraviolet ranges with simulated spectra and identifying combinations of haze and cloud distributions that reproduce observations (Irwin et al. 2008; Fletcher et al. 2016; de Pater et al. 2019a; Dahl et al. 2021; Wong et al. 2023).

The early observations indicated an extensive cloud and haze layer between approximately 0.2 and 0.7 bar consistent with the presence of the ammonia ice cloud as predicted by ECCMs, with an optically thick cloud at the bottom (Simon-Miller et al. 2001). Subsequent modeling studies introduced an additional stratospheric haze layer situated above the tropopause and found that the haze and cloud layer are more expansive. The more extended cloud deck extended from 2 - 4 bars more consistent with a continuous NH_4SH and NH_3 cloud deck (Sromovsky et al. 2017; Braude et al. 2020; Dahl et al. 2021).

Considering the difficulties in observing the upper cloud deck, it is no surprise that we lack direct observational evidence for the water cloud, but there is some indirect observational

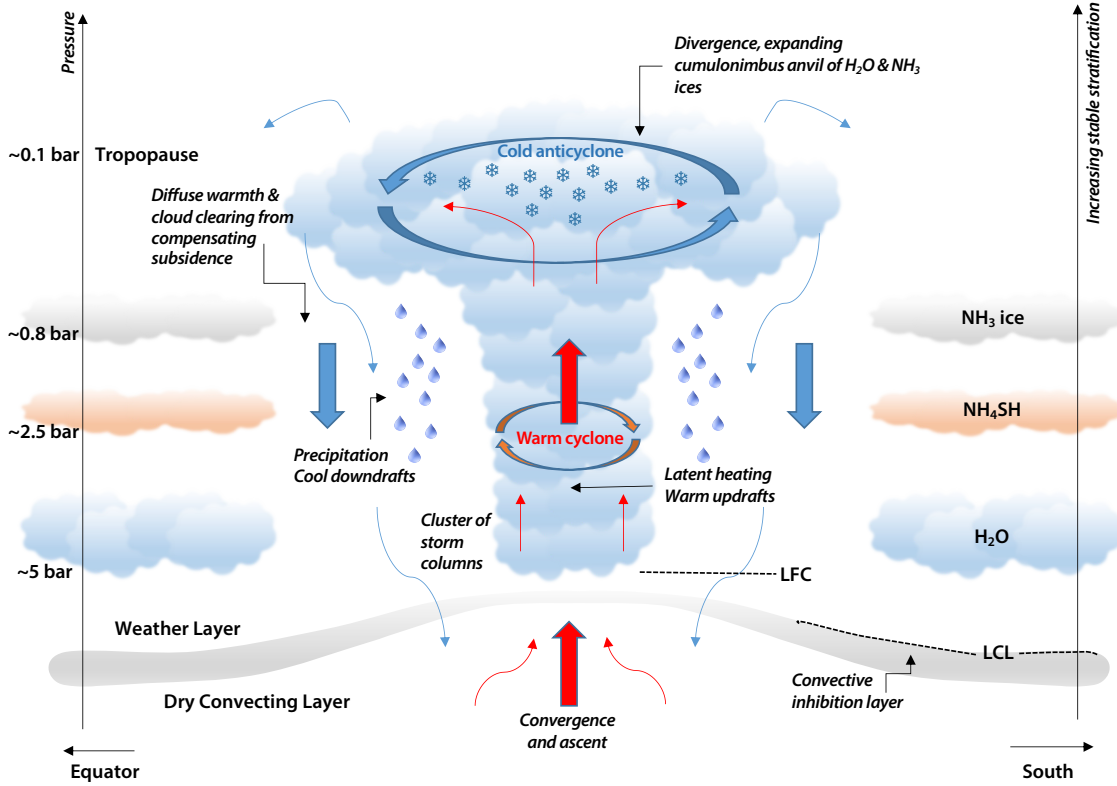


Figure 1.1: Overview of the cloud structure in Jupiter’s convective atmosphere. The left hand side shows the approximate pressures at which the clouds form, while the center shows the various processes involved during a convective upwelling event. Reproduced from (de Pater et al. 2023) and (Fletcher et al. 2020b).

evidence. By comparing ratios of methane filters on HST (Wong et al. 2023) or in the mid-infrared (5μ) through the width of the CDH_3 absorption feature (Bjoraker et al. 2022) we can indirectly constrain the cloud top pressure. The methane filter results point to water clouds being present during storm outbreaks. The mid-infrared feature suggests the presence of the water cloud at around 4-5 bars. However, there are extensive regions where opaque water clouds appear to be missing altogether, potentially replaced by optically thin water clouds (Bjoraker et al. 2022).

Radio observations probing the abundance of ammonia gas below the clouds in the upper and middle troposphere have indicated that Jupiter does not conform to the equilibrium state predicted by cloud models. Early radio observations already revealed distinct differences in abundance between the zones and belts of Jupiter above approximately ~ 2 bar (de Pater

1986). This suggests that vertical motion is required to explain enrichment and detrainment on Jupiter, and modulates the amount of ammonia available to form clouds.

The equilibrium model faced its greatest challenge from in-situ observations conducted with the Nephelometer Experiment (NEP) on-board the Galileo Probe. This experiment was designed to measure haze and cloud particle densities along the descent trajectory of the probe. While the experiment detected several layers with increased particle densities, it identified only one distinct layer around 1.55 bars (Ragent et al. 1992), situated at slightly lower pressures than the expected formation pressure of the NH_4SH cloud. Subsequent analysis of the entry side strongly supports the idea that the probe entered a particularly depleted region of the planet, known as the "5-micron hot spot," due to its anomalously high temperatures at 5-micron (Orton et al. 1998; de Pater et al. 2001). These wavelengths probe thermal emission from the planet, with higher temperatures consistent with low cloud coverage, allowing the thermal emission to escape to space, akin to the increased outgoing mid-infrared radiation at the boundary between the tropics and the temperate zones on Earth. Further analysis indicated that HST observations and Galileo Probe observations are consistent with a thin NH_3 layer and an optically thick NH_4SH cloud (Sromovsky et al. 2002).

Simulations of cloud formation, conducted in both two and three dimensions, have demonstrated that introducing dynamics can significantly alter the equilibrium state predicted by ECCMs (Sugiyama et al. 2011; Sugiyama et al. 2014; Li et al. 2019a; Ge et al. 2024). These simulations reveal that the water layer acts as a stabilizing influence for convection, with intermittent storms capable of breaking through the layer and generating rapid updrafts. These fast vertical updrafts impact both trace gases and clouds. The rapid motion mixes material from deeper within the planet, transporting them to pressures where they condense and form clouds. If the ascent timescales are shorter than the condensation timescales, gases may remain supersaturated. Regarding clouds, simulations predict a much lower density of cloud particles (by four orders of magnitude) compared to analytical mixing-length theory. Additionally, simulations anticipate much faster vertical motions capable of distributing cloud particles over a broader pressure range (Sugiyama et al. 2011). This process can transport cloud particles to altitudes as high as the tropopause on Jupiter.

The condensation and precipitation following rapid ascent not only deplete the atmosphere locally but also affect much deeper layers. When the precipitated material evaporates, the resulting phase changes require energy, leading to local cooling of the atmosphere. Furthermore, the subsiding flow of dry air can deplete trace gases from the atmosphere down to several bars. Despite equilibrium models predicting that the atmosphere should be well mixed, the combined effect is that NH_3 and H_2S are depleted well below their equilibrium values, only becoming well-mixed below the water condensation level (Sugiyama et al. 2011; Sugiyama et al. 2014).

Precipitation

The simulations discussed above have underscored the importance of precipitation as a process controlling the distribution of trace gases, clouds, and temperature structure. Once particles have condensed to form clouds, they coalesce, grow, and precipitate. Due to the absence of a solid boundary, the depth to which droplets can fall is determined by their re-evaporation rate. The pressure range to which these particles fall varies, with some models suggesting that they evaporate quickly, causing a localized increase in ammonia abundance directly under the clouds (Ingersoll et al. 2017; Li et al. 2020). Generally, larger droplets can fall deeper, but there is a maximum size to droplets before they break up, limiting their fall depth to approximately half an atmospheric scale height (Loftus et al. 2021). Moreover, once droplets reach their boiling temperature, they should quickly evaporate. For ammonia, this temperature is reached around 4 bars, while for water droplets, it is approximately 30 bars (Li et al. 2019a). The phase exchange required when trace gases either condense out or evaporate can also locally affect the temperature of the atmosphere. The condensation of ammonia is expected to cause a temperature change of less than 1 Kelvin around the pressures where it condenses (0.7 bar) and re-evaporates (< 4 bars) (de Pater 1986). Conversely, water has a much greater impact, with its condensation expected to change the temperature by around 5 K. Simulations incorporating standard droplets for both ammonia and water indicate that this can affect the atmosphere to a depth of approximately 10 bars (Sugiyama et al. 2014; Li et al. 2019a; Ge et al. 2024).

In the atmospheres of giant planets, precipitation can induce secondary downdrafts. The parcel containing the evaporated material is heavier and colder than the surrounding after evaporation, convecting deeper into the planet (Showman et al. 2005; Sugiyama et al. 2014; Leconte et al. 2017; Guillot et al. 2020a; Markham et al. 2023). As these cold pools sink into the planet, the return flow brings up enriched air from deeper pressures, serving as a mixing agent for the deep troposphere (Sugiyama et al. 2014).

The discovery that the Jovian atmosphere is depleted in ammonia gas to a much greater depth than its boiling point (well beyond 4 bars) cannot be explained by the microphysics or conventional dynamics discussed above (Showman et al. 2005; Young et al. 2019b; Li et al. 2019a; Ge et al. 2024). Given the depths and temperatures at which the atmosphere appears to be depleted in ammonia, the involved processes require large precipitates capable of reaching much higher pressures and temperatures inside the planet. While the size of liquid ammonia droplets is limited (Loftus et al. 2021), water ice can form much larger conglomerates. In terrestrial circumstances, when water is up-drafted at sufficiently high speeds, it can be transported to regions well below its freezing point and form hail. A similar mechanism might operate on Jupiter, where within thunderstorms the transport timescale is much shorter than the condensation timescale, allowing liquid water to be transported well above its freezing point. At these super-cooled temperatures, ammonia vapor can diffuse into water ice at a ratio of 1:2 ammonia to water (Guillot et al. 2020a; Guillot et al. 2020b). The largest of these conglomerates, the so-called "mushballs," can reach high falling speeds and have large thermal inertia to delay melting as they descend into the abyssal atmosphere.

The ammonia trapped inside the hail can reach pressures much higher than those of ammonia droplets. The exact depth to which the water-ammonia hail can fall depends on the size, but Guillot et al. (2020a) estimates a pressure of ~ 15 bar. Once the material is melted, the postulated secondary downdrafts then transport the cold and enriched air to even higher pressures (~ 30 bar) (Markham et al. 2023). On Earth, hailstones precipitate in the vicinity of their formation region, suggesting that this effect should be found in the vicinity of the updraft regions (Allen et al. 2020, and references within).

While ammonia is also brought up from deeper levels in the updraft regions of the storms, it appears that these storms predominantly dry out the upper atmosphere (Li et al. 2015; Li et al. 2023). Instead, horizontal convergence must close the mass budget on Jupiter by advecting moist air from the zones to the belts (Ingersoll et al. 2000; Palotai et al. 2014).

Temperature structure

The main processes controlling the temperature on Jupiter vary between the three tropospheric regions.

Upper troposphere

The radiative convective boundary on Jupiter is located in the upper troposphere. The bottom is controlled by convection arising from the middle tropospheric cell, and the top is cooled by radiation. The radiative cooling at the top of the troposphere causes a decrease in potential temperature with altitude, making this also the transition region where the atmosphere becomes stably stratified. The thermal radiation, which cools the top of the atmosphere, can be observed in mid-infrared and compared to models of the atmosphere to retrieve abundances of gases, haze, and temperature (Simon-Miller et al. 2006; Fletcher et al. 2016). In general, regions with a high infrared flux are indicative of lower cloud densities, as atmospheric radiation from warmer, deeper levels can escape. At 500 mbar, the deepest levels that we can reliably probe with infrared observations, the temperature fluctuations are about 5 K, with the biggest difference between the cold equatorial zone and the warmer tropical belts adjacent to it. Since the atmosphere is stably stratified at these pressures (Young et al. 2019a), the ascent of material would cool the atmosphere, while the descent of air will increase the temperature. Poleward, the temperature variations with latitude drop below the noise and are essentially constant with latitude.

Middle Troposphere

The middle troposphere, spanning the cloud formation region on Jupiter, should be controlled by convection. In this region, the temperature structure is governed by adiabatic adjustment, with the important caveat that the presence of condensible species will alter the adiabatic lapse rate. In the absence of condensible species, the temperature structure would follow a

dry adiabat that is determined by the heat capacity (c_p) of the hydrogen-helium atmosphere with a planet's gravitational acceleration (g):

$$\Gamma_d = \frac{dT}{dz} = \frac{g}{c_p} \quad (1.2)$$

The presence of condensible trace gases in the atmosphere has several effects on the temperature structure (de Pater et al. 1985; Li et al. 2018a). Assuming that the atmosphere is fully convective, the adiabatic lapse rate decreases due to the latent heat release associated with the phase change. On Jupiter, all three cloud condensation regions affect the temperature structure, but water, owing to its relatively large fractional abundance and large latent heat, is the dominant factor (Atreya et al. 1985; Li et al. 2018a). While the effect of NH_3 and NH_4SH condensation has an integrated effect of about 1 K, the condensation of water ($3 \times \text{solar}^1$), on the other hand, is on the order of 5 K (Atreya et al. 1985; de Pater 1986; Li et al. 2018a). At the pressures where clouds are forming, locally the temperature would then be expected to be warmer compared to belts (Gierasch 1976; Gierasch et al. 1986). Indeed, the Voyager flyby enabled radio occultation measurements of the atmosphere that were able to probe the atmosphere below the radiative-convective boundary. The flyby geometry allowed for two measurements, one in NEB during ingress at 12°N , and one during egress at 0° . Initial measurements indicated that the temperature in the cloudy zone ($170 \pm 5\text{K}$ at 0°) was approximately 5 K warmer compared to the NEB ($165 \pm 5\text{K}$ at 12°); however, the uncertainties were too large for any definite conclusions (Lindal et al. 1981; Guillot et al. 2004). A recent reanalysis of the Voyager radio occultation measurements found that the zone was actually colder ($167.3 \pm 3.8\text{K}$), than the NEB ($170.3 \pm 3.8\text{K}$) (Gupta et al. 2022). Nevertheless, even in this new analysis, both measurements still overlap in uncertainty. Furthermore, infrared observations probing until the radiative-convective boundary indicate that the zones are colder than the belts in stark contrast to the expected behavior based on moist convection (Fletcher et al. 2016).

The Galileo Probe, and the Atmospheric Structure Instrument on-board provided the only measurement of the temperature in the cloud-forming regions of Jupiter, allowing us to constrain the atmosphere down to approximately 20 bars. While in itself an amazing feat, the probe entered into a so-called 5 micron hotspot. The large heat flux (Fletcher et al. 2016), the in-situ observations of the cloud particles (Ragent et al. 1992), and the gas distribution (Niemann et al. 1996; Niemann et al. 1998; Wong et al. 2004) all indicated that the region was extremely depleted in trace gases and clouds, and the corresponding temperature structure was close to a dry adiabat, albeit slightly sub-adiabatic (Seiff et al. 1996).

The process described above is thermochemical in nature, but the condensation of water can also impact the temperature structure by influencing the atmospheric dynamics (Guillot

¹Abundances in the giant atmosphere are normally normalized with the protosolar value to facilitate comparison between different species and planets (Asplund et al. 2009). We use $\frac{C}{H^2} = 5.9e - 4$, $\frac{N}{H^2} = 1.48e - 4$, $\frac{S}{H^2} = 2.89e - 5$, and $\frac{O}{H^2} = 1.07e - 3$

1995; Leconte et al. 2017; Li et al. 2019a; Ge et al. 2024). Analytical solutions (Guillot 1995) and simulations (Li et al. 2018a; Ge et al. 2024) suggest that this results in a super-adiabatic region where condensation occurs, locally decreasing the temperature. With convection inhibited, the atmosphere accumulates Convective Available Potential Energy (CAPE) (Emanuel et al. 1994). Once this energy surpasses the inhibition threshold, it is released intermittently in the form of storms. During the storm phase, condensation heats the middle troposphere, while subsequent evaporation cools the lower troposphere, counteracting the super-adiabatic temperature structure (Moeckel et al. 2024b; Ge et al. 2024). Alternative proposals include radiation (Leconte et al. 2017) or diffusive-convection driven by density differences (Guillot 1995).

These large uncertainties in the temperature and the processes have significant implications for our understanding of planetary deep atmospheres and interior models. Most models rely on the 1-bar temperature measurement from radio occultation (Lindal et al. 1981; Gupta et al. 2022) or Galileo probe data (Seiff et al. 1996) as inputs for interior modeling. However, ignoring the influence of stable layers leads to an underestimate of deep atmospheric and interior temperatures (Leconte et al. 2017; Ge et al. 2024).

Lower Troposphere

The temperature structure of the lower troposphere remains the least understood. In the absence of condensable gases, dry convection likely governs the atmosphere, adhering to a dry adiabat determined by Equation 1.2. Although alkali metals are anticipated to condense at several hundred bars, their abundance is small, suggesting only a minor impact on the temperature structure (Bhattacharya et al. 2023).

Intermittent storms

Storms have the ability to alter the temperature structure of all three cells concurrently, albeit intermittently. In the pre-storm phase inhibited convection seizes to control the temperature at the boundary between the lower and middle troposphere, resulting in the formation of a super-adiabatic layer. During the active phase of the storm, latent heat is released as water condenses in the ascending branch of the storm. This latent heat sustains the storm’s energy and transports it upward, warming the upper atmosphere (Ingersoll et al. 2000; Moeckel et al. 2024b). These storms are known to significantly overshoot the cloud deck (de Pater et al. 2019a), thereby heating both the middle and upper troposphere. In the upper tropospheric cell, the subsidence of the return flow through a stably stratified atmosphere further elevates the temperature (Ingersoll et al. 2004), resulting in a net heating of the atmosphere (Orton et al. 2023). Simulations (Sugiyama et al. 2011; Sugiyama et al. 2014; Li et al. 2019a), microphysics models (Guillot et al. 2020a), and observations (Moeckel et al. 2024b) collectively indicate that precipitation can reach the lower troposphere, where subsequent evaporation cools the atmosphere.

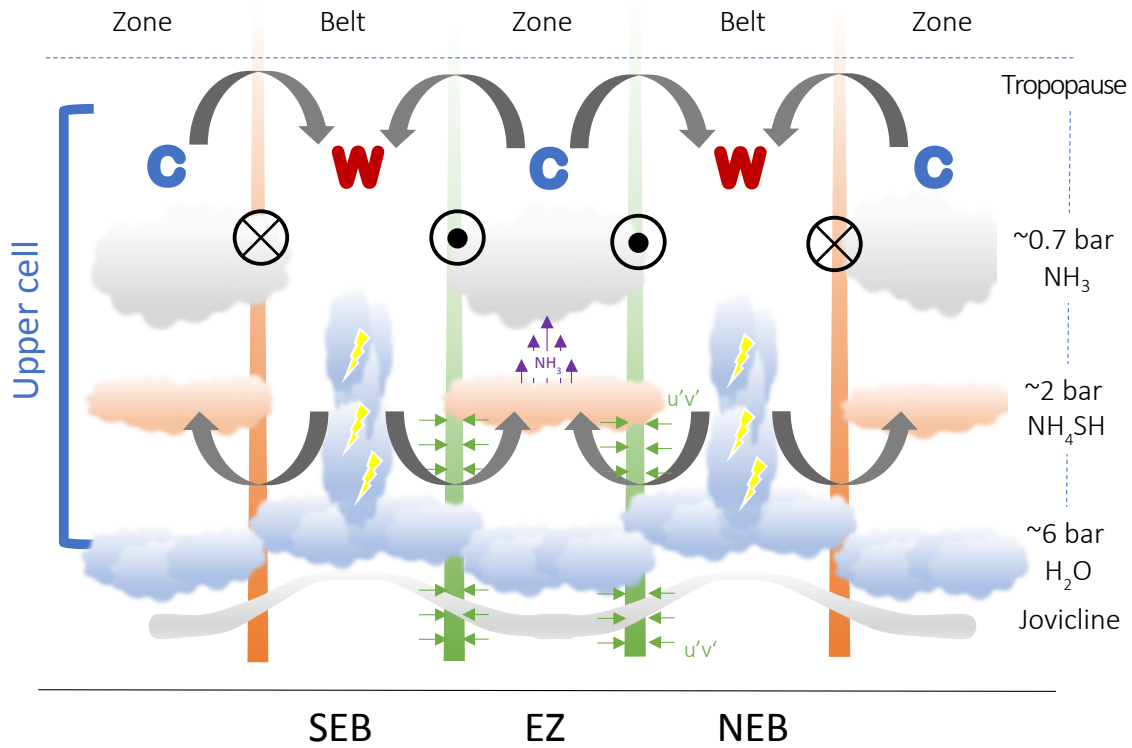


Figure 1.2: Classical circulation model with rising motion in the zones and subsidence in the belts. The warm and cold indications show infrared observations above the green arrows representing horizontal momentum flux responsible for shaping the jets at the interfaces between these regions. Reproduced from (de Pater et al. 2023) and (Fletcher et al. 2020b).

1.3 Canonical shallow view of Jupiter's circulation

Jupiter's global circulation is considered the primary mechanism governing the distribution of materials within its atmosphere. The classical depiction, as illustrated in Figure 1.2, portrays rising motion within the zones and subsidence within the belts. This traditional perspective is substantiated by various observations and encompasses the principal cloud-forming region of Jupiter.

Cloud top observations

Much of our understanding of Jovian circulation stems from observations focused on the cloud tops. This limits our knowledge to the top of the atmosphere, but we can derive indirect implications for the middle troposphere.

The initial insight into the presence of rising and subsiding motion arose from the recognition of horizontal divergence between the anticyclonic zones (high-pressure systems) and the cyclonic belts (low-pressure systems). This divergence necessitates rising motions within the zones, where moist air ascends, forming thick clouds, and subsidence of dry air occurs within the belts (Hess et al. 1951).

Further evidence supporting this dynamic came from comparisons of the vertically extended and expansive cloud deck in the zones relative to the belts. This discrepancy suggests that moist air must be upwelling in the zones, transporting enriched material from higher pressure levels to form dense clouds, while losing substances through precipitation. Conversely, in the belts, the now depleted air descends, with fewer trace gases available to generate clouds (Carlson et al. 1994).

Temperature in the upper troposphere

This understanding gained further credence with infrared observations conducted by the Voyager Infrared Interferometer Spectrometer and Radiometer (IRIS), which measured colder temperatures above the zones and warmer temperatures above the belts (Gierasch et al. 1986). The colder temperatures observed in the upper troposphere suggest the ascent of air through a stably stratified atmosphere, while the warmer temperatures indicate the subsidence of air.

Abundances in the upper troposphere

Inversions of infrared observations conducted with the Galileo Near Infrared Mapping Spectrometer (NIMS) and the Cassini Composite Infrared Spectrometer (CIRS) revealed that ammonia exhibits enhanced concentrations within the cloud deck (at 500 mbar) of the equatorial zone, while being depleted in the adjacent belts (Carlson et al. 1994; Fletcher et al. 2016). However, outside of the tropics, the signal drops below the level of uncertainties, limiting the conclusions drawn regarding ammonia abundance to lower latitudes.

Phosphine (PH_3), which does not condense under jovian conditions, serves as an additional constraint on atmospheric circulation (Fletcher et al. 2009). While it becomes the dominant phosphorous-bearing species deep within the planet at high temperatures ($T > 1240\text{K}$) (Fegley et al. 1985), in the middle and upper troposphere, it oxidizes to P_4O_6 . Its presence at the cloud top indicates rapid vertical transport of material from the planet's interior, where the transport timescale is faster than the oxidation timescale. Infrared observations reveal a phosphine mixing ratio following a pattern similar to ammonia, with an increase in the equatorial zone and depletion in the surrounding belts. The zone's enhancement suggests the presence of air rising from depths of ≥ 80 bars to the upper atmosphere, affirming a connection between the deep and upper troposphere. Belt depletion could result from various factors, such as prolonged residence in the upper troposphere leading to phosphine loss through oxidation or UV-induced destruction. Alternatively, it may indicate

slower mixing from the deep interior in the belts, where a molecular weight gradient could hinder convection and prolong mixing timescales.

Abundances in the middle troposphere

Cloud particles have minimal impact on radiation at radio wavelengths, allowing us to probe below Jupiter’s cloud deck. Radio telescopes detect thermal emission from the atmosphere, with ammonia serving as the main constituent to which we are sensitive. Below the cloud deck, ammonia is considered a passive tracer since its condensation and evaporation minimally affect atmospheric temperature (Atreya et al. 1985; de Pater 1986). We only have indirect information about the variability of the temperature structure below the clouds (Li et al. 2024; Moeckel et al. 2024b). Instead, inversion of radio observations usually attributes variations in the received flux to variations in the ammonia distribution (Li et al. 2017a; Moeckel et al. 2023).

These inversions reveal latitudinal variations in ammonia abundance, notably between the radio-cold, ammonia-enhanced equatorial zone (EZ) and the radio-warm, ammonia-depleted North Equatorial Belt (NEB). Over time, our ability to trace this contrast in ammonia has improved, initially showing NEB depletion to the 2 bar level (de Pater 1986), and later extending to at least 6 bars with the VLA (de Pater et al. 2001), consistent with water condensation levels. Conversely, the EZ exhibits marked ammonia enhancement compared to the rest of the planet.

This brightness temperature contrast between zones and belts persists into mid-latitudes, though less prominently than in the tropics. Outside the tropics, comparable contrasts in latitude and frequency suggest similar processes throughout mid-latitudes, with atmospheric variability decreasing poleward of 45 degrees, suggesting a more well-mixed atmosphere.

Ammonia is therefore used as a passive tracer for the dynamics of Jupiter’s middle troposphere. The gradient in ammonia abundance between deeper, enriched layers and depleted upper layers suggests regions as sources and sinks. Ammonia anomalies across large pressure ranges indicates transport from deeper layers, while localized anomalies suggest weather-related phenomena, such as the enrichments below the clouds likely result from evaporating precipitated ammonia.

Simulations

Simulating Jupiter’s atmosphere remains a challenge due to its immense size and the computational demands of resolving its processes across different scales. Global-scale simulations still struggle to replicate the planet’s jet structure, which distinguishes the zones from the belts (Heimpel et al. 2005; Thomson et al. 2016; Wicht et al. 2019; Wicht et al. 2020). Current climate models focusing on the global upper troposphere are not yet advanced enough to fully capture observed phenomena (Young et al. 2019a; Young et al. 2019b). While these models can reproduce some middle tropospheric features like equatorial plume structure and

overall depletion extending to the water cloud layer, finer-scale structures in mid-latitudes remain challenging to replicate.

To tackle computational complexity, researchers often employ box models, solving equations within spatially confined domains (Dowling et al. 1998; Li et al. 2019a). These models concentrate on various phenomena, including large-scale storms (Sánchez-Lavega et al. 2008), localized features like 5-micron hotspots (Showman et al. 2000), vortices (Hueso et al. 2009), or the impact of local processes on large-scale structure (Showman 2007; Li et al. 2019a; Ge et al. 2024). A major hurdle for these models is the lack of observational data to refine parameterizations of processes such as convection and microphysics. Nevertheless, they commonly emphasize atmospheric dynamics within Jupiter’s weather layer.

1.4 Challenges to the canonical view of Jupiter’s circulation

Theoretical studies, observations, and simulations suggest the presence of a shallow circulation spanning Jupiter’s upper and middle troposphere. However, several observations contradict this classical perspective. Lightning, for instance, is concentrated in the belts rather than the zones. This trend persists even with unbiased lightning detection methods using radio, challenging the notion that belts are regions of atmospheric subsidence (Little et al. 1999; Brown et al. 2018). This could indicate differences in water abundance between the zones and belts, potentially leading to the buildup of Convective Available Potential Energy (CAPE) under the belts (Dowling et al. 1989; Showman et al. 2005). Alternatively, it could suggest reduced water content beneath the zones, facilitating fully convective atmospheric conditions.

Radio observations revealed ammonia depletion extending much deeper than previously assumed, down to 30-40 bars (Li et al. 2017a; Moeckel et al. 2023). Additionally, analyses of well-mixed atmospheric states at 30 bars indicate an intriguing pattern: the zones exhibit depletion compared to the belts, opposite to observations in the middle troposphere (Li et al. 2017a; Moeckel et al. 2023). This discrepancy also may imply a stacked circulation cell with opposing circulation directions in the lower troposphere (Duer et al. 2021), or it could indicate material removal from belts through microphysics deposition into the lower troposphere (Guillot et al. 2020a).

The forcing mechanism behind Jupiter’s jets remains a subject of debate, although most models converge on the concept of an inverse cascade of energy (Young et al. 2017). However, various theories propose different sources of energy, ranging from moist convection (Vasavada et al. 2005) to internal heat sources (Busse 1976; Heimpel et al. 2005). Regardless of the interpretation, it’s essential to balance the flux of eddy momentum for the formation of the jets. This circulation pattern necessitates ascent in the belts and descent in the zones in the middle troposphere (Showman et al. 2005), opposite what the cloud top observations indicate. Similarly, the balance of horizontal and vertical divergence implies material transport from

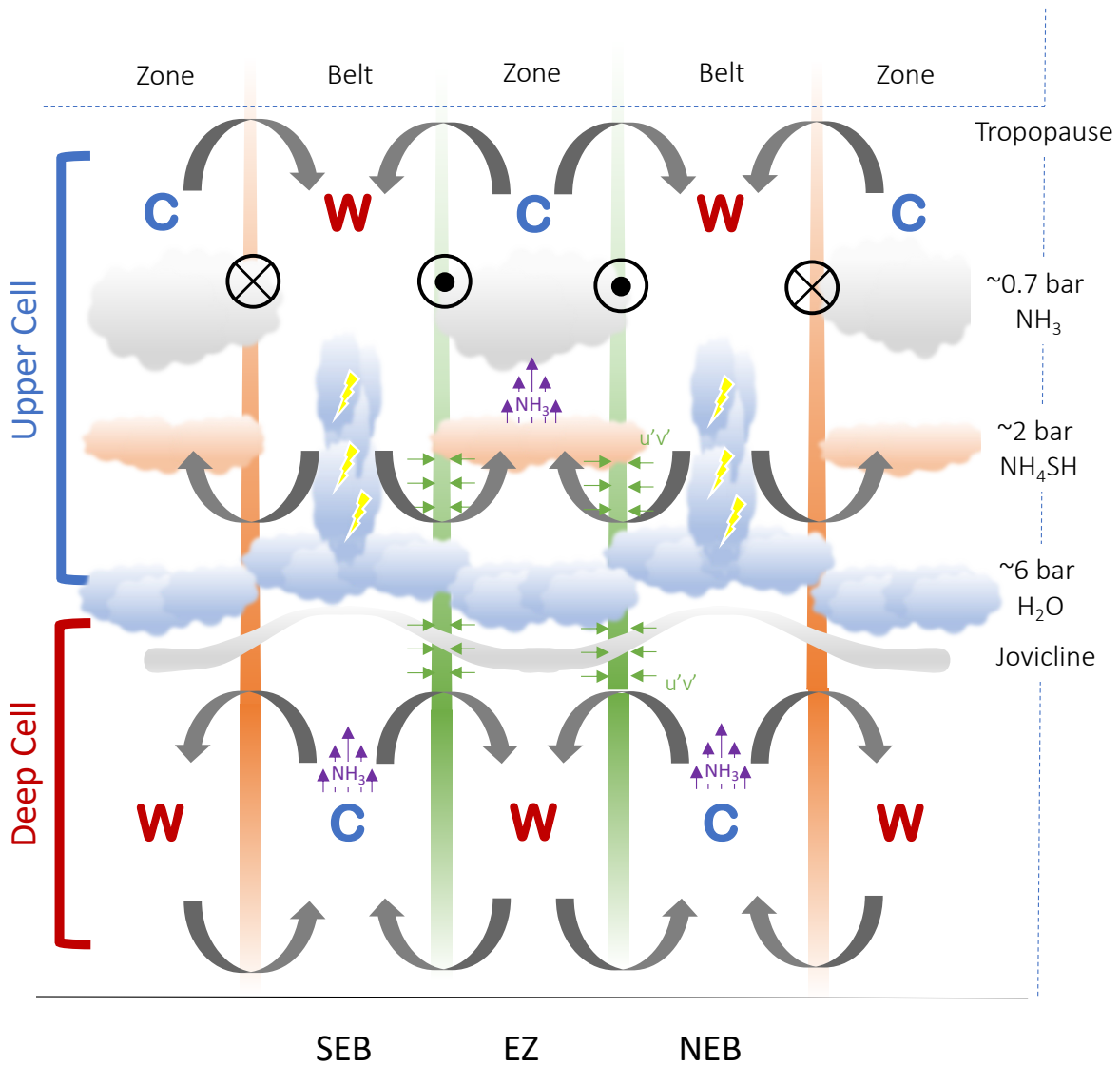


Figure 1.3: Including recent radio observations into the circulation models shows that some of the observations could be reconciled with stacked circulation cell model. Reproduced from (de Pater et al. 2023) and (Fletcher et al. 2020b).

the belts to the zones, contrary to traditional circulation models (Ingersoll et al. 2000; Fletcher et al. 2020b).

Taken all these challenges into account, observations with Juno allowed us to extend the canonical view below the water cloud layer where we find seemingly evidence for a stacked circulation cell (see Figure 1.3).

1.5 Big questions

This leaves us with a few fundamental questions about Jupiter’s atmospheric composition, the dynamics, and the processes controlling the climate that this thesis will address. Some of these questions were partially answered by the Juno mission, however, a completely new set of questions has been revealed.

Circulation

- C1 What are the global circulation patterns on Jupiter?
- C2 Is the atmosphere driven by eddies in the middle troposphere (Lee et al. 2021), driven by injection of internal heat from below (Thomson et al. 2016) or maintained by moist convection (Ingersoll et al. 2000)?
- C3 What role does the distribution of water play in controlling the dynamics of the Jovian atmosphere?

Ammonia cycle

- A1 What are the major processes removing ammonia from the upper and middle troposphere?
- A2 How deep does the weather affect the atmosphere?
- A3 What effects do large-scale structures (vortices, outbreaks, etc) have on the atmosphere?
- A4 How does the water cycle affect the ammonia cycle?
- A5 Why do the NH_4SH and H_2O cloud forming regions not show distinct signals in the ammonia abundance?
- A6 How good is ammonia as a tracer for the circulation?
- A7 What does the ammonia depletion mean for the water distribution on Jupiter?

Formation environment

- F1 How well do the cloud forming regions represent the abundances within the planet?

Thesis structure

This dissertation will touch on many of the fundamental questions listed above. Chapter 2 discusses the pipeline that processes instrument data and how we derive observable quantities for comparison with our atmospheric models. By fitting models to the observations, we can study the zonal distribution of ammonia abundance and address global circulation patterns on Jupiter (**C1**) and compare the weather layer to the lower troposphere (**F1**).

Chapter 3 explores the processes that shape the distribution of ammonia on the planet (**A1-A3**). It investigates the impact of large-scale outbreaks on ammonia and temperature distribution in Jupiter's troposphere. These storms are triggered at the water condensation layer and address how the water and ammonia cycles are coupled on Jupiter (**C2,C3,A4,A5,A7**).

Chapter 4 focuses on the three-dimensional structure of Jupiter's weather based on Juno and VLA observations. It addresses the depth and intensity of the weather (**A2**) and its role in shaping the atmosphere (**A1,A3,A6**). It also discusses which atmospheric phenomena we can trace below the weather layer (**A3**).

This dissertation will touch on many of these fundamental questions listed above. Chapter 2 will discuss the pipeline that takes the instrument data and how we derive the observable quantities to which we compare our models of the atmosphere. By fitting models to the observations, we can study the zonal distribution of the ammonia abundance and address the global circulation patterns on Jupiter (**C1**) and allow comparing the weather layer to the lower troposphere (**F1**).

Chapter 3 explores the processes that shape the distribution of ammonia on the planet (**A1-A3**). It explores the impact of a large-scale outbreak on the ammonia and temperature distribution in Jupiter's troposphere. These storms are triggered at the water condensation layer, and addresses how the water and ammonia cycles are coupled on Jupiter (**C2,C3,A4,A5,A7**).

Chapter 4 focuses on the three-dimensional structure of Jupiter's weather based on Juno and VLA observations. It addresses the depth and intensity of the weather (**A2**) and its role in shaping the atmosphere (**A1,A3,A6**). It also addresses which atmospheric phenomena we can trace below the weather layer (**A3**).

Chapter 2

Measuring Ammonia with Radio Telescopes

This chapter has been published in the Journal of Planetary Science under the title: 'Ammonia Abundance Derived from Juno MWR and VLA Observations of Jupiter' by Chris Moeckel, Imke de Pater, and David DeBoer.

Summary

The vertical distribution of trace gases in planetary atmospheres can be obtained with observations of the atmosphere's thermal emission. Inverting radio observations to recover the atmospheric structure, however, is non-trivial, and the solutions are degenerate. We propose a modeling framework to prescribe a vertical distribution of trace gases that combines a thermo-chemical equilibrium model based on a vertical temperature structure and compare these results to models where ammonia can vary between pre-defined pressure nodes. To this means we retrieve nadir brightness temperatures and limb-darkening parameters, together with their uncertainties, from the Juno Microwave Radiometer (MWR). We then apply this framework to MWR observations during Juno's first year of operation (Perijove passes 1 - 12) and to longitudinally-averaged latitude scans taken with the upgraded Very Large Array (VLA) (de Pater et al. 2016; de Pater et al. 2019b). We use the model to constrain the distribution of ammonia between -60° and 60° latitude and down to 100 bar. We constrain the ammonia abundance to be $340.5^{+34.8}_{-21.2}$ ppm ($2.66^{+0.27}_{-0.17} \times$ solar abundance), and find a depletion of ammonia down to a depth of ~ 20 bar, which supports the existence of processes that deplete the atmosphere below the ammonia and water cloud layers. At the equator we find an increase of ammonia with altitude, while the zones and belts in the mid-latitudes can be traced down to levels where the atmosphere is well-mixed. The latitudinal variation in the ammonia abundance appears to be opposite to that shown at higher altitudes, which supports the existence of a stacked-cell circulation model.

2.1 Introduction

Some of Jupiter’s biggest mysteries remain unsolved despite decades of observations. Questions about its formation environment, the source of energy for its atmosphere, and the distribution of trace gases within said atmosphere remain as open-ended as ever. The vastness of the planet and its atmosphere, coupled with the short time scales on which the atmosphere evolves, implies that a global understanding of the planet requires coordinated observations across many different frequencies. In the early days of observational astronomy, optical images were used to infer the dynamics of the atmosphere by tracking the motion of cloud tops (Peek 1959; Ingersoll et al. 1981). Various techniques were used to correlate images and find the dominant zonal component of the global circulation. The meridional component of the atmosphere is much smaller in magnitude, making it more difficult to observe. Only recent advances in observational capabilities and computing techniques have allowed for direct measurement of the north-south component of the wind by tracking small scale cloud features (Asay-davis et al. 2011).

A key feature in expanding this limited two-dimensional view of the atmosphere is observations of the planet’s thermal emission at infrared (Gierasch et al. 1986) and radio wavelengths. At radio wavelengths the impact of clouds is sufficiently small such that we can still draw conclusions about the atmosphere below, allowing radio observers to speculate as early as the 1960’s about the presence of microwave absorbers in the Jovian atmosphere below the visible cloud tops (Thornton et al. 1963; Welch et al. 1966; Wrixton et al. 1971; Berge et al. 1976). Given the right combination of frequencies, we can use radio observations to construct a full three-dimensional view of the planet and reveal global circulation patterns.

Studying this pattern on the planet requires observations at resolutions high enough to distinguish between the various climatological zones, i.e., the visibly white zones and brown belts on Jupiter. Ground-based observatories use the ability to detect phase at radio frequencies and rely on complex interferometers, with baselines on order of 10s of kilometers, such as the Very Large Array (VLA) and the Atacama Large (sub)Millimeter Array (ALMA), both providing excellent spatial resolution from Earth. The NASA Juno mission opted for an alternative solution, building an orbiter that approaches Jupiter as close as 3000 kilometer. Intriguingly, despite the fact that Juno is five orders of magnitude closer to Jupiter than the VLA, the final resolution at 10 GHz or higher is comparable on the planet when the VLA is in its extended configuration as shown in Figure 2.1. Though both approaches have orthogonal advantages and disadvantages for atmospheric observations, the combination provides a very powerful tool for studying the atmosphere of Jupiter. The ground-based observations have excellent spectral and spatial resolution (both in latitude and longitude), but are limited by the presence of Jovian synchrotron radiation along the line of sight at frequencies below 5 GHz, which hinders the VLA from retrieving information below ~ 10 bar. The proximity of Juno to the planet allows for observations that drastically reduce the impact of synchrotron radiation; however, data are taken along a narrow north-south track so there is limited global context for these observations.

Table 2.1: Radiometer and antenna characteristics of Juno’s MWR.

Channel	1	2	3	4	5	6
Frequency [GHz]	0.6	1.278	2.597	5.215	10.004	22
Bandwidth [MHz]	21	43.75	84.5	169	325	770
Beamwidth [deg]	20.6	20.6	12.1	12.1	12.0	10.8

The model we develop in this work is applicable to both sets of measurements, and provides a reference frame for fitting and interpreting radio observations. In Section 4.2, we present our data reduction pipeline developed for the Juno data, followed by our description of the perturbed thermo-chemical equilibrium model for the atmospheric structure in Section 2.3. Based on a parameterized distribution of trace gases, we can compute the brightness temperature using our radiative transfer code, as described in Section 2.4. In Section 2.5, we present our results that minimize the difference between the observations and the model atmosphere for the mean atmosphere based on the first year of Juno observation, and compare our results to the only other published result for perijove (PJ) 1. Lastly, we touch upon the most important interpretations in Section 2.6. We finish the paper with our overall conclusions and recommendations for the future work.

2.2 Data

Sources of Data

Since Juno’s insertion into Jupiter’s orbit on July 4th, 2016, the spacecraft has remained in a 53 day, highly eccentric, polar orbit, in which the spacecraft spends most of its time outside of the high radiation environment around the planet. Among the suite of instruments, there are several with the primary goal of studying the planet’s atmosphere, including a microwave radiometer (Janssen et al. 2017, MWR,). This instrument couples six radio receivers to a set of antennas (an array of patch antennas and corrugated horns) to receive radio waves with minimal side lobe contributions at six distinct frequencies, from here on referred to as Channel 1 through 6 (see Table 2.1 for details).

Jupiter’s emission at radio wavelengths consists of two components: a thermal component (i.e., the blackbody radiation of the planet’s atmosphere) and non-thermal emission originating from synchrotron radiation by electrons in the radiation belts, spheric emission by lightning on the planet and auroral emission (e.g., Berge et al. 1976; de Pater 1990; Zarka 1998; Brown et al. 2018). As seen from Earth, part of the synchrotron radiation is spatially co-located with the atmospheres’ thermal emission (see, e.g., de Pater 1986), which makes observations increasingly difficult below 7 GHz (the frequency at which synchrotron radiation becomes dominant (Berge et al. 1976)). Juno circumvents this superposition of emitters by dipping between the planet and the radiation belts during PJs, which brings the spacecraft as close as ~ 3000 km above the cloud tops of the planet.

The spacecraft completes one rotation every 30 seconds, in which time its beams sweep across the sky (sky coordinates θ_{sky}, ϕ_{sky}) and obtain 300 beam-convolved measurements (i.e. the brightness temperature T_b) of the sky's brightness (T_{sky}) at positions expressed in spherical coordinates in the spacecraft frame (θ_{sc}, ϕ_{sc}) (Janssen et al. 2017):

$$T_b = \int_0^\pi \int_0^{2\pi} T_{sky}(\theta_{sky}, \phi_{sky}) G(\theta_{sky} - \theta_{sc}, \phi_{sky} - \phi_{sc}) \sin(\theta_{sc}) d\theta_{sc} d\phi_{sc} \quad (2.1)$$

The radiation pattern (or ‘gain’) of the radio antenna $G(\theta, \phi)$ is designed so that 99% of the emission falls within 2.5 times the half power beam width (HPBW) of the Gaussian main beam, limiting the amount of radiation received through the side lobes. The intersection of the main beam with the planet determines the resolution of the measurements, which is highest at nadir viewing, and decreases with increasing slant angle, distance from the planet, and frequency. For ideal operation of the MWR, the antennas scan the planet in a north-south direction to obtain multiple measurements per latitude at varying emission angle (the angle between the antenna’s line of sight and the surface normal). While measurements at nadir probe deepest into the planet, observations at increasing emission angles scan the planet higher up in the atmosphere due to the increased path lengths. Juno’s other science priorities, such as gravity science, require communication antennas to be aligned with Earth so that the satellite does not align with the spin axis of the planet, which deteriorates the emission angle coverage and reliability of the atmospheric signal (such as PJ 10 and 11), which we therefore exclude from this analysis. The most relevant information for the MWR observation campaign are listed in Table 2.2.

The radiation pattern for the six antennas, the spacecraft geometry during PJs, and the corresponding antenna temperature measurements are documented in the Planetary Data System¹ and are utilized in the following analysis.

In addition to the Juno data, we also incorporate observations between 3 and 25 GHz from the Very Large Array (VLA) into this analysis. These were originally published in de Pater et al. (2016) and de Pater et al. (2019b), and we refer the reader to these papers for details on the data reduction and calibration.

Data reduction of the Juno observations

The two quantities needed from the Juno data for our atmospheric retrieval (see Section 2.5) are the nadir brightness temperature at the observing frequency, T_{b0} , and the limb-darkening coefficient p , which numerically represents how the brightness temperature decreases at increasing emission angle θ ($\mu \equiv \cos \theta$) as we probe higher up in the atmosphere compared to nadir observations:

¹Data version 3, <https://pds.nasa.gov/>

Table 2.2: MWR Orbits used in our work

PJ number	Date	Min. dist (km)	PJ [lat,lon]	Lon range
1	2016-08-27	4138	4.3, 95.8	-115, -75
3	2016-12-16	4101	6.5, - 5.5	-18, 5
4	2017-02-02	4234	7.5, 85.1	64, 107
5	2017-03-27	3314	8.6, 175.1	64, 107
6	2017-05-19	3383	9.7, -140	165, -177
7	2017-07-11	3359	10.8, -49.0	-156, 114
8	2017-09-01	3332	11.8, 41.9	-73, -21
9	2017-10-24	3839	13., 132.	30, 73
12	2018-05-24	3201	15.9, 115	-144, -107

Overview of MRW's orbits which yield data useful for atmospheric science. The columns correspond to the PJ number, date of the flyby, minimum distance from the planet, sub satellite location during closest encounter, and the longitude range covered during the flyby.

$$T_b(\mu) = T_{b0}\mu^p \quad (2.2)$$

with $T_b(\mu)$ the brightness temperature of Jupiter at a given frequency convolved with the gain pattern of the antennas (Equation 2.1).

For a full treatment of the problem, the observations can be deconvolved based on an exact knowledge of the antenna pattern and using several overlapping observations (Oyafuso et al. 2020). We choose an alternative approach, and instead correct the observations for the viewing geometry. Since we are interested in obtaining the variation in brightness temperature with emission angle, we must account for the fact that the beam captures a wide range of emission angles. Based on the shape of the planet and the relative position of the antenna beam, we derive a map of emission angle for each observation (see inset in Figure 2.1, and Addendum A). Knowing the detailed shape of the antenna pattern, we can convolve the two quantities to obtain a beam-averaged temperature $T_b(\bar{\mu})$. Assuming that the variations in the observable quantities (i.e. nadir brightness temperature and limb-darkening) across the beam are small compared to variations in brightness due to changes in emission angle, we obtain the final brightness temperature of the observation as the mean brightness temperature across the beam $T_b(\bar{\mu})$ at the mean emission angle across the beam $\bar{\mu}$:

$$T_b(\bar{\mu}) = \bar{T}_{b0}\bar{\mu}^{\bar{p}} \quad (2.3)$$

$$\bar{\mu} = \frac{\int \int_0^{\theta_{sc}} G(\theta_{sc}, \phi_{sc}) \mu(\theta_{sc}, \phi_{sc})}{\int \int_0^{\theta_{sc}} G(\theta_{sc}, \phi_{sc})} \quad (2.4)$$

We note here that other parameterizations for the limb-darkening can be used (such as the two term expansion by Li et al. 2017a)); however, the exact form does not influence the atmospheric retrieval. All we care about for the retrieval is by how much the brightness temperature has dropped at an emission angle of 45° for our model.

We set the limits of the beam convolution equal to 2.5 times the HPBW of the beam, corresponding to the angle within 99% of the total emission is received (Janssen et al. 2017). In case a beam element falls off the planet, we chose to discard that measurement due to drastic brightness contrast between the planet and either the background sky or synchrotron radiation.

To derive the latitudinal structure of the observables, we first collect all measurements where the boresight falls within a 1 deg latitude bin. The resolution of the actual observations is set by the size of the footprints and as such varies between each measurement, often larger than the 1-degree bin size. This bin size, therefore, compromises between resolving the latitudinal structure and the size of the footprints. Inset a) in Figure 2.1 shows an example of this, where we plot all 60 observations where the beam-center falls within the selected region, and the beams at large emission angles indeed span a few degrees of latitude. To that purpose we fit all data within the bin using a weighted linear least squares (Equation 2.5) based on parametric relationship between T_{b0} and p (see Equation 2.3). At the lowest frequencies (Channel 1 - Channel 3) we suspect contamination by synchrotron radiation to be largest, so that use $\bar{\mu}$ as a weight (W). The choice of $\bar{\mu}$ only slightly downweighs the observations ($\mu(\theta = 45) \approx 0.7$), and as such presents a compromise. If we used weights that penalize large emission angles even more, we would lose important information on the limb-darkening, while a smaller weight caused problems at mid latitudes with synchrotron radiation leaking in.

$$\frac{\delta}{\delta X} \sum_{i=1}^n W(Y - AX)^2 = 0 \quad (2.5)$$

$$W = \begin{bmatrix} \bar{\mu}_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \bar{\mu}_i & \dots & 0 \\ \vdots & & & \ddots & \vdots \\ 0 & \dots & & & \bar{\mu}_n \end{bmatrix} \quad Y = \begin{bmatrix} \log T_b(\bar{\mu}_1) \\ \vdots \\ \log T_b(\bar{\mu}_i) \\ \vdots \\ \log T_b(\bar{\mu}_n) \end{bmatrix} \quad A = \begin{bmatrix} 1 & \log \bar{\mu}_1 \\ \vdots & \vdots \\ 1 & \log \bar{\mu}_i \\ \vdots & \vdots \\ 1 & \log \bar{\mu}_n \end{bmatrix} \quad X = \begin{bmatrix} \log T_{b0} \\ p \end{bmatrix}$$

Based on best fit parameters we compute the error ϵ by subtracting the data from the parametric fit, and compute the reduced chi-squared value χ^2 for n data points and n_p parameters:

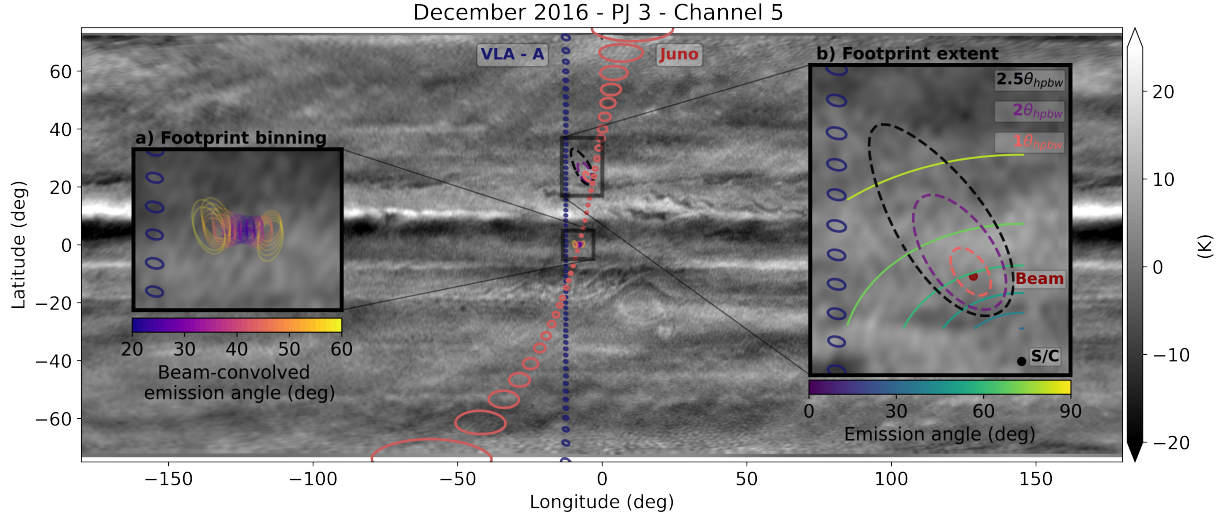


Figure 2.1: PJ3 flyby during December 2016. The map shows X-band (8-10 GHz) VLA observations taken concurrently with the flyby to show the longitudinal structure of the planet (Moeckel et al. 2019, These VLA data will be fully published in a subsequent paper). The red footprints correspond to MWR’s Channel 5 observation, where we have plotted the highest resolution (i.e. smallest emission angle), while the blue footprints correspond to the VLA resolution (Note: In December 2016 the VLA was in the most extended A-configuration). Inset a) is a zoom-in for the indicated region and shows all the 60 individual observations colorized by their beam-convolved emission angle that are centered around the equator. These 60 observations are the basis for fitting the nadir brightness temperature and the limb-darkening at 0° . Inset b) is a zoom-in to illustrate how the emission angle varies across the beam, where the red central dot corresponds to the boresight center and the black dot indicate the position of the spacecraft. The dashed ellipses correspond to the beams’ extent projected onto the planet with the contours showing how the emission angle varies across the beam. The final beam-convolved emission angle is 59.2° when integrating over the $2.5 \theta_{HPBW}$ contour that corresponds to 99% of the emission.

$$\epsilon = Y - AX \quad (2.6)$$

$$\chi^2 = \frac{\epsilon^T W \epsilon}{n - n_p} \quad (2.7)$$

$$(A^T W A)^{-1} \chi^2 = \begin{bmatrix} \left(\sigma_{\log(T)}^{fit}\right)^2 & \rho_{12} \\ \rho_{21} & \left(\sigma_p^{fit}\right)^2 \end{bmatrix} \quad (2.8)$$

The $1\text{-}\sigma$ uncertainty in our parameters corresponds to the square root of the diagonal elements of the covariance-variance matrix in Equation 2.8, while the off-diagonal elements ρ are the correlation between the factors. From there, we obtain the uncertainties for the brightness temperature σ_T^{fit} (by taking the exponential of $\sigma_{\log(T)}^{fit}$) and for the limb-darkening parameter σ_p^{fit} . In Figure 2.3 we verify the fit uncertainties derived from the weighted least square approach through the use of a computational more expensive Markov-Chain Monte-Carlo (MCMC) approach, which samples the solution space and the correlation between the parameters based on the same parameterization in Equation 2.3. The best-fit quantities derived from each other agree within the derived uncertainties, with the MCMC finding larger uncertainties for the derived values. We therefore will carefully assess the impact of the uncertainties on the derived ammonia distributions. The MCMC results also indicate the correlation between the two quantities, where an increase in temperature correlates well with an increase in brightness temperature. We note however that the absolute calibration uncertainty for temperature ($1.5\% \approx 5\text{K}$ corresponding to the example in Figure 2.3) is an order of magnitude larger than the fit uncertainty (0.15K), and as such the correlation is much smaller compared to the absolute calibration. Therefore, we treat them as independent errors in our analysis. The final uncertainty for the brightness temperature is a combination of the fit uncertainty σ_T^{fit} and the absolute calibration uncertainty σ_T^{cal} (Janssen et al. 2017), which we add in quadrature. We adopt an absolute calibration uncertainty σ_T^{cal} of 10% for Channel 1 due to the unknown opacity of absorbers (e.g., ammonia, water, and alkalis) at such high pressures (Hanley et al. 2009; Bellotti et al. 2016; Bellotti et al. 2017; Bellotti 2018), and 1.5% for all other channels (Janssen et al. 2017). The final uncertainty for the limb-darkening coefficient is a relative measurement and therefore corresponds only to the fit uncertainty.

$$\sigma_T = \sqrt{(\mathbf{n} \sigma_T^{fit})^2 + (\sigma_T^{cal})^2} \quad (2.9)$$

$$\sigma_p = \mathbf{n} \sigma_p^{fit} \quad (2.10)$$

Spatial variations of the parameters within the beam and remaining synchrotron contribution both deteriorate the reliability of the fit, making the retrieval prone to errors in case

of an overreliance on these measurements. To fully understand the impact of the uncertainties, we allow $\mathbf{n}$ to vary between 1 and 10 (inset in Figure 2.2 shows the various uncertainty levels), and test the robustness of our results to the uncertainty fidelity $\mathbf{n}$. If our models are sufficiently capture the complex atmospheric structure, the choice of uncertainty should not matter. Thus, as a function of latitude, we have reduced the MWR measurements to two parameters: nadir brightness temperature T_{b0} and limb-darkening coefficient p (with a 1 deg step-size in latitude per PJ) and their corresponding uncertainties.

In addition to the individual PJs, our final goal is to produce a global (i.e., longitude, or orbit-averaged) latitudinal distribution of trace gases. We therefore combine the individual PJs and compute the mean for each channel. We caution the reader that the global mean is based on nine narrow slices of the atmosphere separated both in time and longitude, and is thus not a perfect representation of a global atmosphere. For the uncertainties, we elect not to use the standard deviation between the individual PJs since they (i) reflect spatial variations instead of measurement uncertainties and (ii) do not reflect the absolute uncertainty for the temperature measurements. Instead we compute the average fit uncertainty $\bar{\sigma}^{fit}$ at a given latitude among the PJs and add them to the absolute uncertainty:

$$\sigma_T^{mean} = \sqrt{(\mathbf{n} \bar{\sigma}_T^{fit})^2 + (\sigma_T^{cal})^2} \quad (2.11)$$

$$\sigma_p^{mean} = \mathbf{n} \bar{\sigma}_p^{fit} \quad (2.12)$$

We use $\mathbf{n} = 3$ (i.e., 3σ) for the fit uncertainty when plotting the trace gas distributions, but we also show the retrieved atmospheric quantities for different fidelities ($\mathbf{n}=1,5,10$) in Section 2.5.

Data selection

Despite limiting observations to viewing geometries with 99% of emissions coming from the planet, the low frequency observations show signs of synchrotron contamination. The tell tale sign of synchrotron contamination is a breakdown of the typical relationship between emission angle and brightness temperature. Observations for which the synchrotron radiation off the planet is stronger than the atmospheric signal show a non-physical limb-brightening effect, unlike the limb-darkening that is apparent for atmospheric observations. In the absence of accurate synchrotron radiation models, and given the complexity of the electron distribution and the magnetic field close to the planet (e.g., de Pater 1981; de Pater et al. 1997; Santos-Costa et al. 2017; Moore et al. 2019), we use two different filters to remove observations that are suspect to contamination.

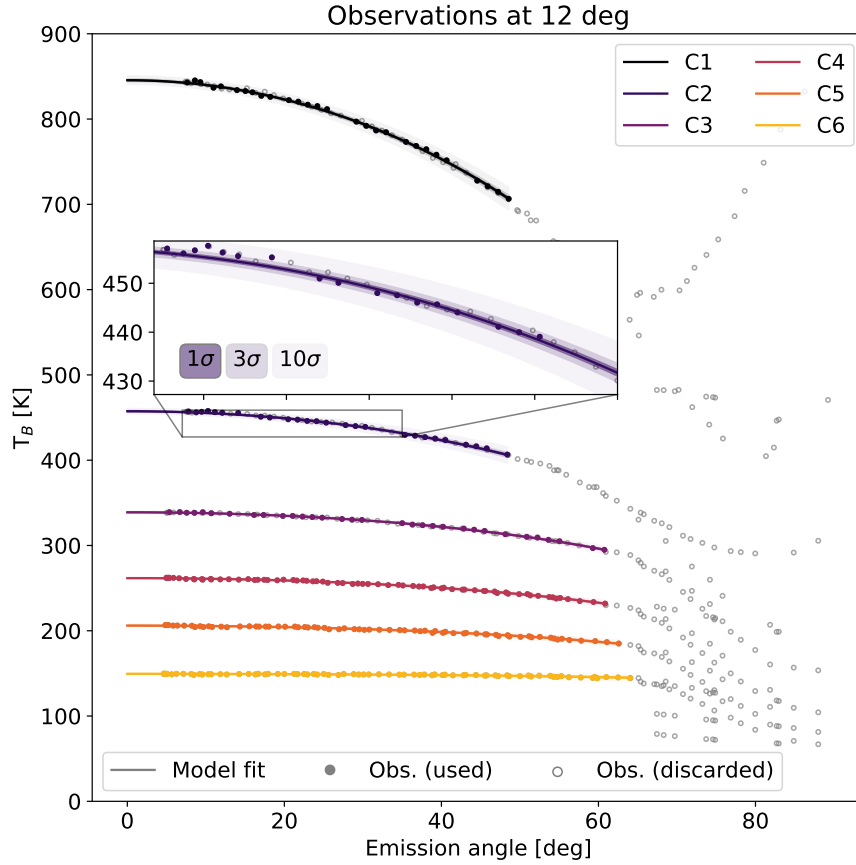


Figure 2.2: Brightness temperature at 12° deg north latitude for the 6 different channels, plotted against the beam-convolved emission angle. The closed circles correspond to the observations considered in the fit, and the open circles to the observations that were removed. Open circles inwards of the cut-off are observations with high susceptibility to synchrotron radiation (spatial filter – see Section 2.2), while open circle outwards are measurements where part of the beam is off the planet. The cut-off is determined such that all beam elements interior 2.5 HPBW are on the planet. The impact of the synchrotron radiation leaking in through the side lobes can be seen in Channel 1 and 2, where the brightness temperature increases beyond 60 deg, while the drop in brightness temperature at higher frequencies is due the cold sky leaking in. The solid line with shading corresponds to the fitted model according to Equation 2.3 and three uncertainty fidelities ($n=1,3,10$). The intersect at an emission angle of zero is the nadir brightness temperature, and the limb-darkening parameter defines the shape of the curve.

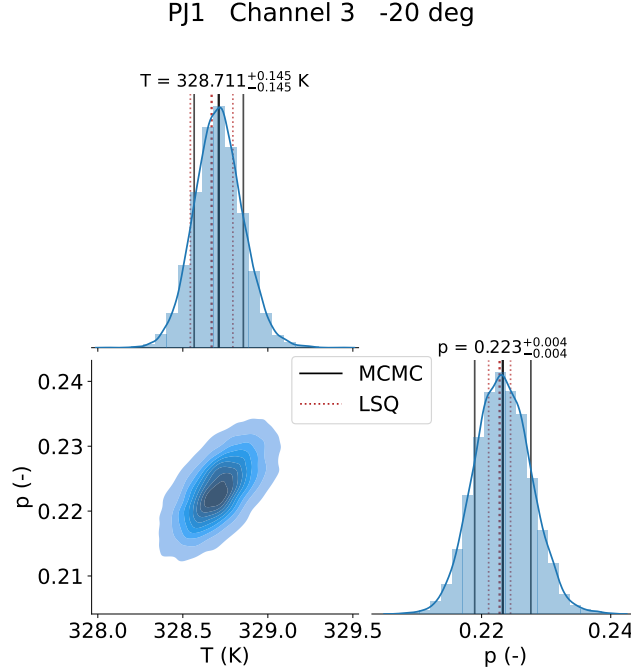


Figure 2.3: Verification of the fit uncertainty derived from the weighted least squares approach (see Equation 2.5) by comparing the results to an Markov-Chain Monte-Carlo (MCMC) method using the same underlying model to fit the data (see Equation 2.3). The solid black lines corresponds to the 16%, 50% and 84% quantiles, while the dotted red lines indicate the errors retrieved from the weighted least square approach. The best-fit quantities for both methods agree well within their uncertainties. The largest difference is found in the uncertainty of the fitted limb-darkening parameter, where the weighted least square errors are smaller than the MCMC results.

Spatial Filter

The main synchrotron radiation belt of Jupiter is constrained to low latitudes around the magnetic equator (e.g., Roberts 1976; de Pater 1981; Sault et al. 1997; de Pater et al. 1998). Despite the low sensitivity of the antenna beam in the side-lobes, the combination of high intensity radiation and large emission area causes problems in observations where synchrotron emission enters through the side lobes. We therefore restrict measurements where the sensitivity to the synchrotron radiation in the side lobes is minimal. In practice, when the spacecraft is at higher latitudes (10-60°), we remove all observations that are looking towards the equator (where the equatorial synchrotron radiation is leaking in) and instead use only observations that look polewards. see Figure 2.2 and Addendum B for examples of this filter.

Limb-Darkening Filter

The fitted limb-darkening coefficient and its deviation from the mean is another constraint that we use to assess the synchrotron contribution to the observations. Observations that are bright at the limb (i.e., a lower than expected value for the limb-darkening) are a telltale sign of contribution by synchrotron radiation. Latitudes where the limb-darkening coefficient deviates more than 5 standard deviations from the mean for the given orbit are replaced by the orbit mean at that latitude.

Orbit average

The geometry during each flyby is dictated by the type of science that is prioritized. For MWR observations, we therefore restrict ourselves to a subset of nine orbits from the first 12 to compute the orbit average (see Table 2.2). We use the retrieved uncertainties in the parameters as weights to compute the mean profiles for brightness temperature and limb-darkening after applying the spatial and limb-darkening filters discussed above.

The results of the data reduction for these Juno data are shown in Figures 2.4 (nadir brightness temperature) and 2.5 (limb-darkening coefficient), where the solid lines correspond to the mean and the thin dashed lines correspond to the various PJ passes. For verification purposes, we also compare our results to published orbit-averaged data of (Oyafuso et al. 2020), indicated by the dotted line. The variations with latitude of radio-cold and radio-warm regions indicate the presence of enriched and depleted trace gases, which modify the opacity for the escaping blackbody radiation, in line with our assumption that the variations in kinetic temperature are small. Some of the latitudinal variations seen in the mean profiles can be traced down across all channels, such as the radio cold region around the equator, indicating the presence of atmospheric variations spanning several orders of magnitude of pressure. At higher latitudes, the profiles show that the variations decay rapidly with depth, highlighting more shallow atmospheric features. Atmospheric variability, as seen by the dispersion between individual PJ profiles, is seen especially at the higher frequencies, which

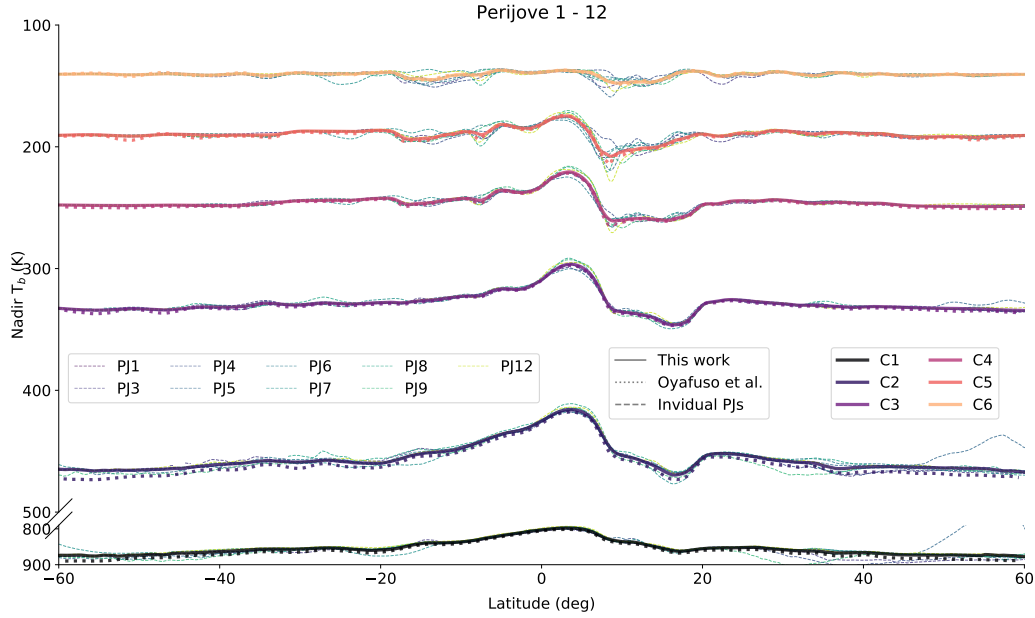


Figure 2.4: Nadir brightness temperature for the 6 channels between -60 and 60 deg, where the thick lines indicate the orbit averaged values, and the dashed thin lines correspond to the individual PJs. The dotted line represents the orbit averaged value based upon a deconvolution algorithm (Oyafuso et al. 2020) and shows a good agreement between the two methods, validating both our approaches.

correspond to the upper layers of the atmosphere where temporal and spatial variability dominate (de Pater et al. 2016).

The structure of the limb-darkening is more chaotic, but to first degree it mirrors a structure similar to the brightness temperature, with the biggest diversions seen in the equatorial zone and the neighboring north equatorial belt. We can see smaller features at higher latitudes corresponding to regions where the white zones and brown-reddish belts alternate. The limb-darkening coefficient is very sensitive to variations in spatial structure within the binned regions, so that it becomes difficult to interpret the signal at higher frequencies, and we caution reading too much into the fine scale structure at the highest frequencies.

2.3 Methods

The presence of radio-absorbing trace gases in a planet’s atmosphere modulates the thermal emission from the atmosphere as it propagates upwards. By prescribing a trace gas distribu-

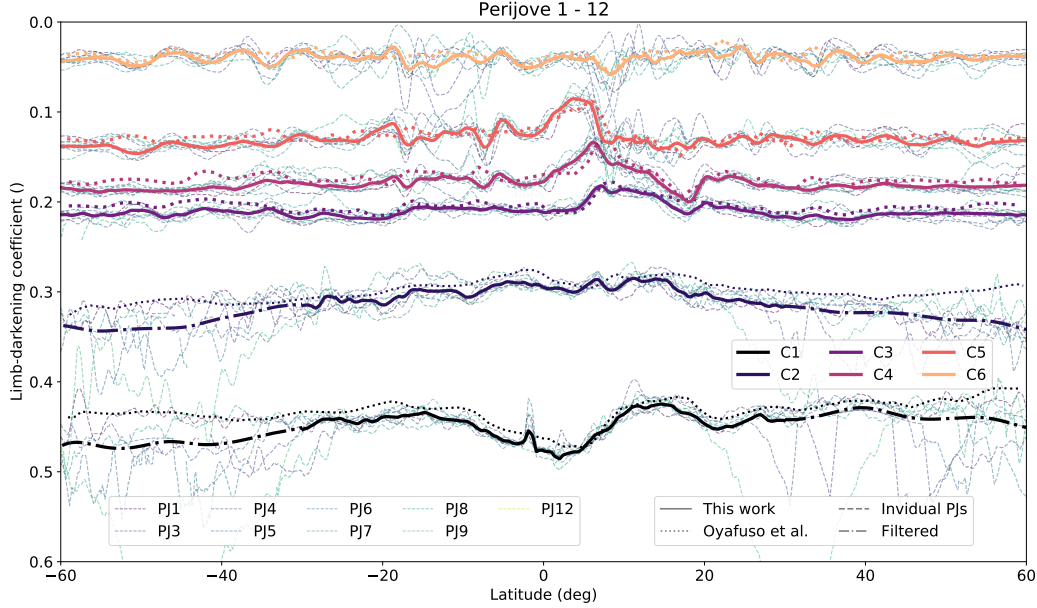


Figure 2.5: Same as Figure 2.4 but for the limb-darkening parameter.

tion with a pre-defined temperature profile for the atmosphere of Jupiter, we can simulate its brightness temperature using a radiative transfer (RT) model, such as that described by e.g., Berge et al. (1976) and de Pater et al. (1985). Such simulated data (see Section 2.4 for the RT code) can then be compared to Juno MWR and VLA observations: by adjusting the abundances and altitude profiles of radio-absorbing trace gases (and/or the temperature profile (Fletcher et al. 2021)), one can find a best fit to the data. In Section 2.5 we focus on the NH_3 abundance, which is the dominant absorber at the frequencies Juno MWR and the VLA are operating (e.g., de Pater 1986). At lower frequencies the presence of water (vapor and cloud particles) starts to have an effect on the observations as well (de Pater et al. 2005). This signal, however, is difficult to interpret and we test the impact of the cloud particles on the retrieval in Section 2.6.

But what is the best way to prescribe the distribution of trace gases? In the past, researchers determined “arbitrary” jumps in the ammonia profile (e.g., de Pater 1986) to find a best fit to their data. de Pater et al. (2001) pointed out that profiles which gave a best fit to the available data did not follow the profile expected from thermo-chemical equilibrium calculations (Weidenschilling et al. 1973; Atreya et al. 1985). Li et al. (2017a) followed a similar route, opting to split the atmosphere in several layers and then use a Markov-Chain Monte-Carlo (MCMC) algorithm to find the stochastic best fit to Juno PJ1 observations. Considering the few Juno observations that we have (i.e., data at 6 frequencies), the problem

is under-constrained, that is, we have more variables to fit than observations constraining them. Additionally, the received radiation is an integrated signal over many layers of the atmosphere, and as such the inversion is not unique. The problem can be further constrained through regularization of the atmosphere, limiting how much the atmosphere can change between pressure levels (Li et al. 2017a), or through the use of thermo-chemical equilibrium models as mentioned above (de Pater et al. 2016; de Pater et al. 2019b). We know from observations of the troposphere on Earth that the atmosphere is more complex than a simple thermo-chemical equilibrium model prescribes. Nevertheless, it adds a-priori information, and we opt to modify the thermo-chemical equilibrium models by introducing factors that quantify the departure from equilibrium in these models.

Model 1: Perturbed thermo-chemical equilibrium model

In the absence of other observations, the simplest description of an atmosphere is a well-mixed atmosphere, where the trace gas abundance² (x_i) is constant with pressure until the saturation pressure, P_{sat} , at temperature T_c for the specific trace gas is reached, at which point the gas starts to condense out to form clouds. We modify the relationship by introducing the relative humidity r_h in Equation 2.13, where a value greater than unity indicates super-saturation, delaying the condensation of cloud particles. On Earth, super-saturation occurs due to a variety of reasons, most commonly the absence of cloud condensation nuclei, or the presence of strong updrafts. Sub-saturation at these levels, corresponding to values less than unity, are most likely a reflection of averaging areas inside the radio beam that are saturated and areas that are not saturated.

$$NH_3(P) = r_h \frac{P_{sat}(T)}{P} \quad (2.13)$$

Below the ammonia ice clouds, the absence (or lack of detection) of hydrogen sulfide (H_2S) gas on Jupiter has been explained by the formation of ammonia hydrosulfide clouds (NH_4SH), where essentially all the H_2S is trapped in the NH_4SH cloud as it combines with the more abundant NH_3 . The onset of cloud formation starts when the product of the two partial pressure controlled by the partial pressure of the two gases, and the reaction rate has been parameterized by Weidenschilling et al. (1973) and Atreya et al. (1985).



The only measurement of sulfur on the planet so far comes from the Galileo probe measurements (Niemann et al. 1996; Wong et al. 2004) in a so-called 5- μm hot spot (i.e., a region devoid of clouds), which showed a solar enrichment of H_2S similar to that of NH_3 . Since our results for the ammonia abundance at high pressures ($\gtrsim 20$ bar) are lower than the estimates from the Galileo experiment (see Figure 2.8), we opt to not use the Galileo probe

²We express trace gases in both parts per million (ppm) and in proto-solar abundances: $\frac{C}{H^2} = 5.9e-4$, $\frac{N}{H^2} = 1.48e-4$, $\frac{S}{H^2} = 2.89e-5$, $\frac{O}{H^2} = 1.07e-3$ (Asplund et al. 2009)

measurement. Instead we retrieve the H₂S abundance indirectly through its effect on the NH₄SH cloud formation, which equally removes NH₃ from the atmosphere. Additionally, we account for uncertainties in the pressure at which the NH₄SH cloud forms by introducing a factor, η_{NH_4SH} , to the equation by (Lewis 1969) that allows the cloud formation to be delayed. At a value of one, the reaction occurs at the predicted pressure, and for values less than one, the clouds form higher up in the atmosphere than predicted by thermo-chemical equilibrium models:

$$\log_{10}(P_{NH_3}P_{H_2S}) = \eta_{NH_4SH}\log_{10}K = \eta_{NH_4SH}(-4715/T + 14.83) \quad (2.15)$$

We did not find a constant ammonia abundance below the NH₄SH cloud layer that could explain both the VLA and Juno observations; therefore, we introduced a parameterization for the region between an assumed deep, globally uniform atmosphere and the NH₄SH cloud layers. Processes such as dynamics (Showman et al. 2005) or microphysics (Guillot et al. 2020a) can locally enrich or deplete the atmosphere, leading to gradients in abundance with pressure. We started with the simplest model by fitting a single mixing parameter between a top and a bottom pressure, and a deep ammonia abundance. The mixing gradient is defined such that a positive gradient constitutes an increase in ammonia with increasing pressure.

$$NH_3(P) = NH_3^{deep} - H_{mix}(\ln(P_b) - \ln(P)) \quad (2.16)$$

$$H_{mix} = \frac{\delta NH_3}{\delta \ln(P)} \quad (2.17)$$

We postulate that at some depth, the atmosphere is well mixed across all latitudes. The most well-suited observations for constraining a global deep abundance come from MWR Channel 1, which probes deepest into the atmosphere (see Figure 2.7). Unfortunately, the inversion of the observations at low frequencies is also the most uncertain, due to scarcity of high pressure and temperature experiments simulating the conditions in the gas giants (Hanley et al. 2009; Bellotti et al. 2016; Bellotti et al. 2017). Different published ammonia absorption coefficients lead to differences as large as many tens of Kelvin for modeled temperature in Channel 1. We therefore opt to reduce the influence of the lowest frequencies, by applying large absolute uncertainties to the Channel 1 measurements, so that we instead rely on the higher frequency channels. Lastly, for the global ammonia abundance maps, we opt to prescribe the deep ammonia abundance and only derive the pressure below which the atmosphere is well mixed. This is in line with our assumption that there exists a deep, well-mixed reservoir of trace gases on the planet.

While H₂S gas on Jupiter does not contribute noticeably to the absorption at radio wavelengths, water has a non-negligible effect on the observations at frequencies below ~ 6 GHz (see, e.g., de Pater et al. 1985; de Pater et al. 2005; Janssen et al. 2005). For the main analysis, we enriched the water abundance by the same solar enrichment factor that we retrieved for the ammonia gas (2.66), and let it condense out at the water condensation point. This is the simplest assumption and is in line with the results for the Equatorial Zone

(EZ) (Li et al. 2020). For this part of the analysis, we included only an indirect effect of the water cloud on the ammonia: about 3% of gaseous ammonia can be absorbed into the liquid water rain drops (Weidenschilling et al. 1973). This effect causes a small local decrease in ammonia at the water cloud level, ~ 6 bar.

Model 2: Stochastic variations between pressure nodes

In addition to the perturbed thermo-chemical equilibrium model, we developed a model similar to the one used by (Li et al. 2017a), that fits gradients between pressure levels. Moving up from 100 bar we introduce pressure nodes between which we assume an exponential gradient that mimic processes locally enriching or depleting the atmosphere in trace gases. We set the pressure nodes to 40, 20, 15, 10, 6, 4, 2 and 1 bar above which the atmosphere follows the saturation-vapor pressure curve as defined in Equation 2.13. Since the problem is underconstrained we introduce a 'lasso'-regularization constraint (Tibshirani 1996) that aims at smoothing the vertical variations, penalizing large gradients between pressure nodes (see Equation 2.20).

2.4 Radiative Transfer Model

We use our open-source radiative transfer model radioBEAR (Radio BErkeley Atmospheric Radiative-transfer³) to simulate the brightness temperature for a given distribution of trace gases and a prescribed temperature structure in the atmosphere by splitting the atmosphere into multiple layers and calculating the contribution from each individual layer. This model has been described by de Pater et al. (2005), de Pater et al. (2014), and de Pater et al. (2019b). The opacities for ammonia and water were derived from lab experiments that simulate the high-pressure environment for a given hydrogen-helium atmosphere by (Devaraj et al. 2014; Hanley et al. 2009; Bellotti et al. 2016; Bellotti et al. 2017). For the Channel 1 frequency, the (Bellotti et al. 2016; Bellotti et al. 2017) modeled brightness temperatures were too high and not reconcilable with the Juno observations, so that we favored the earlier lab measurements as did Li et al. (2017a).

Temperature Structure

The temperature structure in the atmosphere is a crucial element for the retrieval, since both trace gas and temperature variations can alter the observed brightness temperature, and we can only observe the combined effect. While observers have used mid-infrared wavelengths to derive the temperature at pressures $P \lesssim 0.7$ bar (Fletcher et al. 2009), the temperature structure below the radiative-convective boundary cannot be obtained with these techniques.

The temperature at the depth where radio waves originate are controlled by atmospheric dynamics, microphysics, and wave patterns in the atmosphere, and to date, there are very

³<https://github.com/david-deboer/radiobear>

few temperature measurements below the radiative-convective boundary (~ 0.5 bar). The first measurements come from the Voyager flyby, which used radio-occultation measurements to probe the temperature structure down to the 1 bar level on ingress and egress to measure the temperature of the North Equatorial Belt (NEB, 165 ± 5 K) and the Equatorial Zone (EZ, 170.4 ± 5 K), respectively (Lindal et al. 1981; Guillot et al. 2004). The latent heat release of condensation in the EZ decreases the temperature gradient in the atmosphere, leading to higher temperatures at the same pressure levels compared to an atmosphere that follows a dry adiabat. Hence, the observed temperatures in the EZ and NEB are consistent with a local enrichment of trace gases in the EZ compared to the NEB. The only true in-situ measurements come from the Galileo probe experiment, which entered a highly trace-gas depleted region of the atmosphere, somewhat similar to the conditions found in the NEB, and measured a temperature structure resembling a dry adiabat down to 20 bars.

We have built two temperature profiles—a wet and a dry adiabat—that are anchored to the Voyager and Galileo measurements (Figure 2.6). Starting from deep within the planet, the absence of condensible species implies that the temperature follows a dry adiabat:

$$\Gamma_d = \frac{dT}{dz} = \frac{g}{\sum_i \frac{C_{p,i}}{x_i}} \quad (2.18)$$

The heat capacity C_p of an parcel of air is the sum of the heat capacities of the individual atmospheric species weighted by their mixing ratio (see de Pater et al. (1985)). We updated the heat capacity for normal, para- and ortho-hydrogen based on the formalism of Leachman et al. (2009) that is accurate to within 0.1% compared to experimental results until 1000K, corresponding to about 400bar. For the gravity, we take the gravity coefficients up until J_4 into account to model the gravity as a function of latitude and depth (Iess et al. 2018). The profile follows the dry adiabat until the water condensation level is reached, at which point the two temperature profiles start to diverge. While the dry adiabat reaches 166.1 K at the 1 bar level (Galileo anchor point (Seiff et al. 1996)), the latent heat from water decreases the temperature gradient for the wet adiabat, so that in the EZ a temperature of 170.4 K is reached at the 1 bar level. Higher up in the atmosphere ($P \lesssim 0.7$ bar), we use profiles obtained from the mid-infrared (Fletcher et al. 2009) and merge the two temperature profiles to cover the full depth which radio waves probe. In the radiative zone the profiles reverse, that is, the NEB becomes warmer than the EZ as shown by the dotted lines in Figure 2.6.

For our global ammonia maps we prescribe a dry adiabat, however, we test the impact of a wet adiabat on the vertical ammonia distribution in Section 2.6.

Weighting functions

Thermal emission captured at radio wavelengths originates over a range of atmospheric pressures, and the final signal is the integrated emission over these layers. The weighting functions illustrate this effect numerically, by showing the depth of and range from where we receive the emission. We plot the weighting functions in Figure 2.7 for the EZ and the

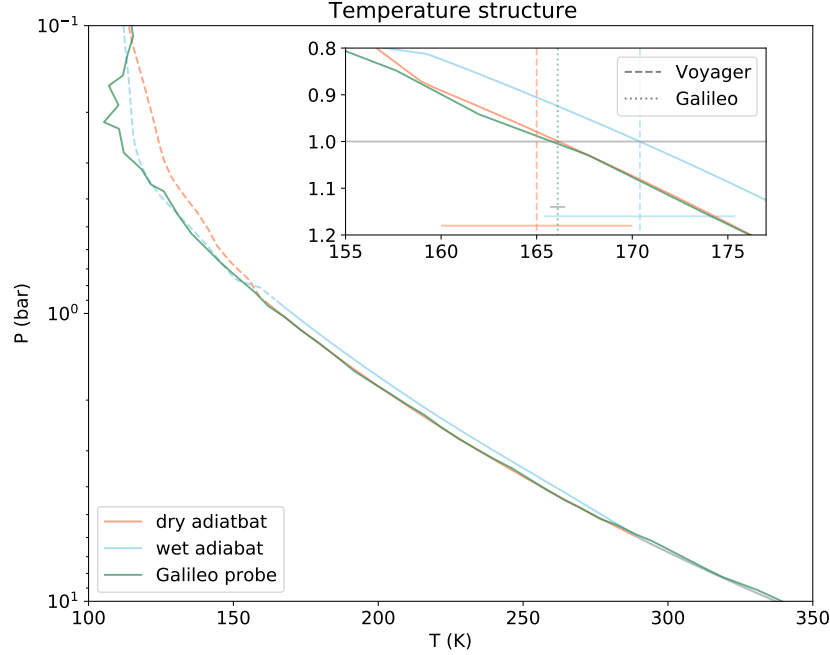


Figure 2.6: Compilation of the relevant temperature profiles which we assume for our retrieval. The temperature profiles are anchored at the 1 bar level to the radio occultation measurements of Voyager (Lindal et al. 1981) and to the Galileo probe measurements (Seiff et al. 1996). Above the 0.7 bar level we use profiles obtained via infrared measurements (Fletcher et al. 2009). Below the 1.0 bar level we use the expected wet and dry adiabatic lapse rate until the two profiles merge at the height of the water cloud. The little cutout shows the anchor points at the 1 bar level, with the corresponding uncertainties.

NEB, exemplifying the end members in terms of ammonia gas distribution covering the most enriched and most depleted region of the planet. At lower frequencies, the radio waves originate over a wide range of pressures going down to a few hundred bars, while at higher frequencies the weighting functions become more peaked, indicating that they probe a smaller pressure range. The center of the absorption feature is at 22 GHz, so that observations at this frequency probe highest in the atmosphere, while observations both at higher and lower frequencies probe deeper into the atmosphere. Lastly, the depletion of trace gases in the NEB allows for probing deeper into the atmosphere, enabling retrieval of ammonia abundances at higher pressures.

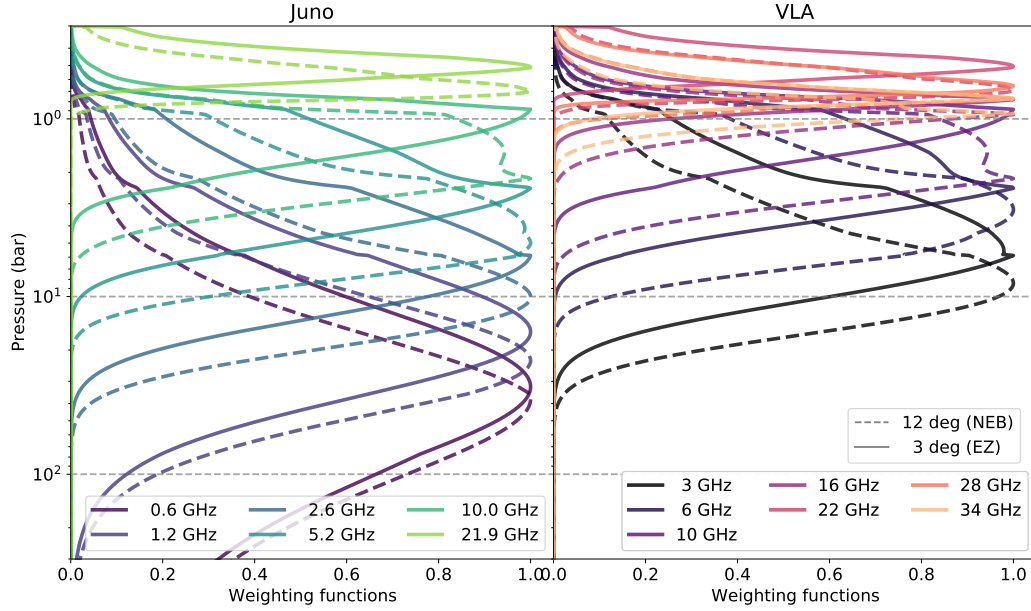


Figure 2.7: Weighting functions visualize the pressure levels from which radiation is received. We plot the functions for both end members on the planet, a highly enriched part in the atmosphere (solid line corresponding to the EZ), and a highly depleted part (dashed line corresponding to the NEB) showing the depth and range from which we receive the signal. The abundance profile for which we compute the weighting functions are taken from our fit to the orbit-averaged MWR data (see Figure 2.9). The left hand side shows the relevant functions for the Juno spacecraft, and the right hand side shows the function for the VLA.

Optimization

For a given distribution of trace gases, we can simulate the brightness temperature and the limb-darkening coefficient; these modeled parameters are referred to as T_m and p_m . By matching our simulated atmosphere to the observations, we retrieve the best-fit distribution of ammonia gas. We opted to retrieve the distribution per 1-deg bins, independent of neighboring latitudes, for a robust retrieval. We first determined the optimum using the scipy⁴ Nelder-Mead optimizer to find an atmospheric composition that minimized the difference between the model (T_m, p_m) and the observations (T_{b0}, p), weighted by the uncertainties ($\sigma_{T_{b0}}, \sigma_p$) as shown in Equation 4.1. It is here that the choice of 'n' for the uncertainties has a largest impact on where the optimal solution is, as the cost function is modulated by the uncertainties. The uncertainties are essential for combining the various observational

⁴<https://www.scipy.org/>

quantities and weighing them appropriately.

$$C_{Model1} = \sum_1^6 \frac{(T_m - T_{b0})^2}{\sigma_{T_{b0}}^2} + \sum_2^5 \frac{(p_m - p)^2}{\sigma_p^2} \quad (2.19)$$

For our stochastic model we include a regularization function that penalizes large gradients ($\frac{\delta NH_3}{\delta P}$) between pressure nodes. We chose $\lambda = 1E4^5$ with which the penalty is much smaller in magnitude than a typical cost function result, to avoid interferences with the retrieval.

$$C_{Model2} = C_{Model1} + \lambda \left| \sum \frac{\delta NH_3}{\delta \ln(P)_i} \right| \quad (2.20)$$

We only use the limb-darkening information from Channel 2 to Channel 5. We discarded Channel 1 limb-darkening measurements as we cannot match the opacity of Channel 1 with only ammonia. Other absorbers such as water (de Pater et al. 2005, (both vapor and droplets)) and alkalis (Bellotti 2018) are known to add opacity at these low frequencies. We also discarded Channel 6 because it is very insensitive to our variations in the ammonia abundance and mostly driven by spatial variations (see the VLA maps published in de Pater et al. (2016) and de Pater et al. (2019b)). This established a combination of parameters that minimize the difference, but does not indicate the range of possible solutions within the constraint. We therefore coupled our retrieval with a Markov-Chain Monte-Carlo (MCMC) (Foreman-Mackey et al. 2013) for the set of parameters x to find the uncertainties in the fit parameters and the correlations between the parameters. The MCMC maximizes the log-likelihood function $\ln p$:

$$\ln p(T, p | x, \sigma) = -0.5 \left(\sum_1^6 \ln(2\pi\sigma_T) + \frac{(T_m - T_b)^2}{\sigma_T^2} + \sum_2^5 \ln(2\pi\sigma_p) \frac{(p_m - p)^2}{\sigma_p^2} \right) \quad (2.21)$$

2.5 Results

In this section we present our best-fit ammonia distribution for the average of the first 12 orbits when MWR was able to observe the atmosphere (see Table 2.2) and compare our results for the first PJ to the inversion by Li et al. (2017a).

Well-mixed reservoir

The first quantity we constrain is the amount of ammonia in the region that is globally well-mixed. Based on Figure 2.7, we can see that even at the lowest frequency observations of Juno, the signal from depths over 50 bar is poorly constrained, due to the wide range of pressures the signal originates from. There are four observed quantities from the

⁵The mixing gradient in this paper is always converted to parts per million for ease of understanding

orbit-averaged quantities that constrain the deep ammonia abundance: the brightness temperatures of Channel 1 to Channel 3, and the limb-darkening coefficient of Channel 2. Since our model cannot find an ammonia distribution that fits all four quantities, we instead search for a solution that minimizes the overall error. The key parameter we vary is the factor n for the fit uncertainties ($T_b \pm n * \sigma_T^{fit}$, $p \pm n * \sigma_p^{fit}$) and we test the sensitivity of our solution to the chosen fidelity factor n . As a reminder, a value of 1 corresponds to the 1-sigma results when fitting the nadir brightness temperature and limb-darkening (Equation 2.11). We consider four different combinations:

- 1- σ : This option uses the mean error in the **fit uncertainty** based on the nine limb-darkening profiles. This combination maximizes the fit to the limb-darkening coefficient of Channel 2, at the cost of fitting the brightness temperature in Channel 1 and Channel 2. We interpret this number as a lower limit to the deep abundance.
- 3- σ : This combination compromises the fit between all quantities, and we use this for the final result.
- 5- σ : Similar to 3- σ , where the limb-darkening coefficient still influences the retrieval.
- 10- σ : With these large uncertainties, the brightness temperature is the main quantity driving the retrieval. While the limb-darkening uncertainty changes by a factor of 10, the total uncertainty in the temperature changes by less than 2% due to the large calibration errors. This retrieval we interpret as an upper limit to the retrieved ammonia abundance.

For our final results, we first fit the ammonia abundance between -45 and 45 degrees independently at 1 deg steps, and then average the result over the chosen latitude range. We adopt the value at 100 bar as the deep NH_3 abundance. We compile previous results for the averaged deep ammonia abundance as a function of pressure in Figure 2.8 where the red line corresponds to the thermo-chemical equilibrium model (Model 1) and blue line to the stochastic model (Model 2), while the shading indicates the sensitivity of the retrieved results to the uncertainties in the retrieval. The 3- σ profile for Model 1 converges at $340.5^{+34.8}_{-21.2}$ ppm, where the uncertainties correspond to the 1- σ and 10- σ profiles. The final value corresponds to an enhancement over solar of $2.66^{+0.27}_{-0.17}$. We can see that our results confirm the results from the preliminary inversion of the temperature only measurement of PJ 1 (Li et al. 2017a) (362^{+33}_{-33} , $2.45^{+0.22}_{-0.22}$) and are less than Galileo results (Wong et al. 2004) and the VLA results (de Pater et al. 2019b), which are based on the Galileo results and are very insensitive to ammonia at these depths.

Orbit mean

With the deep ammonia constrained to a constant global value, we can turn our attention to obtaining a profile averaged over Juno's primary mission by fitting parameters to the

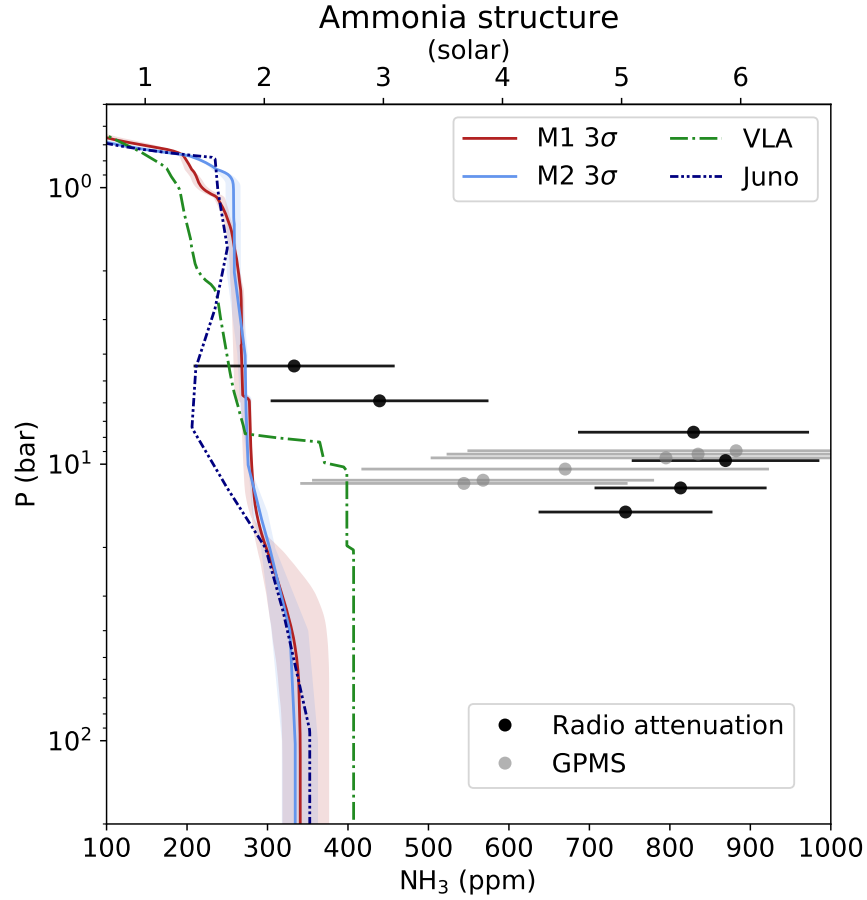


Figure 2.8: Globally averaged $[-45^\circ, 45^\circ]$ ammonia profile as a function of depth. The red profiles corresponds to our thermo-chemical equilibrium model, and the blue line corresponds to our stochastic model with the shading corresponding to $n = 1, 10$. The blue dashed curve is based on the results of Li et al. (2017a), and the green curve is based on the VLA data from de Pater et al. (2019b). The radio attenuation (Folkner et al. 1998) and Galileo Probe Mass Spectrometer (GPMS) (Wong et al. 2004) are superimposed.

average of the first two years of the mission between -60° and 60° (Table 2.2). Poleward of 60 degrees the spacecraft's larger distance from the planet reduces the resolution and increases contamination from the sidelobes, reducing the reliability of the data inversion. The nine orbits are widely separated in longitude reflecting a global latitudinal structure, but we caution that the observations were taken over the course of a year, during which time the atmosphere underwent some large scale changes, such as the storm outbreak between the North Temperate Belt (NTB) and the North Tropical Zone (NTrZ) (Sánchez-Lavega et al. 2017), and the outbreak in the South Equatorial Belt (SEB) (e.g., de Pater et al. 2019a). In Figure 2.9 we compare the average atmosphere based on the $3\text{-}\sigma$ option to the results obtained from the VLA, which were taken between Dec. 2013 and Dec. 2014 (de Pater et al. 2016; de Pater et al. 2019b). The VLA results are based on the brightness temperature at 21 different frequencies between 3 and 25 GHz, i.e., at a frequency resolution of 1 GHz; these data are sensitive to pressures $\lesssim 8\text{--}10$ bar (and down to ~ 20 bar in the NEB). In contrast, the Juno observations cover a much wider frequency range, from 0.6 to 22 GHz, at 6 distinct frequencies (Table 2), probing down to 100's of bars (see Figure 2.7). Although these data have a lower frequency resolution, there is further information in the Juno data by adding a second quantity to fit models: the variation of the limb-darkening coefficient with latitude. The Juno observations agree with the overall structure of the planet that the VLA has seen at $P \lesssim 8$ bar, that is a depleted atmosphere above a well mixed region, while extending this analysis to greater depth. The overall structure is characterized by alternating columns of enriched and depleted ammonia gas. The equatorial zone is highly enriched in ammonia, corresponding to the cold radio-temperatures around the equator. The Juno observations add fine scale structure, such as the increase of ammonia with altitude in the EZ at $P \lesssim 50$ bar, the only location on the planet with such peculiar structure (see also the yellow lines in Figure 2.10). We can also observe the expansion of the equatorial column into the NEB at pressures between 2 and 20 bars. The ammonia abundance in the EZ peaks high up in the troposphere and is enhanced over the deep ammonia abundance. This feature ('ammonia enhancement factor') was instrumental to derive the water abundance in the EZ based on Channel 2 - 6 observations by (Li et al. 2020). The largest depletion of ammonia on the planet is in the adjacent NEB, where we fit a depletion of trace gases down to several tens of bars, quite similar to that derived from the VLA data, though slightly shifted northwards in latitude at larger pressures. At pressures of 40 bars, the depletion tapers off to the deep ammonia abundance. At higher latitudes the variation in brightness temperature with latitude becomes smaller resulting in a more homogeneous atmosphere, with most changes seen in the upper few bars, similar to the VLA results (e.g., de Pater et al. 2016).

We assess the goodness of our fit by computing the brightness temperature and limb-darkening coefficient for the given ammonia distribution in Figure 2.9. Next to the best-fit results that is the basis for our interpretation (i.e., the $3\text{-}\sigma$ option), we also show the sensitivity of the our retrieved atmosphere for the other combinations of uncertainty ($n=1$ and $n=10$) in Figures 2.11 and 2.12 through the use of shading. The width of the shading for Channel3 - Channel 6 is very small which indicates that the uncertainty matters little for the higher frequencies in fitting the observations, and our best-fit distribution can explain the

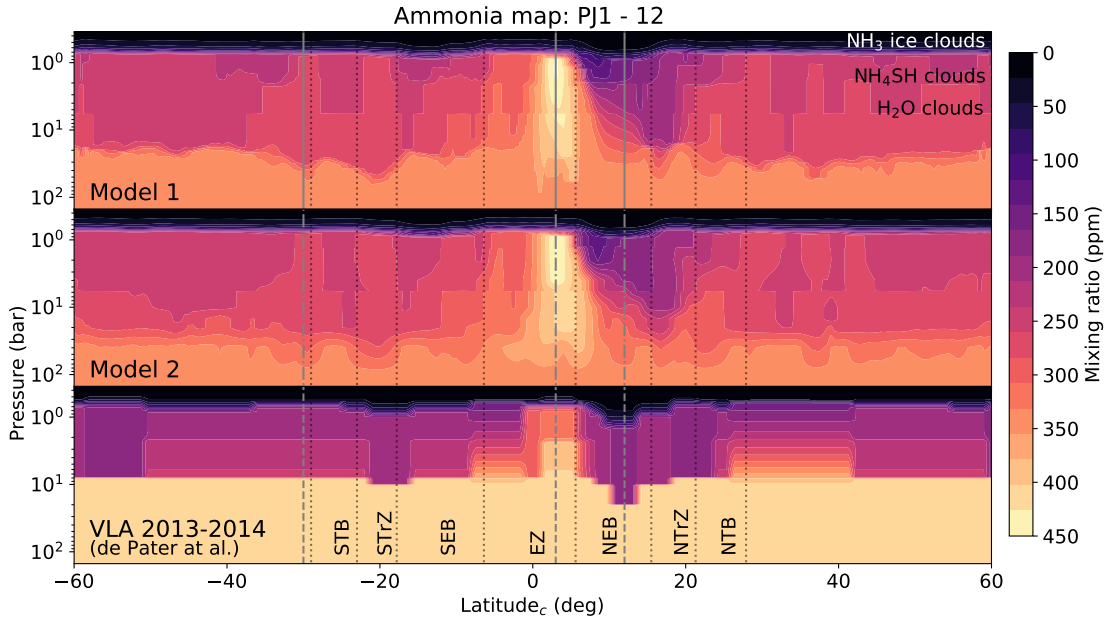


Figure 2.9: Ammonia abundance map based on Juno’s orbit average brightness temperature and limb-darkening with a $3\text{-}\sigma$ fit uncertainty level. The map shows familiar features such as the column of enriched ammonia in the EZ and the depletion of ammonia in NEB, with smaller scale features at the mid-latitudes. Plotted on the same color scale is the original VLA map based on observations between 2013 and 2014 (de Pater et al. 2016; de Pater et al. 2019b). The overall structure is very similar between the two maps, with the Juno data allowing to resolve more structure at depth and the transitions in the atmosphere due to its low frequency observations. The dotted lines indicate the latitude at which the zonal wind speed peaks, and with that denotes the difference between the zones and belts. The vertical gray lines correspond to locations of the atmospheric cross sections in Figure 2.10.

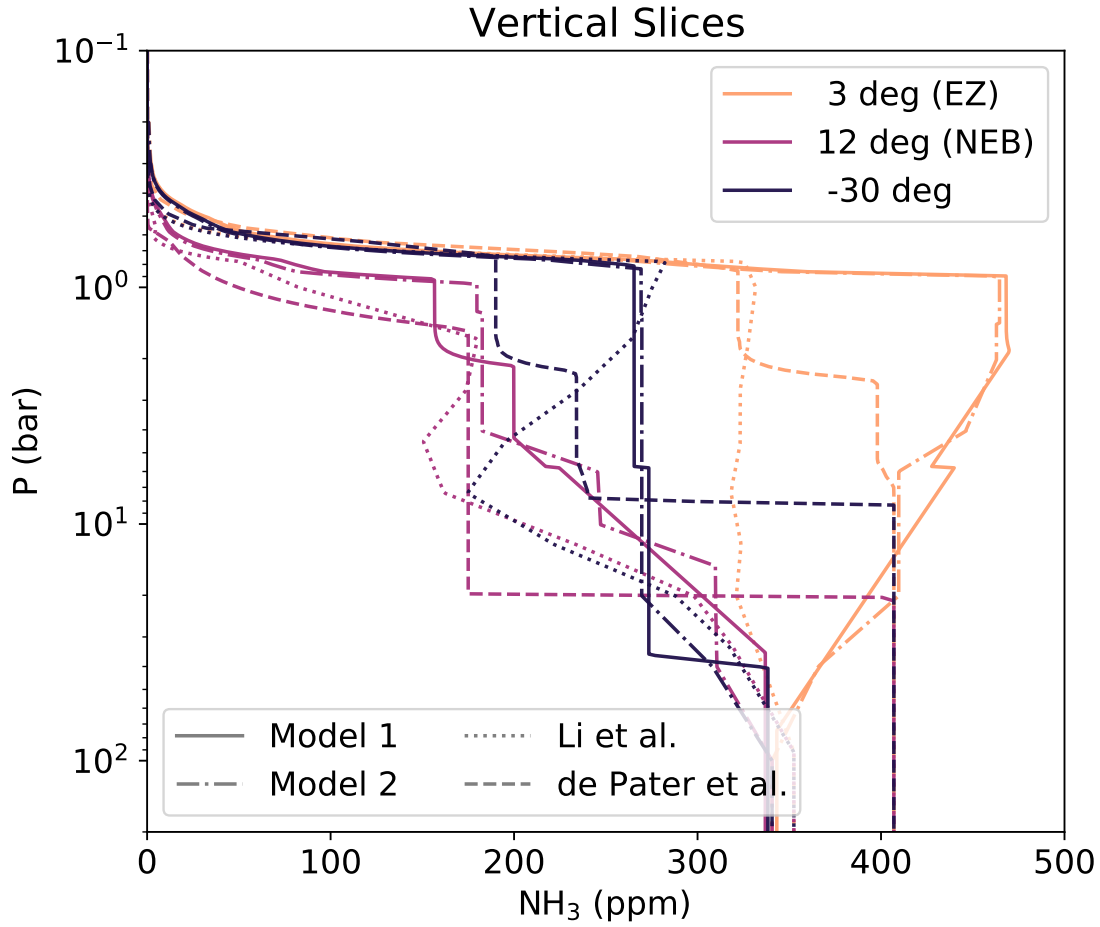


Figure 2.10: Comparison of the atmospheric structure at the locations indicated in Figure 2.9. The two models developed for this work agree well on the overall structure of the atmosphere despite different modeling frameworks. The biggest difference in the ammonia distribution between our results and VLA results (dashed lines) (de Pater et al. 2016; de Pater et al. 2019b) is that we add more information about the fine-scale vertical structure. Compared to the PJ1 results (Li et al. 2017a), we find no strong evidence for the inversion at midlatitudes.

observed brightness distribution within the Juno MWR uncertainties. The biggest impact of our confidence in the uncertainties appears in Channel 2, where the various combinations trend to a more depleted deep atmosphere ($n=1$, $1-\sigma$) or a more enriched deep atmosphere ($n=10$, $10-\sigma$), reflected by the increased width of the shading. The brightness temperature fit in Channel 2 is anti-correlated with the limb-darkening fit in Channel 2. The temperature fits best when using a large scaling factor n (such as 10) for the fit uncertainty, in which case the brightness temperature drives the retrieval. A scaling factor of $n=1$, on the other hand, means we fit the limb-darkening at the cost of brightness temperature. We also show the brightness temperature (green line) for the distribution determined by the VLA (de Pater et al. 2019b). We can see that the VLA observations, while not being in perfect agreement reflect the overall structure of the atmosphere pretty well. The VLA model (based on the lower end of the Galileo Probe data (Wong et al. 2004)) is generally too cold for Channel 1 to Channel 3, due to its lack of sensitivity to radiation from the deeper layers in the planet (see Figure 2.7).

While latitudinal structure in the limb-darkening coefficient is more chaotic, we still manage to fit the overall structure of the planet to first degree. The large features around the equator and the neighboring belt are mostly captured by the fit, only the smaller diversion at higher latitudes tend to not be captured well by our fit. This figure shows the additional value of the limb-darkening coefficient in constraining the atmosphere. While the brightness temperature for the VLA distribution was comparable to the Juno observations (Figure 2.11), the limb-darkening coefficient for Channels 2 and 3 does not match, and indicates that the atmosphere is well-mixed at altitudes much deeper than the 10 bar level that was inferred from the VLA data. Higher up in the atmosphere the VLA observations agree well with the Juno observations; near the ammonia ice cloud, the VLA shows larger latitudinal variations than the Juno data, which likely results from the higher frequency resolution. While we do not fit Channel 1, it is still interesting to see that all models produce similar results, with much larger coefficients than observed.

Perijove 1

We now turn our focus to compare our model to results published by Li et al. (2017a, between 40°S and 40°N). Figure 2.13 shows our map ($3-\sigma^{fit}$) for PJ 1 together with the results from Li et al. (2017a); the latter were based solely on the brightness temperature (Li et al. 2017a). We can reproduce the enhancement of ammonia at the equator and the depletion in the North Equatorial Belt. The Li et al. (2017a) map shows that latitudinal variations are constrained to the top few bars of the atmosphere, above an ammonia inversion, i.e., minimum in the ammonia abundance at all latitudes, with a well-mixed deeper layer. In contrast, our model converges to a solution that monotonically increases the ammonia abundance with increasing pressure. The depth that we can trace this variation to, however, is deeper than the Li et al. (2017a) results.

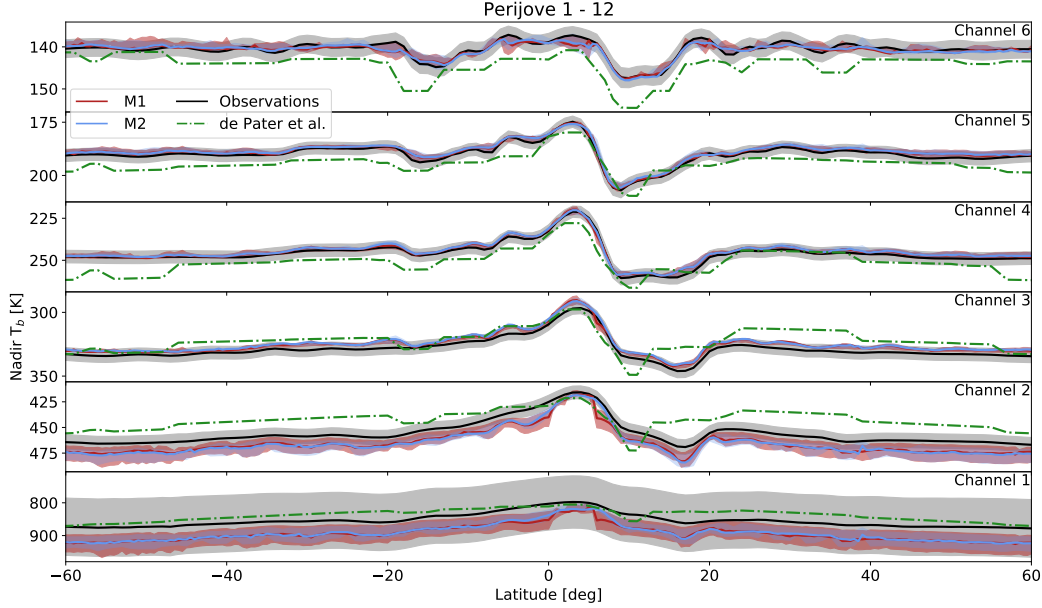


Figure 2.11: Forward modeling results based on the best fit distribution of ammonia trace gases compared to the Juno observations, plotted against latitude. The Juno nadir brightness temperatures are the solid black lines and with their uncertainties represented by the shading. The red and blue lines correspond to temperatures based on the ammonia distributions as shown in Figure 2.9. The shading of the red and blue lines indicates the sensitivity of the results to the uncertainties ($n=1,10$). The green line is the forward model based on the VLA data (de Pater et al. 2019b). Overall, our forward models fit the brightness temperature well within the uncertainties.

In Figures 2.14 and 2.15 we forward model the ammonia distribution in PJ1 using our radiative transfer code and compare it to the observations for PJ1 (our models: blue and red solid lines; Li et al. (2017a): blue dash-dotted line). The four highest frequencies corresponding to the upper layers of the atmosphere are well fit within the uncertainties, and our results in all channels match the data better than the results in Li et al. (2017a). This highlights how degenerate inversions based on radio observations can be, where quite different ammonia profiles can approximate the observations well.

Combined VLA 2013-2014 and Juno PJ1-12 results

With the updated deep ammonia abundance based on the Juno data, we can now add further observational constraints using the longitudinally averaged profiles of the VLA data taken ~ 2

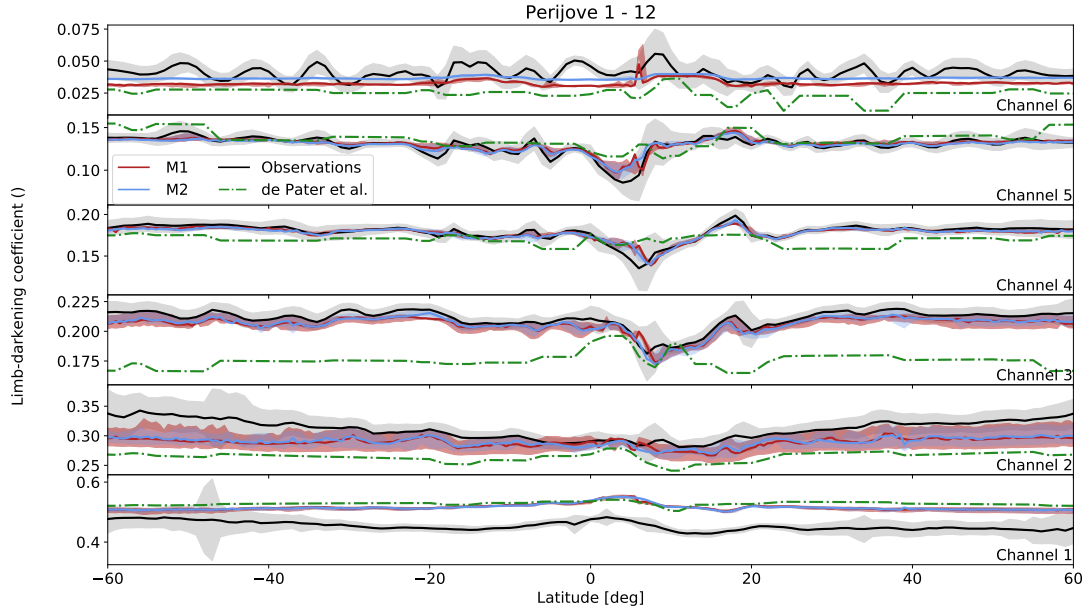


Figure 2.12: Same as Figure 2.11 but for the limb-darkening coefficient. While we can fit the overall structure of the atmosphere within the uncertainties, the solutions for Channel 2 all result in less limb-darkening compared to the observations. The solution closest to the observations (upper end of the shaded area) corresponds to the retrieval that creates a larger mismatch for the brightness temperature. The results that best fit the brightness temperature ($10\text{-}\sigma$) have the largest misfit for the Channel 2 limb-darkening, and the $1\text{-}\sigma$ results fit the limb-darkening best.

years prior to the Juno orbit insertion (de Pater et al. 2016; de Pater et al. 2019b). Figure 2.16 shows our ammonia abundance results, as retrieved from the combined VLA/Juno frequency coverage. Due to the different viewing directions of Juno (nadir) and the VLA (looking from Earth) we chose not to convert the VLA observation into nadir viewing, **which would require assumptions about the limb-darkening**. Instead, we model the atmosphere as seen from Earth, that is zonally averaged latitude slices between 3 and 24 GHz separated by 1GHz where the emission angle is determined by the observing geometry (see also (de Pater et al. 2019a; de Pater et al. 2019b)). This adds further constraints on the atmosphere down to ~ 10 bar level, at deeper levels Juno Channel 1 to Channel 3 observations constrain the ammonia distribution. Both our models converge to a solution that shows an atmosphere that is depleted in trace gases down to $\sim 20\text{-}30$ bar, above which the atmosphere shows variations between zone-belt variation on the order of 50 ppm. The bottom panel of Figure 2.16 shows an atmosphere where we include the effects of scattering and absorption by cloud

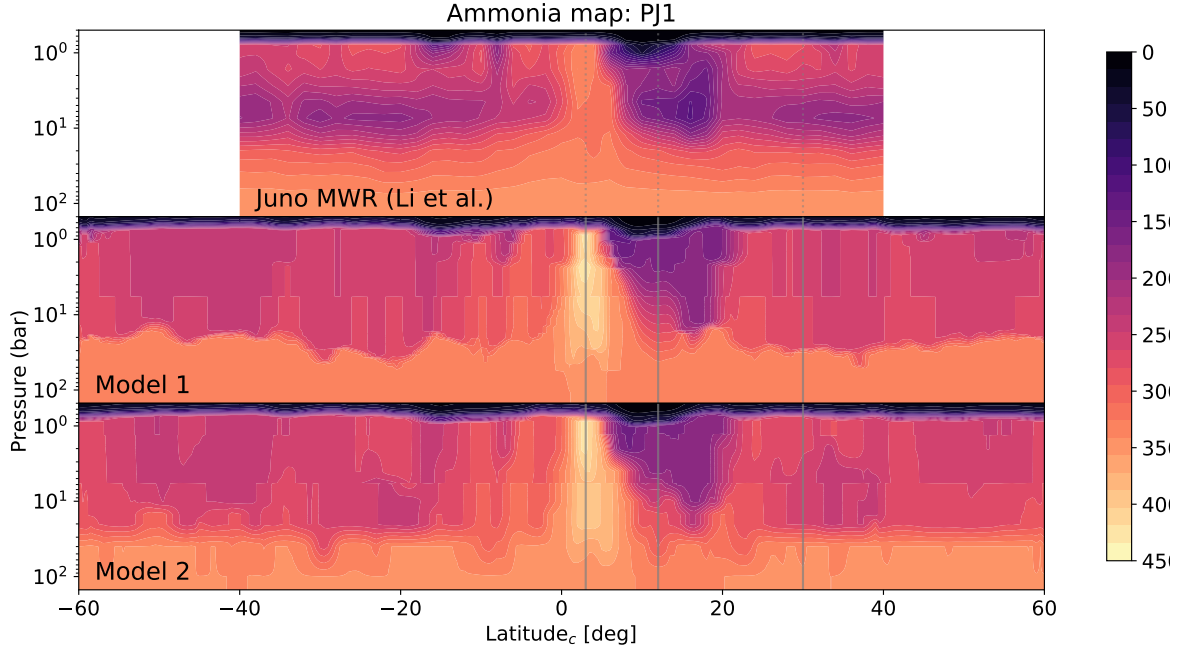


Figure 2.13: Comparison of ammonia abundance map for PJ1, based on the preliminary retrieval (Li et al. 2017a) and the best-fit model in this paper. The overall structure looks very similar, with the biggest difference that we do not find evidence for the ammonia inversion centered around 6 bars in the earlier retrieval as obtained by Li et al. (2017a).

particles in the radiative transfer model based on parameterization by de Pater et al. (1985) and de Pater et al. (2005). There are many unknowns regarding the clouds including the cloud particle density, the imaginary index of refraction and their vertical distribution. Our cloud parameterization represents the end member case by assuming large values for the cloud density. The goal is to show that the overall structure of the atmosphere does not change dramatically, rather it modifies the small scale structure. Most notably, it removes ammonia higher up in the atmosphere since cloud particles provide extra absorption. The largest effect is visible in the equatorial zone, where ammonia does not increase substantially as compared to the upper two panels which ignore cloud opacity. We model the impact of clouds on the equatorial structure in some more detail in Section 2.6.

2.6 Discussion

In this section we first discuss the uncertainties in the retrieved atmosphere by showing results of MCMC fits to only the Juno MWR observations, and then we focus on the dynamics of

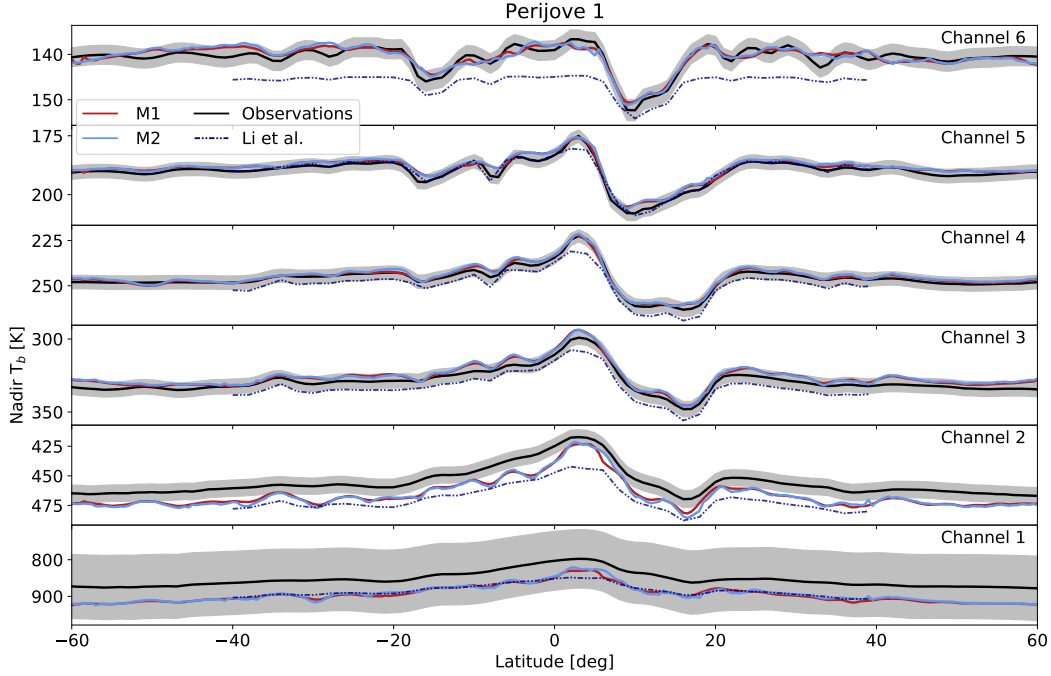


Figure 2.14: Same as Figure 2.11 but for the PJ1 observations. The MWR brightness temperature observations are given by the solid lines, their uncertainty is given by the shaded region. The red and blue solid lines are the brightness temperatures for the abundances as plotted in Figure 2.13. The dash-dotted line corresponds to the forward modeling results based on the ammonia distribution as published by Li et al. (2017a). We note that while model the structure of the atmosphere differently, both models are close to the uncertainty.

the atmosphere based on the retrieved parameters and what inferences we can make from the radio data. Two particularly interesting features emerge in Jupiter’s atmosphere: the inversion in the equatorial zone, and the structure at mid-latitudes where Li et al. (2017a) found an inversion at ~ 6 bar. These features are studied in more detail in Section 2.6 by combining the Juno and VLA data.

Uncertainties for dynamical tracers

In order to assess the uncertainties in our results, we performed a MCMC retrieval based on just the Juno data on selected slices of the atmosphere in the EZ and NEB. MCMC results add two more layers of information: uncertainties in and potential correlations between parameters. In Figure 2.17 we overplot our results from the MCMC result onto the optimizer

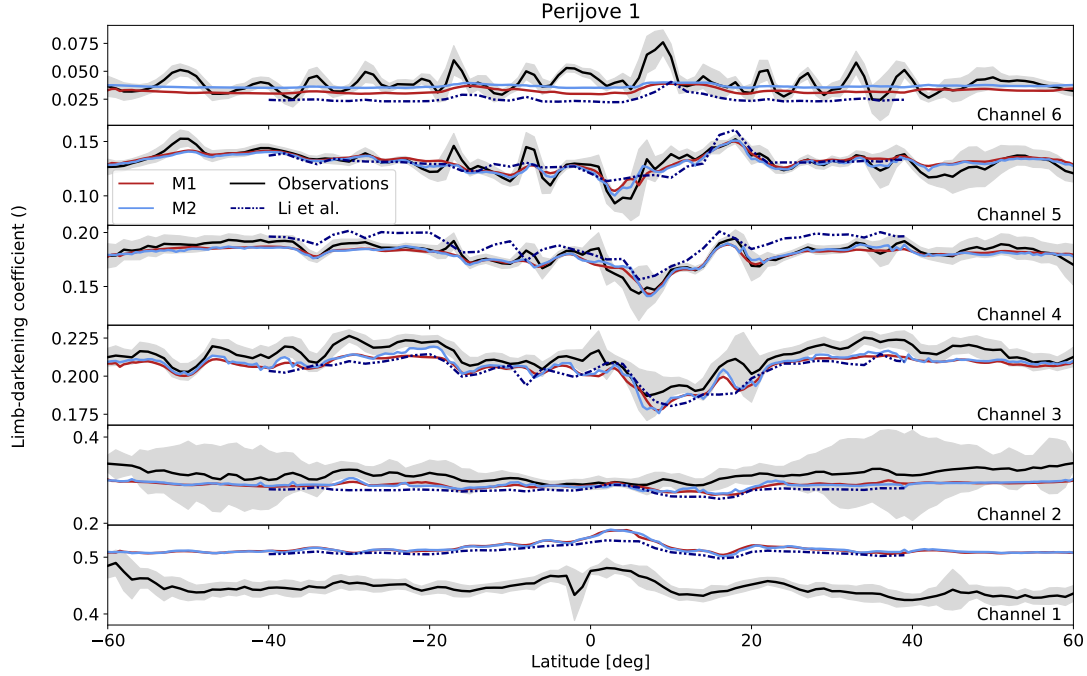


Figure 2.15: Same as Figure 2.14 but for the limb-darkening coefficient.

results as shown in Figure 2.10, where the spread between the various MCMC draws shows the confidence in the optimizer solution. The left panel shows the variations for our therm-chemical equilibrium approach, while the right panel shows the results for the stochastic model. Despite variations on the order of 50 ppm between the MCMC draws, the overall structure is reproduced in the MCMC results indicating that the optimizer results are well-constrained by the observations and representative. Both models indicate an increase of ammonia abundance with altitude in the equatorial zone.

The diagonal elements of the corner plots in Figures 2.18 and 2.19 show the distribution of solutions for the given parameters with the error bars corresponding to the mean, and the 0.16 and 0.84 quantiles. The off-diagonal elements indicate the correlation between parameters. Starting at the top of the atmosphere, we can see that the relative humidity in the ammonia ice cloud is well constrained. We find a high relative humidity in the EZ, and low humidity in the NEB, which is in line with the thick white cloud deck seen at visible wavelengths around the equator and the lack of the white ammonia clouds in the NEB. Such differences in relative humidity were first suggested by Klein et al. (1978), and later verified from VLA observations (e.g., de Pater 1986; de Pater et al. 2016; de Pater et al. 2019b).

Sitting below the ammonia clouds is the postulated NH_4SH cloud, that forms around

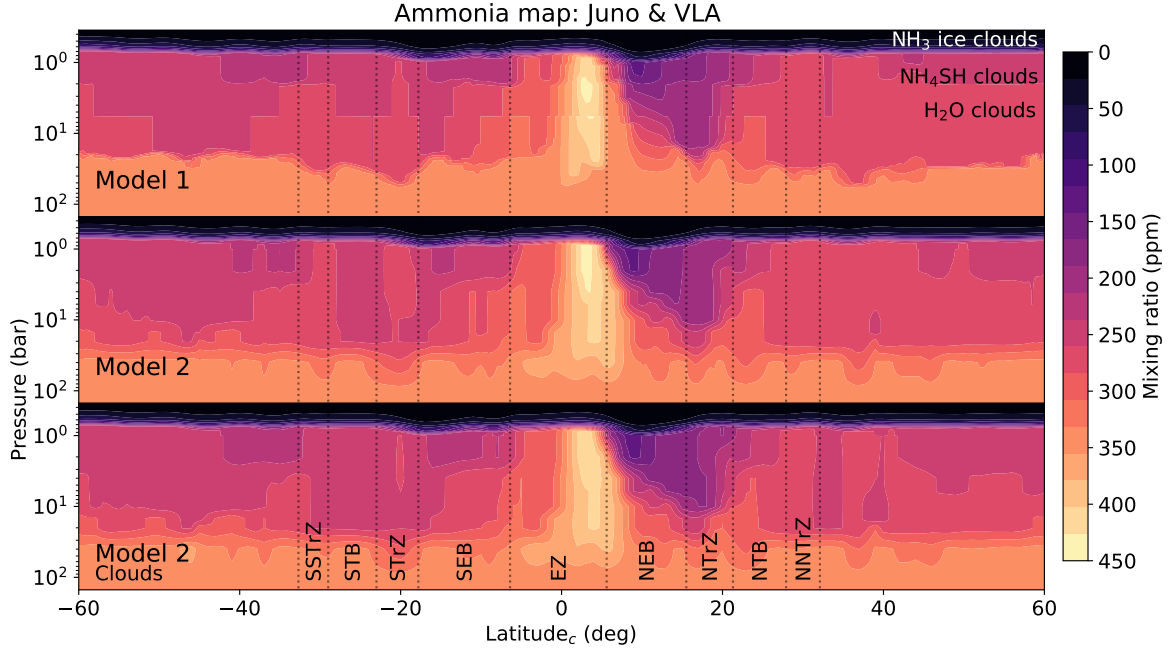


Figure 2.16: Ammonia distribution based on the combined Juno and VLA observations. The top panel shows the distribution based on the thermo-chemical equilibrium model, the middle panel is based on the stochastic model, while the lower panel shows the effect of clouds onto the radio spectrum.

2-3 bar. From our retrievals we find that both the pressure at which the clouds forms and the amount of H_2S in the atmosphere is poorly constrained. This is mostly due to the fact that we have limited coverage at the pressures where the clouds supposedly form due to the wide spacing of the MWR frequencies.

We define the region where mixing occurs by three parameters (see Equation 2.17): the gradient (H_{mix}) between a bottom pressure (P_b) and a top pressure (P_t). The standing column of ammonia around the EZ leads to poor constraints on the mixing region, however all solutions in the MCMC run support an increase of ammonia with altitude (see more in Section 2.6). In contrast, the mixing range in the NEB occurs deeper in the planet, and both P_t and H_{mix} are much better constrained.

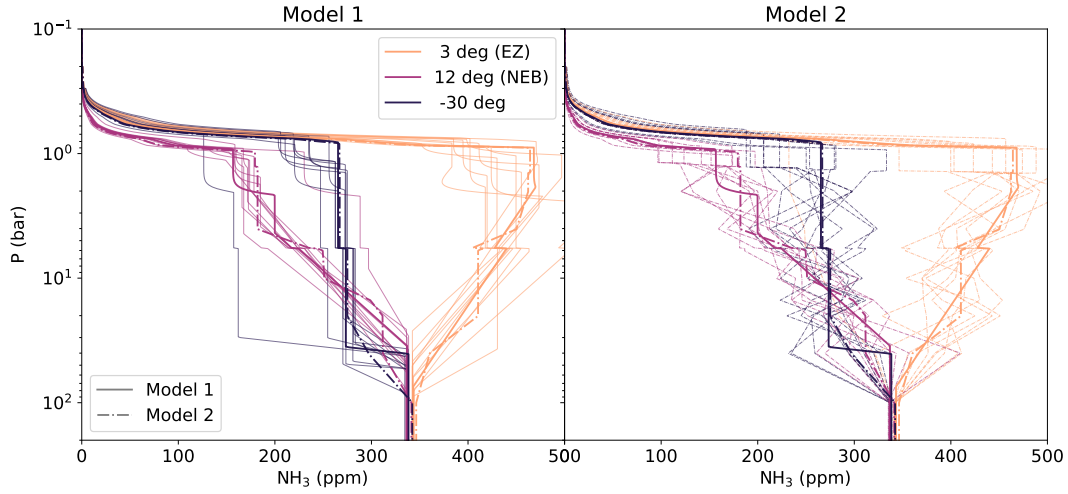


Figure 2.17: Slices through the atmosphere at the same locations as indicated in Figure 2.9. We plot additionally here 10 draws from the MCMC results to show the spread in solutions that are consistent with the observations. The left panel shows the solutions for our perturbed thermo-chemical equilibrium model while the right hand side shows the results for our stochastic model. We can see that overall structure is reproduced well by the MCMC draws, indicating the confidence in the retrieved solutions.

Atmospheric Dynamics

In the following we use our retrieved parameters for the ammonia distributions as a proxy for atmospheric dynamics. Our approach to combine measurements into 1 deg bins and retrieve the parameters per bin results in a large spread between adjacent latitudes, while the spatial resolution of the individual observations is coarser than 1 deg (Figure 2.1). To improve the signal we average the parameters over 5 degrees of a latitude-rolling-average to show trends across the zones and belts. Figure 2.20 shows the retrieved best-fit parameters for the set of uncertainty combinations.

Relative humidity

We obtain an increased relative humidity in the equatorial zone along with a decreased relative humidity in the adjacent NEB and SEB compared to other latitudes. Moving further towards the poles, the signal of the South Tropical Zone and North Tropical Zone can be seen by the increase in relative humidity until the relative humidity settles to a stable mean below 50% (see panel a) in Figure 2.20). The Juno beam is large in comparison to cloud features, so that we interpret a value of less than 100% saturation as a mixture of clouds and cloud-free regions.

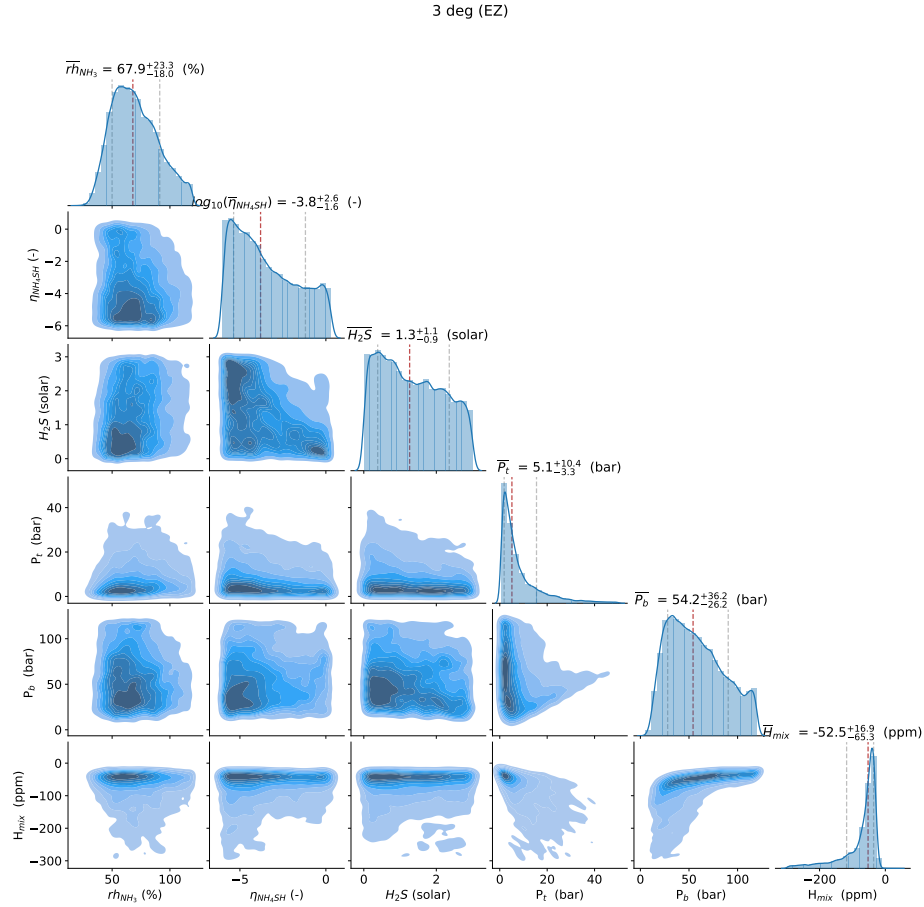


Figure 2.18: Uncertainties for and correlations between the retrieved parameters in the Equatorial Zone.

NH_4SH cloud formation

The MCMC runs revealed that the actual pressure where NH_4SH cloud formation starts is poorly constrained, however, our 3- σ models return a consistent value close to unity for $\eta_{\text{NH}_4\text{SH}}$. A value close to 1 indicates that the onset of cloud formation happens as predicted by the thermo-chemical equilibrium models, while a value less than one indicates that the reaction is happening at lower pressures than predicted. The nominal pressure at which NH_4SH is the more favorable state of the trace gases is nominally around 2.3 bars for a value of 1, whereas a value of 1e-3 pushes that cloud formation to a pressure of 1.4 bar. This can either mean that the process is a lot less efficient than postulated (Weidenschilling et al. 1973), for example if there are updrafts that "supercool" the gas before NH_4SH formation takes place. The disagreement between the various linestyles in panel b) of Figure 2.20

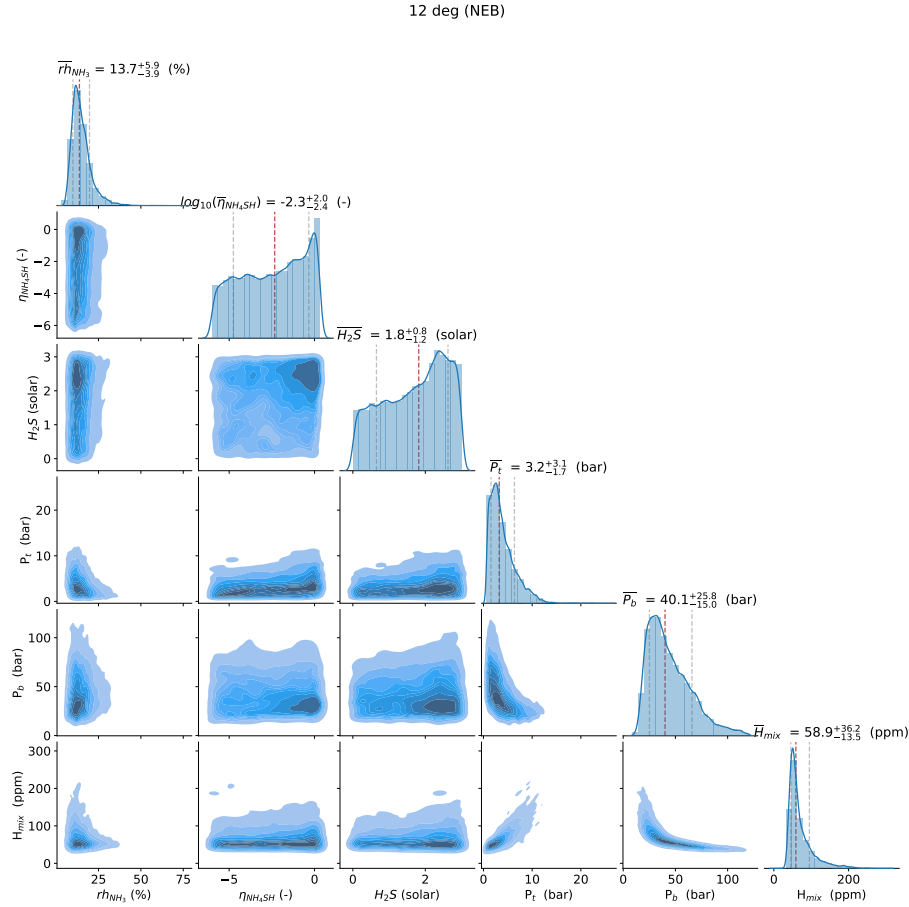


Figure 2.19: Same as Figure 2.18 but for the North Equatorial Belt.

however indicates that this result depends much on the choice of uncertainties. Alternatively, this could also reflect a lower abundance of H_2S , which we only constrain indirectly. The retrievals for the EZ and the NEB (see Figures 2.18, 2.19) show that H_2S abundance (EZ = $1.5^{+1.2}_{-1.0}$ solar, NEB = $2.1^{+0.9}_{-1.4}$ solar) in both regions is lower than the ammonia abundance (2.66), however it is poorly constrained as seen by the large spread.

Mixing regime

Juno's MWR covers a wide frequency range at the expense of spectral coverage, resulting in very few constraints on the deeper atmosphere. Our thermo-chemical equilibrium model prescribes a single gradient ($H_{mix} \equiv \frac{\delta N\text{H}_3}{\delta \ln(P)}$) starting from a bottom pressure (P_b), over a certain pressure range (ΔP). For clarity we report on the absolute change in the ammonia abundance ($\Delta N\text{H}_3$) over the mixing regime, as the gradient itself is a lot less constrained,

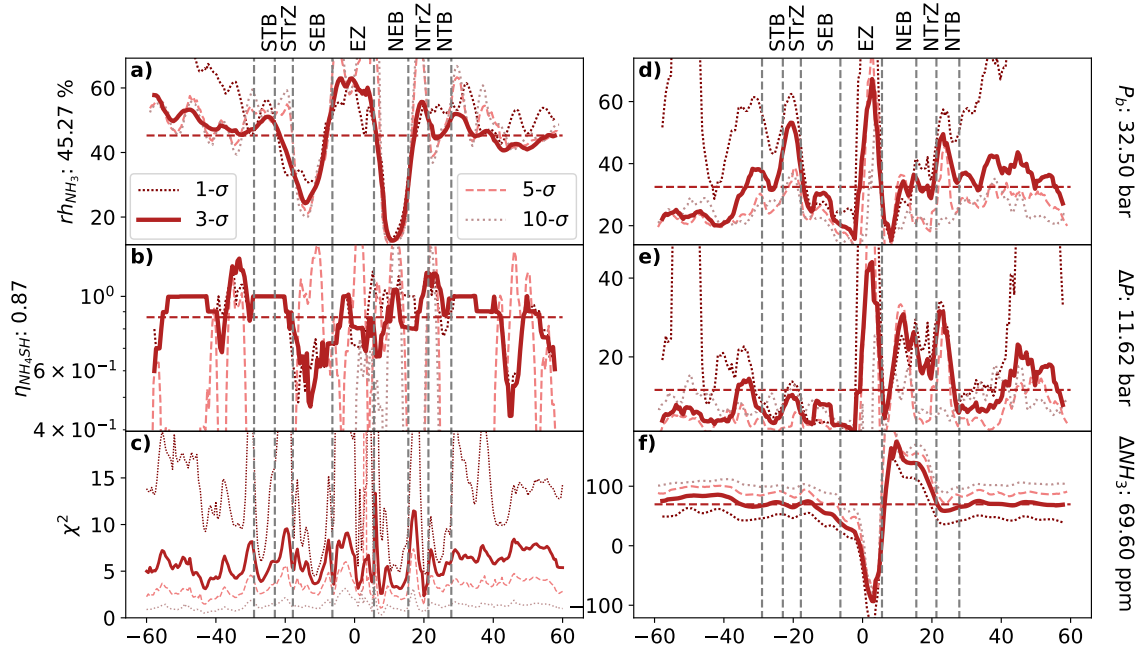


Figure 2.20: Retrieved atmospheric parameters as a function of latitude (with the individual zones and belts denoted by the vertical dashed lines) and for various combinations of uncertainty (different colors and linestyles). **Left:** a) Relative humidity of ammonia gas, b) Cloud formation efficiency, c) The reduced - χ^2 value for the retrieved atmosphere. **Right:** d) Bottom pressure of mixing region, e) Pressure range over which mixing occurs, f) Absolute change in ammonia abundance in the mixing region.

but the product of the mixing over a certain pressure region is well constrained. The mean bottom pressure at which we constrain the mixing to start is around 30 bars, but with significant difference between the tropical region and the mid latitudes (see panel d in Figure 2.20). The pressure range over which mixing occurs is consistent in the extra-tropical region where the mixing occurs over a rather small pressure range ($\lesssim 5$ bars), as shown in panel e of Figure 2.20. This mixing is very consistent across uncertainties, and much more localized in pressure than the results shown in Ingersoll et al. (2021), which derived a map based on both limb-darkening and nadir brightness temperature information.

When we take a closer look at the structure where the atmosphere transitions from depleted to enriched (~ 20 bars) in Figure 2.16, a pattern emerges. The bottom pressure at which the atmosphere approaches the level of the global deep ammonia abundance, shows a persistent pattern between zones and belts. The zones while enriched in ammonia higher

up in the atmosphere, are depleted deeper in the atmosphere. This pattern was also picked up by Fletcher et al. (2021), who referred to this as the jovicline, akin to the thermocline in terrestrial oceans. The presence of this pattern supports the existence of a vertically-stacked circulation cell (Showman et al. 2005; Duer et al. 2021). The difference in at what pressure the atmospheres are well mixed between zones and belts is on the order of 10 bar as shown in panel d of Figure 2.20.

Interestingly, the mixing occurs at levels well below the water clouds (~ 6 bar), which was long thought to be the main interface between vertically-stacked circulation cells, inhibiting convection from below (Showman et al. 2005; de Pater et al. 2019a). Our results confirm that the atmosphere is not well mixed below the cloud levels (NH_3 , NH_4SH , solution cloud), as inferred as early as the 1980s when radio measurements showed the presence of a radio-hot NEB, which was interpreted as a depletion in the ammonia gas abundance (de Pater 1986). VLA measurements showed this depletion to extend down to the ~ 20 bar level (de Pater et al. 2019b), and we show that it extends even deeper.

Despite its large size, and the inherent computational problems with modeling planets this size, (Young et al. 2019a; Young et al. 2019b) have managed to simulate the dynamics of Jupiter, and found an ammonia depletion down to ~ 8 bars, with the exception of the EZ, implying that dynamics may play a large role in shaping the atmosphere of Jupiter. Recently, microphysics has been invoked to explain the depletion of trace gases by trapping ammonia in water ice and raining it out (Guillot et al. 2020a). It remains to be seen if this process can deplete an atmosphere down to tens of bars, i.e., well below the melting point of water ice.

While the mid-latitudes seem to have a very consistent signal for the mixing region, with $\Delta\text{NH}_3 \sim 100$ ppm (panel f in Figure 2.20), the EZ and the NEB show the largest deviation from that number. Most notable, the EZ shows a reversal in the sign of the gradient, which results in an increase in the ammonia abundance with altitude, while the NEB shows the biggest gradient.

Equatorial Zone structure

The equatorial zone in Figures 2.10 and 2.16 and shows a peculiar structure with ammonia increasing with altitude from ~ 50 bar to the cloud deck, in stark contrast with the monotonically decreasing ammonia mixing ratio at all other latitudes. The retrieval favors a solution where the ammonia abundance peaks in the upper troposphere, just below the NH_4SH cloud. While a similar structure was found by (Li et al. 2020), we want to show the fidelity of this solution. We test our assumptions and limitations by expanding both the parameter space and the observational constraints. In our atmospheric fit, we add the zonally averaged VLA observations between 3 and 25 GHz (de Pater et al. 2016; de Pater et al. 2019b) probing the troposphere down to 10 bars (see Figure 2.7). For the MWR uncertainties we select the $3\text{-}\sigma$, which compromises between the limb-darkening measurements and the brightness temperature measurements. In terms of the parameters, we use the stochastic model, which can

better resolve vertical variations in the atmosphere than our thermo-chemical equilibrium model that only fits a single mixing gradient. This is especially relevant for the presence of potential fine scale structure, such as introduced by a cloud precipitation and evaporation feedback cycle below the clouds. Since we introduce a regularization constraint on the vertical variations, we first test the effect of the regularization constraints. In Figure 2.21 we show the results of three MCMC runs that have different levels of regularization (Panel a - none, b - mild, and c -moderate). We took 5000 samples from our MCMC run and compute the statistics from them, where the center line corresponds to the mean and the shaded region indicates the 0.16 and 0.84 quantiles. While the regularization changes the small scale structure by smoothing the profile, the overall increase in ammonia is very robust to the regularization constraint. Furthermore the small scale structure, such as the local decrease of ammonia between 10 and 20 bar as seen in the retrievals without constraint is well within the uncertainties of the retrieval and as such not very well constrained by the observations. Therefore, we favor the moderate regularization as it produces a smoother atmosphere when we relax other assumptions. Since the mixing gradient is pretty continuous across the whole domain we average the mixing gradient and show corner plots for this retrieval in Figure 2.22, where we show clearly that the ammonia abundance is increasing with decreasing altitude (i.e. a negative mixing gradient) and we exclude solutions with decreasing or constant ammonia abundances with altitude.

As explained in Section 2.4, we assume a temperature pressure profile and attribute variations in the observed quantities to variations in the ammonia abundance. The Voyager radio observations showed that the EZ had a higher temperature than the NEB, so we test the sensitivity of our retrieved ammonia abundance to the temperature structure. The ammonia structure in Figure 2.23-panel a shows the MCMC results compared to the results based on a dry adiabat in panel b, where the shading indicates the 0.16 and 0.84 quantiles based on the last 5000 samples of our runs. The profile for a wet adiabat differs above ~ 6 bar, the condensation pressure of water, which decreases the adiabatic lapse rate. This higher temperature of the wet adiabat is compensated by higher ammonia abundances above 6 bars to match the MWR and VLA observations. Next we relax the assumption that the atmosphere approaches a state of being well-mixed globally deep in the atmosphere and we allow the deep ammonia abundance to vary along with other parameters in the model, instead of using the deep ammonia abundance as an a-priori constraint. Panel c of Figure 2.23 shows the results of MCMC simulations. We plot the distribution of the final parameters in Figure 2.24 to show how well constrained the parameters are. While the top of the atmosphere remains unchanged, the mixing gradient is slightly decreased which is compensated by an increase in the deep ammonia abundance by 22 ppm compared to the global mean of 340 ppm, which is still within the errorbars of our retrievals (see Section 2.5).

One of the big assumptions is that effect by clouds can be ignored. To test the validity of this assumption we include absorption by clouds based on the parameterization by de Pater et al. (1985) and de Pater et al. (2005). Cloud densities in these models are computed like adiabatic liquid water contents for terrestrial clouds, i.e., they represent maximum cloud densities based upon assuming no loss by precipitation. The results for the atmosphere are

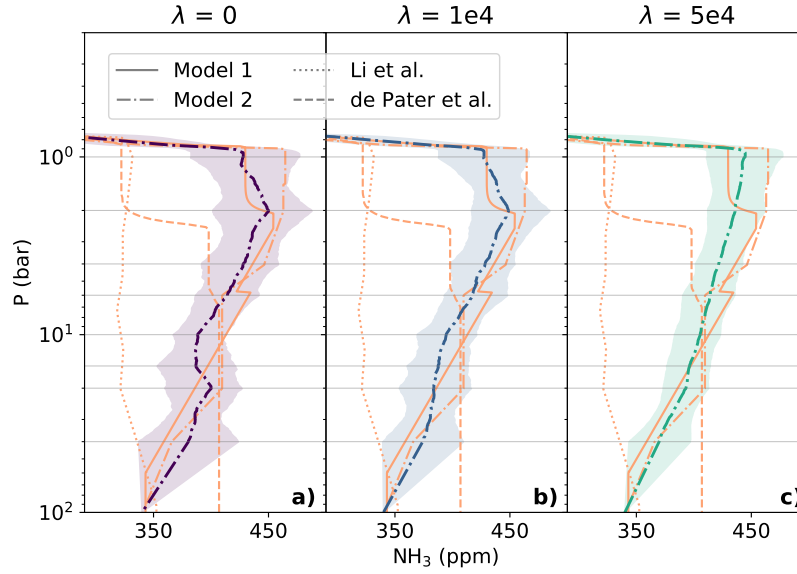


Figure 2.21: Effect of regularization constrain on the ammonia abundance profile in the EZ when fitting to the combined VLA and Juno data. The yellow lines show the results of various different retrievals (and are the same as in Figure 2.10), while the horizontal lines are the pressure nodes between which the gradient can vary. The three different panels show the effect of the vertical regularization as described in Section 2.3, where the shading corresponds to the 0.16 and 0.84 quantiles from the MCMC runs. The left panel has the regularization turned off ($\lambda = 0$ in Equation 2.20), with a mild regularization constraint in the middle and a moderate constraint on the right. While the regularization constraint changes how smooth the profile is with altitude, it changes very little about the overall structure.

shown in panel d of Figure 2.23, where the ammonia abundance profile has clearly changed significantly compared to the previous models. Below the water condensation level the atmospheric structure is consistent with a constant abundance (1-H mixing gradient), with a change in gradient above the water cloud level signified by a sharp increase in the ammonia abundance (2-H mixing gradient) consistent with a rain-evaporation cycle. The retrieved deep ammonia abundance (see Figure 2.25) of 379 ppm is just outside of the 1σ limit of the global ammonia abundance that we retrieved without considering the opacity by clouds. This structure is most consistent with physical models, however beckons the question what other impact the poorly known cloud particles may have on the retrieved atmospheric parameters.

Mid-latitude structure

The presence of the inversion at pressures around 6 bar (see Li et al. (2017a)) has lead to

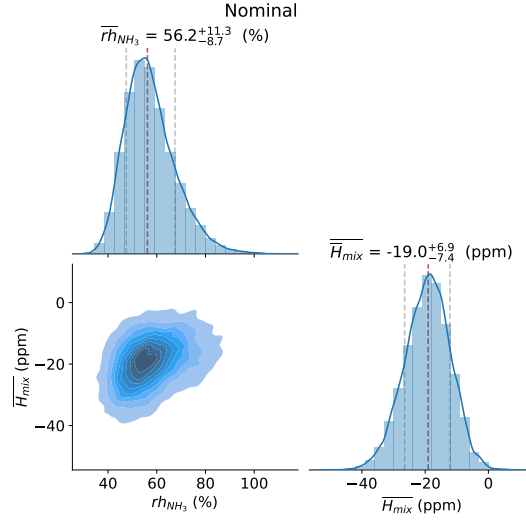


Figure 2.22: Corner plots for the nominal model (panel b in Figure 2.23 where we show the average between the 8 mixing gradients in the atmosphere between 100 and 1 bar. The combined VLA and Juno retrieval indicates a lower humidity in the EZ compared to the pure Juno retrieval (see Figure 2.18), but the mixing gradient clearly shows a well-defined increase of ammonia abundance with altitude.

much speculation on the physical processes that could cause such a structure. A possible explanation would be a set of ferrel cells extending polewards that alternately enrich and deplete the atmosphere (Duer et al. 2021). While our thermo-chemical equilibrium model with a singular mixing gradient would not be able to resolve such a structure, our stochastic model built upon the framework by Li et al. (2017a) should be able to find such a structure. In our optimizer results we could not find any consistent evidence for the depletion as seen by Li et al. (2017a) (see Figures 2.9 and 2.16). The biggest factor in controlling this structure is the amount of regularization we introduce for the vertical gradients, so that we tested our retrieval against various regularization constants λ . Additionally, we increased the constraints by adding the VLA information to use all available observations. We chose -30 degree latitude where Li et al. (2017a) found a strong inversion signal with the ammonia dropping down to 175ppm compared to 275ppm at the ammonia ice cloud level. In Figure 2.26 we show the results for various vertical regularization constants on the retrieved structure, similarly to Figure 2.21. Panel a shows the resulting atmospheric structure for a retrieval with no vertical regularization, while panel b and d correspond to mild and moderate. Regardless of regularization constant we cannot reproduce the inversion at ~ 6 bar (dotted line in Figure 2.26.) We also test if our choice of uncertainty ($n=3\sigma^{fit}$) could influence the results. In panel c we show the results of using $n=1$ for the fit uncertainty, i.e. an increased influence of the limb-darkening parameter on the retrieval. The resulting structure develops a slight

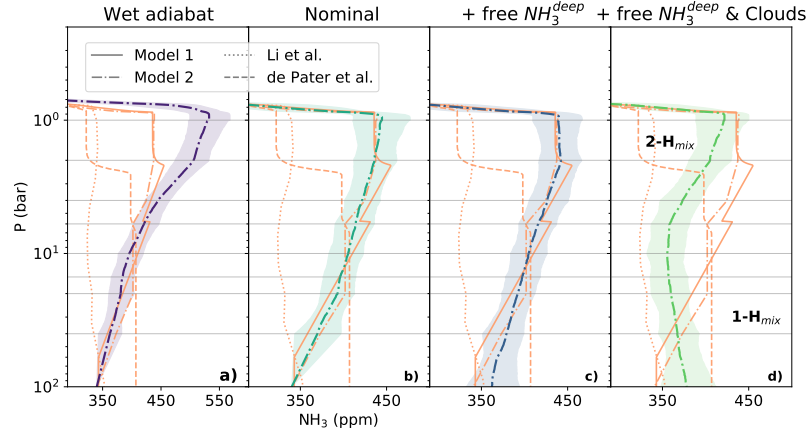


Figure 2.23: Testing the robustness of the vertical structure against various assumptions in the retrieval compared to various other retrievals (different line styles). Model 1 and Model 2 are slices through Figure 2.16, the ammonia abundance map based on the joint retrieval of the combined VLA and Juno MWR dataset. In panel a we retrieve the atmospheric structure for a wet-adiabatic temperature profile (see Figure 2.6), and show a large increase of the ammonia abundance (note the different scale for this panel). We compare this to the vertical profile of the nominal dry adiabat in the panel b. The panel c relaxes the assumption that the atmosphere approaches a globally well-mixed ammonia abundance and instead we retrieve the deep ammonia abundance simultaneously. The right most panel shows the effect of including absorption by cloud particles.

negative gradient, however, no consistent inversion. This agrees with the conclusion by de Pater et al. (2019b), who showed that ammonia abundance profiles by Li et al. (2017a) gave an inferior fit to the data as compared to their derived abundance profile. Similarly, Ingersoll et al. (2021) used Perijove 1-7 observations and did not find a structure consistent with an inversion at mid latitudes.

2.7 Conclusions

Radio observations allow to disentangle some of the mysteries that Jupiter still holds for us. A combined analysis of VLA and Juno observations allow us to constrain the vertical structure of the atmosphere; however, this is not unique due to the fact that radio waves originate from a range of pressures. We introduce disequilibrium factors into a thermo-chemical equilibrium model (Weidenschilling et al. 1973; Atreya et al. 1985) that describe the distribution of trace gases and use these factors in our inversion technique. Fitting the required quantities, however, also requires a good understanding of the fidelity of the data product. For

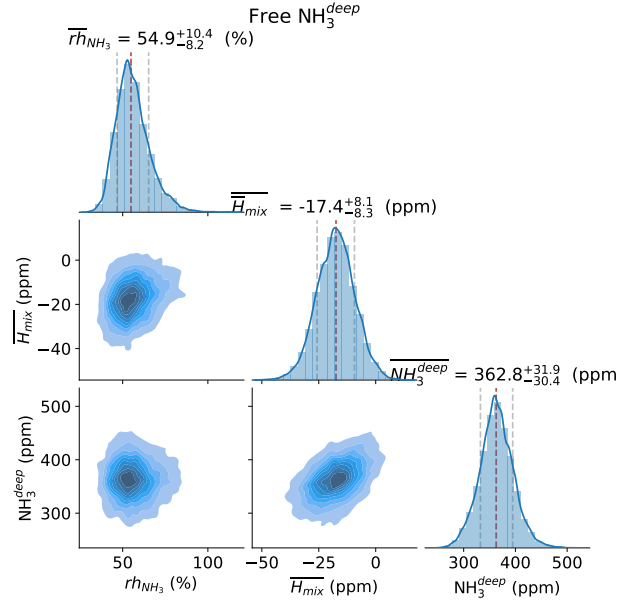


Figure 2.24: Corner plots for the equatorial inversion corresponding to the profiles shown in Figure 2.23. In this retrieval we relaxed the assumption that the ammonia is well-mixed and allow the deep ammonia to vary in the fit.

this reason, we developed a data reduction pipeline, that obtains the brightness temperature and limb-darkening coefficient along with their uncertainties. Coupling these two, results in a distribution of trace gases (see Figure 2.9), the sensitivity of our solutions to the fit uncertainties (see Figure 2.20) and our certainty in the derived atmospheric distribution (see Figures 2.18 and 2.19).

Our approach recovers an atmosphere that confirms the structure that was seen by the VLA in the past (de Pater 1986; de Pater et al. 2019b) and by Juno (Li et al. 2017a), however, we also find some remarkable differences. We find that the deep ammonia abundance of $340.5^{+34.8}_{-21.2}$ ppm ($2.66^{+0.27}_{-0.17} \times$ solar abundance) is lower than the Galileo (Wong et al. 2004) and VLA results (de Pater et al. 2016; de Pater et al. 2019b, which were based on the Galileo results), and confirm the Juno results (Li et al. 2017a). The atmosphere only approaches a state of being well-mixed at pressures greater than 30 bars, sitting under a layer between 20 and 30 bar in which the ammonia abundance decreases with increasing altitude. The atmospheric structure requires processes that deplete the atmosphere down to such high pressures, or alternatively require a mechanisms that locally enrich the atmosphere, such as in the equatorial zone. The systematic deeper depletion of ammonia abundance in the zones compared to the belts supports the existence of a vertically stacked circulation structure that is constrained to the top 20-30 bars of the atmosphere. At the top of troposphere the

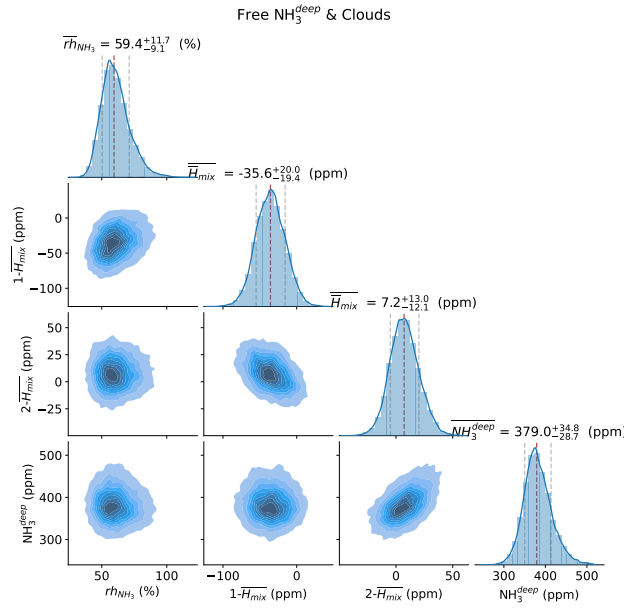


Figure 2.25: Corner plots for the equatorial inversion including the effect of radio absorption by cloud particles. The mixing gradients correspond to 1-H to mixing above 6 bar, and 2-H corresponds to mixing below.

formation of the NH_4SH and ammonia cloud layers dominates the vertical structure in the ammonia abundance.

The uncertainties that we retrieve from the raw Juno observations allow us to study the sensitivity of our results to these observational uncertainties. Especially the low frequency observations are hard to fit, where the limb-darkening coefficient and the brightness temperature favor different solutions for the structure of the atmosphere at altitudes below 10 bar. Higher up in the atmosphere the uncertainties have a very small effect on the retrieved atmosphere (see Figure 2.8).

The equatorial zone represents an interesting diversion from the general atmosphere. It shows the highest ammonia abundance on the planet, with an indication that the ammonia is increasing with altitude, in stark contrast to the rest of the planet. This signal is robust to the chosen uncertainties (see Figure 2.20) and can be reproduced even when we loosen the assumption and let the deep ammonia vary. This structure can also be reproduced when adding the VLA observations (see Figure 2.23) and indicates an increase in ammonia over a large pressure range. Interestingly, when adding absorption by clouds the structure is consistent with an increase starting only at the pressure of the water clouds.

So how can we advance our understanding of the deep atmosphere? First and foremost, we need to investigate the signal in Channel 1 which so far has been mostly ignored. With the differences between the various ammonia absorption coefficients at high pressures (Hanley

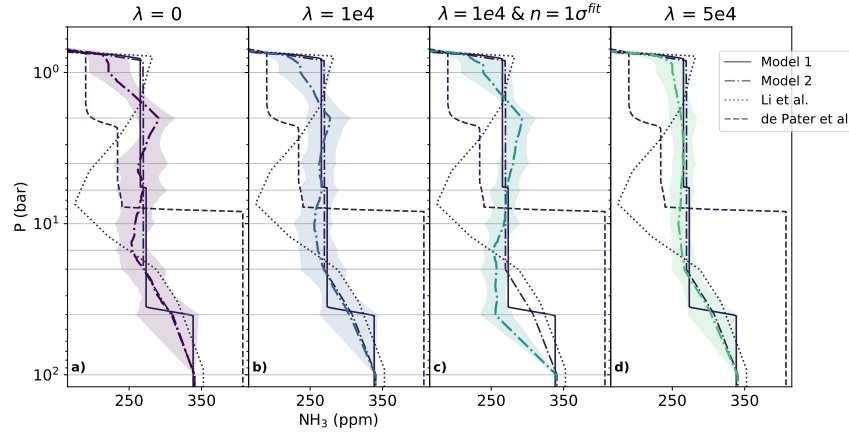


Figure 2.26: Testing for the inversion signal at midlatitudes as seen by Li et al. (2017a), by retrieving an atmosphere based on both VLA and Juno data. We test the effect of vertical regularization on the mid latitude structure to show the confidence in the retrieved mid-latitude structure. The panels correspond to no (panel a), mild (panel b) and moderate vertical regularization (panel d). The various line style corresponds to the various retrievals, with the dot-dashed line and the shading indicated the 0.16 and 0.84 quantiles of the MCMC results. Panel c uses mild vertical regularization but reduces the uncertainty fidelity to $n = 1$. Regardless of chosen regularization we cannot reproduce the magnitude of the inversion as seen by the dotted line.

et al. 2009; Bellotti et al. 2016; Bellotti et al. 2017) alone, Jupiter’s deep atmosphere remains poorly understood. Furthermore, at low frequencies the absorption by water clouds (de Pater et al. 2005) and other species such as alkalis (Bellotti 2018) becomes significant, both of which are poorly understood and often ignored in the RT models. Both lab measurements at high pressures and temperature and ab-initio calculations are essential to fully model these contributions to the opacity. The other big unknown is the temperature structure below the clouds. While mid-infrared observations can probe down to ~ 0.8 bar, the structure below is largely unconstrained, and usually assumed to be adiabatic (wet or dry). Remote observations cannot retrieve the temperature structure directly; understanding atmospheric dynamics better can help construct more realistic atmospheric temperature profiles.

Addendum A - Beam-Convolved Emission Angle

As explained in Section 4.2, for each observation we compute the beam-convolved emission angle to account for the large range of emission angles within the beam. Since we are interested in the relationship between the emission angle and the brightness temperature we

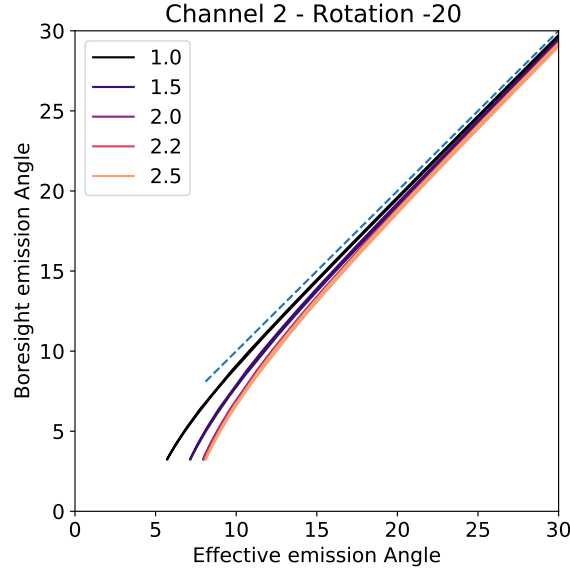


Figure 2.27: Relationship between the beam-convolved emission angle and boresight emission angle. The different colors indicate the integration region in units of the HPBW. Further away from the beam center, the beam sensitivity is dropping rapidly, and the contribution to the averaging becomes small. Therefore, the results converge for sufficiently large integration regions. Our final results are based on 2.5 HPBW, which contains 99% of the emission. This example is for Perijove 1 - Channel 2 observations just before closest approach to the planet.

must assure that the emission angle is representative of the observations. Especially at low emission angles, the extended beam covers a wide range of emission angles, and the boresight emission angle is not an adequate indicator for the observation. Figures 2.27 and 2.28 shows the relationship between the two quantities for a full rotation of the spacecraft. The large beam-size of Channel 2 makes the effect more pronounced than the observations in Channel 5.

Addendum B - Synchrotron filter

To best understand the spatial synchrotron filter, in Figure 2.29 we show a region of the planet where the radiation from the main synchrotron belt is leaking in when looking towards the equator. Compared to Figure 2.2, where the measurements all fall onto the same curve, we can see that in regions with heavy synchrotron contribution, there are two branches to the radiation. We have separated out the signal that is looking towards the equator (upper branch of empty circles), while the useful data are the ones looking towards the poles of the

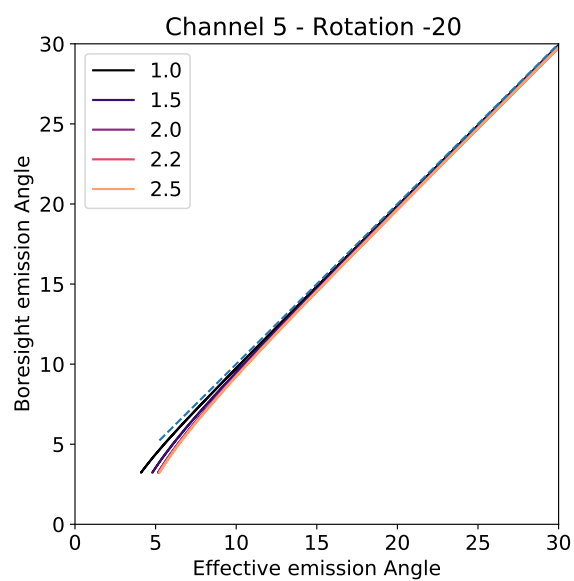


Figure 2.28: Same as Figure 2.27 but for Channel 5.

planet. Even at low emission angle the impact of the synchrotron radiation can be large.

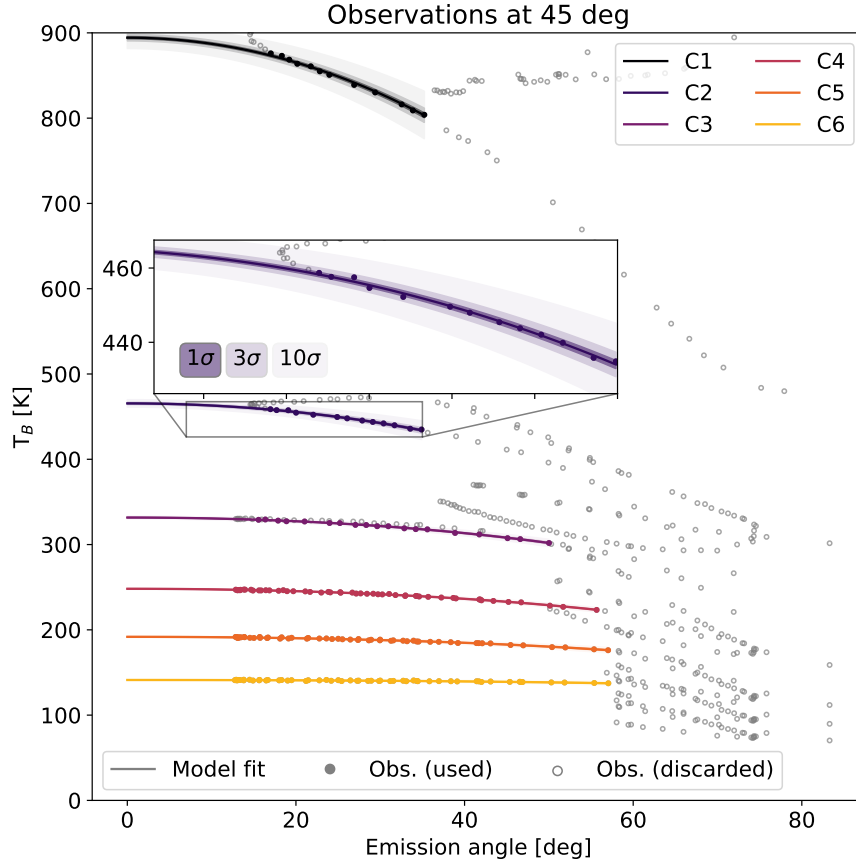


Figure 2.29: Same as Figure 2.2 but for a latitude where the synchrotron contribution is noticeable. Note that there are two branches in Channel 1 and 2 that have a large difference in the temperature for the same emission angle. The increase temperature is due to the synchrotron leaking in through the side lobes. Our spatial restriction can handle the synchrotron contribution well, ignoring the upper, contaminated branch of the observations.

Chapter 3

Effect of Storms

This chapter is currently under review in Science Advances under the title: 'Tempest in the Troposphere - Mapping the Impact of Giant Storms on Jupiter's Deep Atmosphere' by Chris Moeckel, Huazhi Ge, and Imke de Pater.

Summary

Storms are emerging as key drivers in shaping hydrogen-dominated atmospheres. Condensation of trace gases can suppress convection and disrupt the distribution of energy and material in hydrogen atmospheres. On Jupiter, the presence of water has been invoked to control the occurrence of large-scale storms; however, the impact of storms on the ammonia and temperature distribution is unknown. We use Juno Microwave radiometer observations of a large-scale storm in 2017 to study the aftermath of such a storm on the atmosphere. Anomalies in the retrieved ammonia abundance and atmospheric temperature show how storms deplete and heat the upper atmosphere while simultaneously depositing material well below the layers they were triggered at. These observations, aided by simulations, show that the water and ammonia cycles are coupled and that their combined effect plays a key role in explaining the depletion of ammonia in the tropospheres of Jupiter and Saturn.

3.1 Introduction

Our understanding of the redistribution of material and energy in Jupiter's troposphere and its effect on the planet's global atmospheric dynamics remain limited. The incoming solar insolation is of the same order of magnitude as the contribution of the internal heat flux (Hanel et al. 1981; Pirraglia 1984), resulting in a system that is forced equally from the top and the bottom. Furthermore, unlike terrestrial planets, where short-wave radiation is converted into long-wave radiation on the planetary surface, Jupiter's incoming solar radiation is scattered and absorbed throughout the upper troposphere. The pressures at which solar energy is absorbed ($P < 6$ bars) cannot explain the atmospheric dynamics and

variability at the pressures at which large-scale storms erupt ($P \approx 6$ bar). Radio observations in recent decades have revealed a two-layer system in the troposphere of Jupiter, where trace gases do not follow the behavior predicted by thermochemical equilibrium models (Li et al. 2017b; de Pater et al. 2019b; Moeckel et al. 2023). In particular, the global depletion of ammonia in the upper troposphere (cloud condensation pressure at 0.7 bars) compared to the lower troposphere (~ 50 bar) cannot be explained with our current understanding of chemistry or Jovian atmospheric dynamics. Storms have emerged as a potential explanation (Showman et al. 2005; Li et al. 2015; Guillot et al. 2020a; Li et al. 2023), however, little is known about how deep these storms can disturb the atmosphere. Since radio observations are sensitive to the combination of trace gas and temperature anomalies, they represent our best window into the dynamics of the atmosphere. In this work, we retrieve variations in the ammonia abundance or physical temperature anomalies and trace the effect of the storms below the visible cloud deck for the first time.

In December 2016, amateur astronomer Phil Miles captured the onset of a storm system in the South Equatorial Belt (SEB) (14.5° deg S, planetocentric), $\sim 60^\circ$ East of the Great Red Spot. The timing coincided fortuitously with a ground-based, multi-wavelength observation campaign to support the Juno perijoves (PJ) encounters. Observations with the Atacama Large (sub)-Millimeter Array showed that the base of the water cloud is the likely region from which the storms originated (de Pater et al. 2019a). We define the base of the water cloud (~ 5 bar), sitting just above the Lifting Condensation Level (LCL) of water around ~ 6 -7 bar. The fact that the condensation and evaporation can power storms is consistent with our understanding of giant storms on Saturn (Li et al. 2015) and the mechanism invoked to revive the SEB after it had faded away (Fletcher et al. 2017). Observations at optical wavelengths of the storm system in March 2017 found that the storm clouds were more extended in depth compared to the typical cloud deck in the surrounding regions, consistent with a deep source for this region (Dahl et al. 2021). Observations at $5 \mu\text{m}$ showed an increase in ammonia and water abundance coupled with an opaque water cloud at the location of the storm plume, confirming that the plume is bringing up water and ammonia from deeper levels within the atmosphere (Bjoraker et al. 2022).

3.2 Results

We use a combination of Juno MicroWave Radiometer (MWR) observations and Hubble Space Telescope (HST) observations to constrain the vertical extent of the storm system. The MWR data were obtained during PJ4 (Feb. 2nd, 2017, closest approach at UTC 12:57), when Juno flew over the still ongoing storm region and observed the atmosphere at six distinct frequencies in the radio regime (Janssen et al. 2017). The signal is the opacity-weighted brightness temperature of the atmosphere integrated over a range of pressures, with ammonia being the dominant opacity source in the microwave on Jupiter; however, the observations are also sensitive to physical temperature variations. The horizontal resolution of the observations is set by the convolution of the atmospheric thermal emission with the sensitivity

pattern of the beam and thus is variable across the domain. The vertical resolution, that is the depths over which the thermal signal is integrated, is frequency dependent. At lower frequencies (that is C1 and C2), the observations probe deeper into the planet and also cover a wider pressure range (see Figure 3.5 and Table 2.1), while the upper channels (C4-C6) probe into the middle and upper troposphere. From the calibrated antenna temperatures, we retrieve the nadir brightness temperature and limb-darkening parameters as a function of latitude (Moeckel et al. 2023), and fit vertical atmospheric profiles to these quantities using a radiative-transfer model (radioBEAR - Radio BErkeley Atmospheric Radiative-transfer¹). To resolve smaller-scale structures in the brightness-temperature distribution, we use a deconvolution algorithm to map radio observations onto spatially resolved HST storm observations.

The HST observations were taken in support of the Juno mission during Juno’s flyby (PI: Mike Wong). The UVIS detector on the WFC3 instrument covers the UV, visible, and near-infrared in seven distinct filters (Dressel et al. 2023). The data were processed and navigated (Wong et al. 2020a), and are available on the Barbara A. Mikulski Archive for Space Telescopes².

Even about a month after the initial outbreak, the longitude-averaged observations shown in Figure 3.1 show a distinct signature in the SEB at the location of the storm outbreak. The storm signal can be seen in the upper 4 channels (C3-C6), as seen in both the nadir brightness temperature and especially the limb-darkening coefficient when comparing the observations with the mean of the first 12 perijoves (Moeckel et al. 2023). The fact that we can trace this signal all the way to Channel 4 already indicates that this storm is not contained to the traditional weather layer (cloud condensation region), where we see the majority of variability in the atmosphere, but affects the atmosphere to much greater pressures.

The deconvolved brightness temperature maps detail the finer-scale structure within the storm system, highlighting the variations across the storm domain. The deconvolved measurements in Figure 3.2 depict the brightness-temperature anomaly overplotted on concurrent HST observations. We define the anomaly as the difference in the PJ4 nadir brightness temperature for a given channel and the mean based on the first 12 orbits. Higher frequencies (C5 and C6) probe the region where the ammonia ice clouds are forming, and the cold brightness temperature correlates well with the haze and cloud topology as captured by the HST observations. The cloud itself is surrounded by visually darker regions, associated with a depleted ammonia abundance, which is confirmed by a warm brightness temperature anomaly. We can see that the brightness temperature anomaly decreases at longer wavelengths (C3 and C4) but remains colocated with the storm topology. At the lowest frequencies (C1 and C2), which probe deepest into the planet, the brightness temperature anomaly becomes negative across the domain. The two lowest channels have the widest beam-width and the least amount of coverage due to filtering of synchrotron radiation. Thus the results in C1

¹<https://github.com/david-deboer/radiobear> (de Pater et al. 2005; de Pater et al. 2014; de Pater et al. 2019b; Moeckel et al. 2023)

²<https://archive.stsci.edu/hlsp/wfcj>

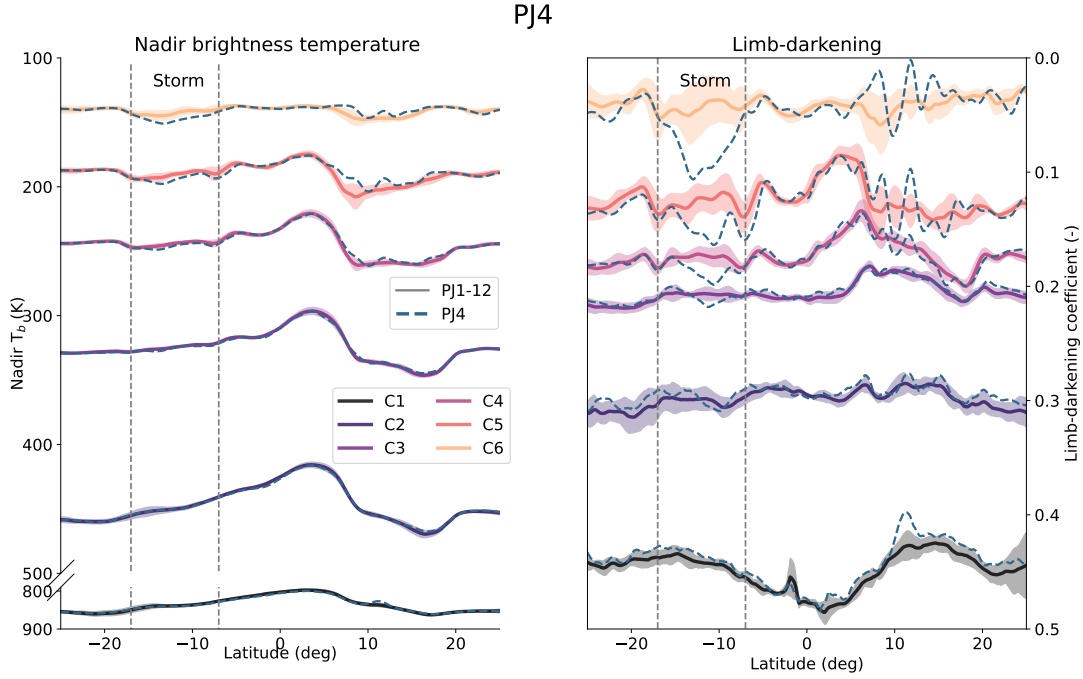


Figure 3.1: Comparison of PJ4 observables (colored dashed lines) with the mean observations (solid lines, shading corresponds to the standard deviation) based on the first 12 perijoves. The nadir brightness temperature is on the left, while the limb-darkening coefficient is shown on the right. The storm broke out in the SEB (indicated by the gray vertical dashed lines). The effect is strongest for the upper channels, with its strength decreasing at lower frequencies. We see an increase in brightness temperature at the location of the storm, indicating either a drying out of the upper atmosphere in ammonia or an increase of the physical temperature.

and C2 should be seen an upper limit, that is the negative brightness residual might be even colder. The location of the previously studied upwelling plume is slightly west of the covered domain, with our observations covering an adjacent plume (Bjoraker et al. 2022).

We selected three regions in Figure 3.2 to retrieve the ammonia abundance to study the effect of the storm on the atmosphere. In Figure 3.3 we show the impact of the storm on the atmosphere of Jupiter, either in the form of disrupting the ammonia profile or by affected the temperature structure. We first fit a reference profile (dashed lines) based on the averaged quantities from the first 12 perijoves at those latitudes coupled to a dry adiabat. Relative to this background profile, we then find an ammonia abundance (solid line) that reproduces the observed brightness temperature anomaly shown in Figures 3.2 and 3.6. The colors correspond to the locations on the inset map: the blue color is centered on the storm plumes

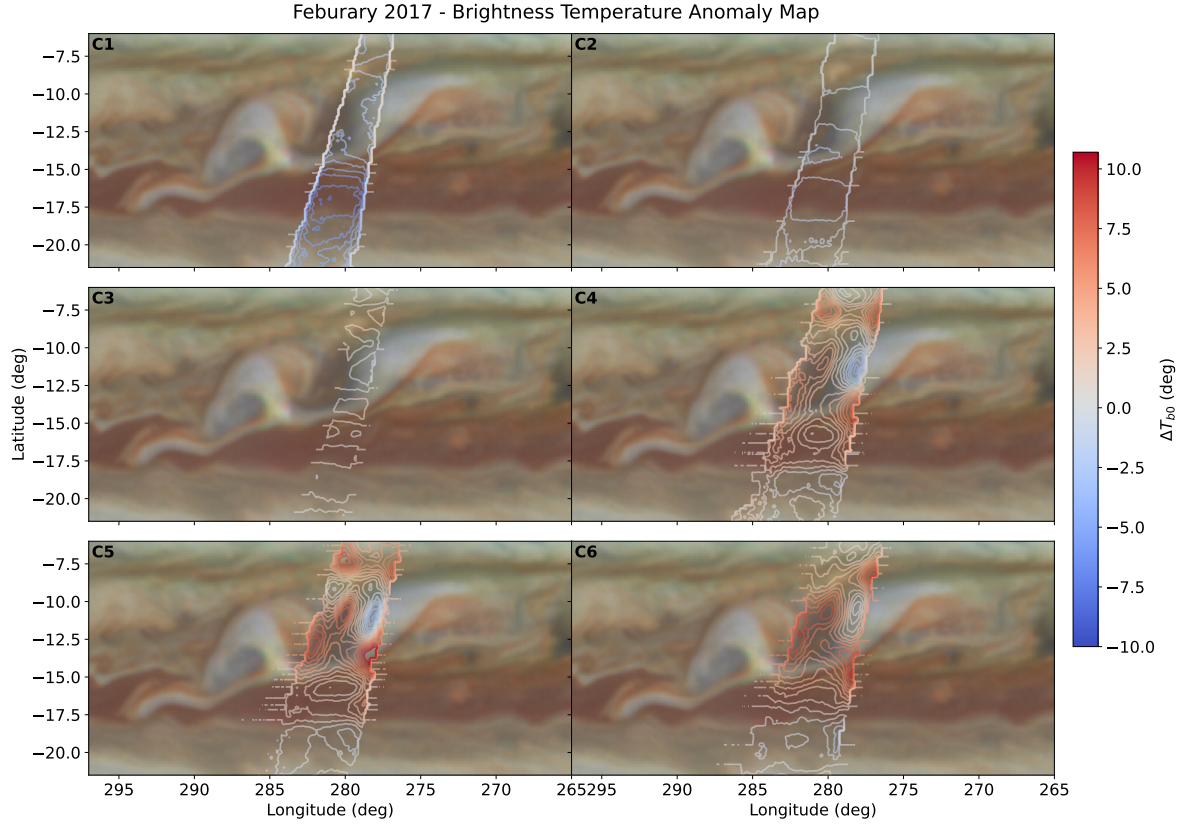


Figure 3.2: Brightness temperature anomaly maps for each channel. The contours outline the difference between the mean background atmosphere (PJ1-PJ12) and PJ4. The positive outlines indicate an atmosphere that is radio-warmer than the average atmosphere, while blue contours indicate a radio-colder atmosphere. All six maps are shown on the same color-scale showing that the signal is strongest in the upper two channels and decays with increasing depth.

with the largest negative brightness temperature anomaly; the dark red color corresponds to the southern edge of the clouds where we find the strongest positive anomaly; and yellow corresponds to the region just west of the cloud. For now, we assume that there is no change in the temperature structure and we attribute the brightness temperature anomaly fully to the ammonia abundance, rendering this result an upper limit to the ammonia variability. The profiles show two distinct regions, with the majority of the variability occurring at altitudes above the 4 bar level, as shown by the strong signal in the upper three channels. The two warm regions are characterized by a depletion of ammonia, while the radio-cold regions show a large localized ammonia enhancement that peaks around the ammonia ice condensation pressure. Surprisingly, deeper in the atmosphere, the ammonia anomalies change sign. In the region where the gas is enhanced at the ammonia cloud deck, we require a depletion that extends down from the water cloud to ~ 15 bars to fit the observations. In the regions where we find a depletion in the upper layers, we find a small but significant increase in the ammonia abundance that starts around 4 bars and extends to ≥ 20 bars.

In addition to affecting the distribution of ammonia, the outbreak is expected to also significantly heat the atmosphere through the release of latent energy as trace gases condense in the upward branches of the storm and through subsidence of air in a stably stratified atmosphere. To explore the other end-member case, we kept the ammonia abundance constant at the averaged background level, and instead we fit a pure physical temperature anomaly. We parameterize the temperature anomaly with two Gaussian temperature deviations from the nominal dry adiabatic profile, where each Gaussian has an associated depth, width, and magnitude. The retrieved deviations in temperature, along with their uncertainties, are shown on the right side of Figure 3.3. We find that the temperature anomaly is inversely proportional to the ammonia anomaly. Instead of a depletion in ammonia, the observations are also consistent with strong heating in the upper atmosphere, with the physical temperature anomaly that we retrieved similar in magnitude to the observed brightness temperature anomaly. Below the water cloud base, the observation could also point to significant cooling at pressures between 10-20 bar. At these higher pressures, the required physical temperature anomaly to fit the observations is factor of a few larger than the brightness temperature anomaly. The enhancement in the storm plume could also be explained by a strong cooling at 1-4 bar, with the physical temperature anomaly and the brightness temperature anomaly of roughly the same magnitude. No further change in the physical temperature below the plume was required to fit the observations. Comparing the observed brightness temperature anomaly with the retrieved brightness temperature anomaly shows that both assumptions explain the observations well, despite very different structures in the atmosphere (see Figure 3.6).

We attempted to break the degeneracy by allowing both the temperature and ammonia to vary across the full pressure domain simultaneously. With the available measurements, we found no significant constraint on either of them. Note that we do not have an independent measurement for the limb-darkening effect for our analysis.

Instead, we use simulated temperature structures based on non-hydrostatic simulations (Li et al. 2019a) that allow us to both compare the retrieved temperature structure to

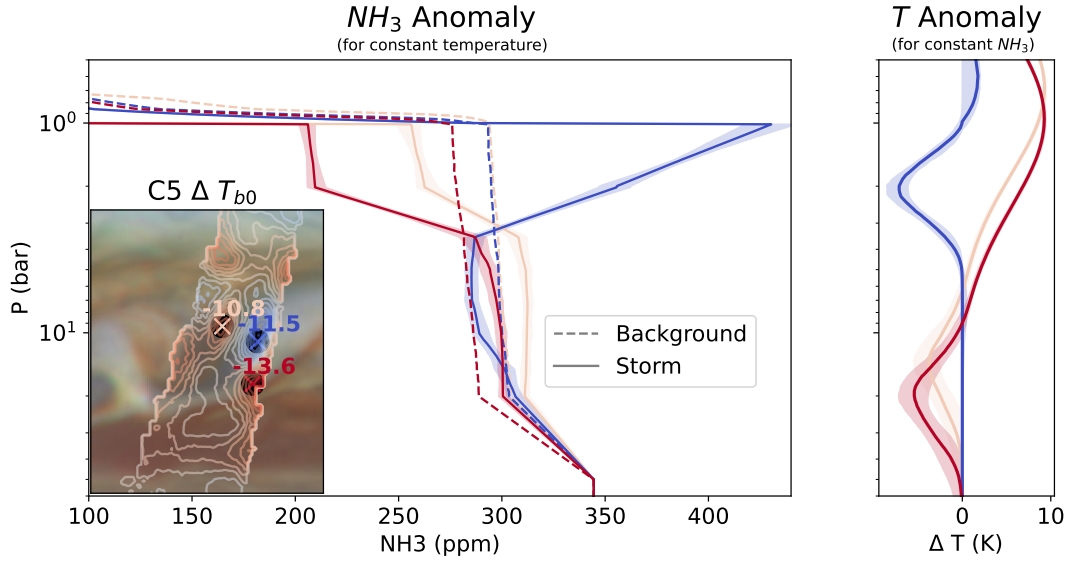


Figure 3.3: Left panel: Vertical ammonia abundance profiles that compare the mean background atmosphere (dashed line) with the results from the relative retrieval assuming no changes to the physical temperature structure (solid lines). The locations of the profiles are indicated in the inset map that shows the C5 brightness temperature anomaly, while the shading corresponds to the uncertainty in the retrieved solutions. For all three profiles, we find a strong anomaly in the upper atmosphere, sitting over a smaller, but opposite sign anomaly located below the water cloud. Right panel: Retrieved temperature anomaly assuming that the ammonia abundance remains fixed at the background level. The regions adjacent to the clouds are characterized by strong atmospheric heating in conjunction with cooling deeper in the atmosphere.

the simulated values, and also to study the correlation between ammonia and temperature anomaly. In Figure 3.4 we fit the anomalies at -10.8°S (upper panels) and -11.5°S (lower panels) and retrieve the abundances of ammonia for a range of different simulated temperature profiles. The right-hand side of Figure 3.4 shows the temperature deviation with respect to a dry adiabat informed by the simulations, where each line style corresponds to a different assumption. The inset map shows a cross section of the simulated storm outbreak that shows the ammonia abundance around 1 bar: regions in red are depleted in ammonia, while blue corresponds to enhanced ammonia.

The averaged temperature structure in the simulated domain is a good proxy for the mean atmospheric temperature that we use to fit the background profile (blue dashed lines). The most significant feature is a super-adiabatic layer around and above the lifting condensation level of water due to the mass loading of water, which is heavier than the predominantly hydrogen atmosphere (Guillot 1995; Sugiyama et al. 2014; Leconte et al. 2017; Li et al.

2018a). Comparing the blue and red dashed lines, we find that including super-adiabatic temperature structure in the weather layer of Jupiter results in less ammonia to fit the data. Interestingly, while the super-adiabatic temperature layer is limited to altitudes above 10 bar, the effects on the retrieved ammonia abundance can be traced to much greater depths due to the broad weighting functions (Fig. 3.5).

Storms occur periodically every three to four years in the simulation, and we choose a snapshot of the simulation during an on-going outbreak. The simulations allow us to compute local temperature anomalies, that is the change of temperature with respect to the simulated background reference profiles. For our storm profiles (solid blue lines), we averaged 20 distinct temperature anomalies (thin gray lines) in the simulation, where each profile was selected based on the similarity between the retrieved and simulated ammonia profiles. The small inset map on the left-hand side is a cross-cut through the simulated ammonia abundance at 1 bar and the 20 dots show that we sampled a number of distinct regions in the simulations. In addition to the super-adiabatic layer, the storm profiles predict strong heating of the upper atmosphere as a consequence of the latent heat release of water. For regions with a positive brightness temperature anomaly (upper row), our observations of heating in the upper atmosphere are consistent with the simulations. Indeed, the simulated temperature increase in the upper atmosphere is large enough to explain the signal in the upper channels and we do not require any depletion in ammonia above 4 bar (blue solid line). At higher pressures, we still require an anomaly in the ammonia abundance that extends down to ~ 20 bar. For the storm plume (lower row), the region where we found the strongest cold brightness temperature anomaly, we require a slight increase in ammonia abundance to compensate for the warmer upper troposphere.

In reality, the brightness temperature anomaly is most likely caused by a combination of ammonia and thermal anomaly. We leverage the simulation results, which show no significant variation in ammonia abundance below 10 bar, and restrict the ammonia anomaly to only occur at altitudes above 10 bar. In addition to the ammonia anomaly, we introduce a Gaussian temperature deviation. The upper row shows that we could fit the region adjacent to the cloud through a combination of a depleted upper atmosphere down to 4 bars, sitting over a cold-temperature anomaly around 12 bars (dot-dashed cyan lines), at a pressure similar to that obtained for the pure temperature anomaly (see Figure 3.3). For the retrieval of the storm plume, we find a persistent but slightly decreased ammonia enhancement under the clouds (left-hand side), with a strong positive physical temperature anomaly concentrated around 7.5 bar.

3.3 Discussion

Previous observations (Gierasch et al. 2000; Fletcher et al. 2017; de Pater et al. 2019a; Dahl et al. 2021; Bjoraker et al. 2022), simulation results (Li et al. 2019a) and results from comparable storms in the solar system (Porco et al. 2005; Sánchez-Lavega et al. 2008; Li et al. 2015) all indicate that water is the main driving force of such large-scale storms. These

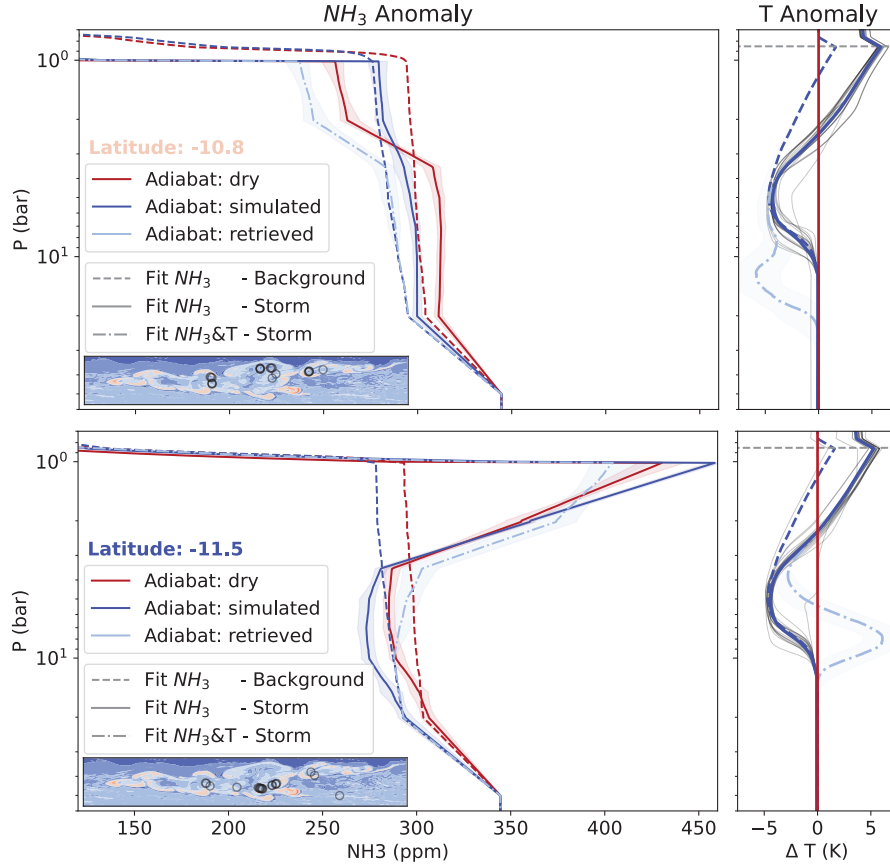


Figure 3.4: Retrieved ammonia abundance results for different assumptions about the physical temperature structure in the atmosphere. The upper panel corresponds to the depleted region west of the storm plume (10.8°S on inset Fig. 3.3), while the lower panel shows results for the region that is co-located with the storm plume (11.5°S). The red lines indicate the background (dashed) and storm (solid) profile for our nominal assumptions of a dry adiabat, while the blue lines show the results including physical temperature variations, as shown on the right. We have included a super-adiabatic layer above the water cloud (dashed line), a subadiabatic region during the storm outbreak (solid line), and a Gaussian temperature anomaly that fits the data assuming that there is no ammonia variation below 10 bar (dot-dashed line). The thin gray lines show a range of temperature anomalies that we obtained from the simulation, where each location is indicated by the gray circle in the inset map on the right-hand side.

are the first observations to quantify the effect of these storms on the ammonia abundance and temperature structure below the visible cloud deck and show how deep the atmosphere is disrupted in the aftermath of the storm. Our retrievals reveal two distinct regimes that have been affected by the storms: a strong anomaly located above 4 bar and a smaller, but opposite anomaly, extending well below the water cloud base to about 20 bars. We have fit several different ammonia and temperature profiles to the brightness temperature anomalies and found that a wide range of models is consistent with the brightness temperatures.

The visually darker regions are indicative of a lack of thick ammonia clouds and are interpreted as a sign of down-welling of dry air. Our observations are consistent with subsidence regardless of the assumptions about the main source for the observed anomalies. We observe subsidence in the form of depleted air (Showman et al. 2005; Sugiyama et al. 2014) or adiabatic heating in a stably stratified atmosphere (Ingersoll et al. 2004). The heating of the upper atmosphere is also consistent with non-hydrostatic simulations that predict a subadiabatic region from 4 bar upwards.

At higher pressures below the visually dark regions, the observations point towards processes that transport condensates well below the level where the storms originally broke from, causing either an abundance or temperature anomaly below the water cloud. For the former case, the retrieved ammonia anomaly switches signs around 4 bars, consistent with the maximum depths that large ammonia rain droplets could reach (Li et al. 2019a). The fact that we find a persistent enhancement at much higher pressures requires processes that deliver ammonia to temperatures well above its boiling point and below the predicted depths from simulations that include standard droplets (Sugiyama et al. 2014; Loftus et al. 2021).

Alternatively, if we assume that the signal has a thermal anomaly contribution, we would require significant cooling around 15 - 20 bars. The temperature anomaly is located about one scale height (H) below the water condensation pressure and with that deeper than the maximum depth ($0.5H$) predicted for the largest stable water droplets to fall under Jovian conditions (Loftus et al. 2021), but still above the boiling point of water at ~ 30 bar (Li et al. 2019a). Instead, we argue that the depth of the anomaly requires even larger precipitates, consistent with the so-called mushballs, a mixture of frozen water and ammonia ice that can form in regions of strong updrafts (Guillot et al. 2020a). Both the depths of the anomaly (~ 15 bar) and the observed temperature anomaly (~ 4 K) are consistent with the predicted range for pressure (5 - 30 bar) and temperature (2 - 17 K at 15 bar). We note that the mushballs could also cause an ammonia anomaly at these depths, and indeed simulations of the processes indicate that they should affect the atmosphere down to pressures of ~ 30 bar (Markham et al. 2023).

In contrast, for the storm plume we find that the ammonia anomaly is consistent with the storm dredging up ammonia and thereby drying out the deeper atmosphere and enhancing the upper atmosphere. The increase of ammonia until the cloud based follows the signature of local condensation and evaporation around the cloud top (Weidenschilling et al. 1973; Ingersoll et al. 2017; Li et al. 2020). While the cooling around 2 bars is consistent with ammonia evaporation, it is unlikely that ammonia can cause such a strong temperature anomaly. Neither the expected temperature change on the order of 1 Kelvin (de Pater 1986)

nor the simulations are consistent with such strong cooling. Therefore, we prefer ammonia as the main source for the anomaly higher up in the atmosphere. Indeed, the in-between case, where ammonia and temperature are allowed to vary (dot-dashed line in Figure 3.4), reconciles both ammonia and temperature anomaly with our expectations for up-welling within the storm plume. In the ascending branches of the storm, a significant amount of latent heat is released as the water condenses. The heating at 7.5 bars points to significant condensation of water, consistent with the existence of the opaque water cloud in these storm plumes (Bjoraker et al. 2022). The latent heat release further fuels the ascent of the parcels, delivering ammonia to the top of the atmosphere forming thick ammonia ice clouds (Dahl et al. 2021; Bjoraker et al. 2022). The combined ammonia and temperature interpretation confirms the role that moist convection plays in providing energy for the storm to maintain itself for long periods (Ingersoll et al. 2000; Gierasch et al. 2000; Li et al. 2015), and an excellent indicator of how dynamics and microphysics could interact to shape the atmosphere of Jupiter, and possibly on the other giant planets.

Although our results are encouraging, there are a few open questions. The retrievals for the regions surrounding the clouds require the upper atmosphere to be subsiding, while the enhancement in ammonia or cooling below the water cloud necessitates rain-out and evaporation. Could the subsidence of the upper atmosphere due to the outbreak trigger secondary smaller-scale storms that produce mushballs? In the region where the upper atmosphere is consistent with strong updrafts as inferred from both in the HST images and from the radio retrievals, the lower atmosphere appears either depleted in ammonia gas or significantly heated, contrary to what moist downdrafts (Showman et al. 2005) or the mushball evaporation model predict (Guillot et al. 2020a).

Regardless of the interpretation of the observations, we find that storms originating at the water condensation pressure have a significant impact on the atmosphere of Jupiter. This is the first time that we see observationally how the ammonia and water cycles are coupled, and how storms redistribute the energy and trace gases in the atmosphere. These outbreaks are often long-lived, lasting for many months, and we show how they continuously disrupt the atmosphere of Jupiter as they evolve. This also confirms that storms play an important role in delivering heat through the atmosphere (Gierasch et al. 2000), how they can change the appearance of complete belts (Fletcher et al. 2017; de Pater et al. 2023) and help explain the global depletion of ammonia down to ~ 30 bar as determined by MWR radio observations (Li et al. 2017b; Moeckel et al. 2023).

3.4 Methods

Deconvolution Algorithm

We developed an algorithm that obtains sub-beam size brightness temperature distribution based on overlapping observations. This method was developed for use with Juno’s MicroWave Radiometer (MWR) due to its irregular sampling of the domain during the flyby,

but is generalizable to any type of observation. The algorithm compares each individual observation with a best estimate of the brightness temperature on the planet, and the differences are then remapped onto the planet. This approach is similar to the approach that retrieves the gridded distribution of the brightness temperature (Zhang et al. 2020). The final resolution of the map is determined by the overlap of the individual observations, resulting in non-uniform resolution throughout the domain.

To obtain a first estimate of the brightness distribution on the planet, we bin all observations at a given frequency ν as a function of boresight latitude θ (Moeckel et al. 2023). The zonal nadir brightness temperature $T_{b0}(\theta, \nu)$ and the limb-darkening coefficient $p(\theta, \nu)$ are then obtained by fitting a parametric relationship between the observed brightness temperature and the emission angle (Moeckel et al. 2023). In Figure 3.7 we show the C5 observations color-coded by the nadir brightness temperature to show the longitudinal coverage obtained for a given flyby geometry. The vertical bar to the east represents the fitted zonal average nadir brightness temperature $T_{b0}(\theta, \nu)$.

We aim to construct a two-dimensional map of the nadir brightness temperature on the planet $T_{b0}(\theta, \phi, \nu)$ that matches the observations. For each integration, we compute the transformation from the instrument frame (azimuth and elevation) of each channel to the planet frame (longitude and latitude): $((\theta_{sc}, \phi_{sc}) \rightarrow (\theta, \phi))$ and map the beam pattern onto the planet out to twice the half-power beam width (Moeckel et al. 2023). For each facet of the beam we obtain the corresponding location on the planet and the emission angle for each beam element with respect to the spacecraft ($\mu \equiv \cos(\theta_e)$). By convolving the brightness temperature map with the projected beam sensitivity and the emission angle distribution across the planet, we can then simulate the observed antenna temperature T_A^{sim} :

$$T_A^{sim} = \frac{\int \int_0^\theta G(\theta, \phi) T_b(\theta, \phi) \mu^{p(\theta, \phi)} \sin(\theta_{sc}) d\theta_{sc} d\phi_{sc}}{\int \int_0^\theta G(\theta, \phi) \sin(\theta_{sc}) d\theta_{sc} d\phi_{sc}} \quad (3.1)$$

The mismatch between the expected antenna temperature and the actual observations: $\Delta T_A = T_A^{sim} - T_A^{obs}$ corresponds to a missing structure on the scale of the beam within the map. We can then update the brightness temperature map for each observation with the computed mismatch:

$$\Delta T_{b0}(\theta, \phi) = \Delta T_A G(\theta, \phi), \quad (3.2)$$

where the beam (G) is normalized so that the residual integrated over the beam is ΔT_A .

For the zonal average, we obtained an independent measure of the limb-darkening coefficient by comparing measurements at different emission angles for a given latitude. By convolving the nadir brightness temperature map with the observation geometry, we can no longer directly constrain the limb-darkening effect. Instead, we must assume prior knowledge for the limb-darkening coefficient to compute the simulated antenna temperature. The simplest assumption ignores the longitudinal variation in the limb-darkening coefficient and uses the zonal average (Zhang et al. 2020). If we interpret variations in the brightness temperature as variations in the atmosphere, it is expected that the limb-darkening coefficient

changes accordingly with longitude. Therefore, we calculated the local correlation between the nadir brightness temperature and the limb-darkening coefficient ($\partial p / \partial T_{b0}$) from the zonally averaged data and linearize the system to obtain an estimate for the variation in the limb-darkening coefficient.

$$\Delta p = \frac{\partial p}{\partial T_{b0}} \Delta T \quad (3.3)$$

The residual that we obtain is limb-darkened, however, we do not correct for the emission angle effect when we are adding back the residual to the map. If we define the beam-integrated emission effect to be $\bar{\mu}$, this effectively reduces the amplitude of the residual by the factor $\bar{\mu}$. While this approach slows down the convergence of the residual, it has the advantage that this method is less sensitive to the assumption about the limb-darkening effect and reduces spurious artifact for beam facets with large emission angles.

We repeat this process for each individual observation and sum up each individual residual to obtain a two-dimensional distribution of brightness temperature and a correlated limb-darkening coefficient. We also keep track of the number of observations (contribution map) constraining a given region using a normalized projected beam, where the center of the projected beam is scaled to unity.

After all observations have been processed, we normalize the system by dividing the $\Delta T_{b0}(\theta, \phi)$ - map with the contribution map. Panel a) of Figure 3.8 shows an example of the ΔT_{b0} - map for Channel 5, which shows the summed residual after convergence is reached (15 iterations). The cross section of panel b) indicates how much structure is added during each iteration, with the added signal decreasing with each iteration. The y-axis on the right shows a cross-cut through the contribution map, a proxy for the number of measurements for a given region. Towards the center of the domain, we have values of up to 75, with the distribution falling off rapidly towards the edges resulting in a roughly 10 degree slice. To avoid edge effects caused by poor sampling toward the boundary of the sampling domain, we have chosen to taper the residuals for regions where the contribution map falls below a value of 5, disregarding a significant number of observations. The shape of the retrieved residuals correlates well with the cloud and haze morphology of the concurrent HST observations, affirming that we are obtaining realistic longitudinal variations. We then add the ΔT - map and Δp - map to our previous estimate and start the next iteration.

We track the convergence of the method by comparing the standard deviation of the retrieved mismatch with the theoretical error based on MWR error budget (Janssen et al. 2017) (see Figure 3.9). The error budget specifies 0.1% of the individual antenna measurement, which translates to 0.2K in Channel 5. The method converges within 5-15 iterations for most observations, upon which further iterations no longer improve the overall mismatch. The remaining mismatch between observations and the model can be explained by the effect of limb-darkening variation across longitude or structure on scales smaller than we can resolve. The final product is a distribution of nadir brightness temperature with their resolution set by the observation geometry: close to the center, the map has the highest resolution,

which decreases towards the edge due to larger individual footprints and less overlapping observations.

To decrease the impact of synchrotron radiation at the longer wavelengths, we removed observations when the beam is pointing toward the equator (Moeckel et al. 2023), where the strongest source of synchrotron radiation is expected to be in the sidelobes (Santos-Costa et al. 2017). This reduces the available measurements for the deconvolution algorithm for C1 - C3 and limits the width of the final maps at the lowest frequencies, as seen in Figure 3.2.

Relative Retrieval

We are interested in the change in the atmosphere due to the ongoing storm. Therefore, we aim to retrieve a brightness temperature anomaly compared to our mean model that matches the observed brightness temperature anomaly for the PJ4 observations. This represents a relative measurement, which reduces the impact of the absolute calibration uncertainty and puts tighter constraints on the effect of the on-going storm system. This comes with the caveat that our retrieved abundances are only valid with respect to the mean atmospheric model.

We first identify the latitude of regions with large anomalies in Figure 3.2, for which we retrieve the background atmosphere. For the mean background atmosphere we use the zonally averaged brightness temperature and limb-darkening coefficients with their corresponding uncertainties to constrain the vertical distribution of ammonia abundance (Moeckel et al. 2023). In practice, we minimize the following cost function using a MCMC framework:

$$\begin{aligned} \ln(p(T, p|x, \sigma)) = & -0.5 \left(\sum_1^6 \ln(2\pi\sigma_T) + \frac{(T_m - T_b)^2}{\sigma_T^2} + \sum_2^5 \ln(2\pi\sigma_p) \frac{(p_m - p)^2}{\sigma_p^2} \right) \\ & + \lambda \left| \sum_1^8 \left(\frac{\delta NH_3}{\delta \ln(P)} \right)_i \right| \end{aligned} \quad (3.4)$$

We are interested in the consequence of the dynamical impact of the storm, and we chose a regularized stochastic model where the pressure can change between preset pressures (Li et al. 2017b; Moeckel et al. 2023). We have selected our nine nodes to sample the atmosphere around the ammonia cloud and the water cloud pressure to constrain the dynamical impact of trace gas condensation ($P_{nodes} = 1, 2, 3.5, 5, 7, 10, 15, 20, 50$ bar). The regularization, the last term on the right-hand side of Equation 3.4, aims to reduce the amount of vertical fluctuations by minimizing the change in ammonia with pressure. Based on the average of the last 5000 draws from the MCMC chain, we can model the brightness temperature $\bar{T}_{model}$ corresponding to a given latitude.

Once we have obtained the mean background model, we can retrieve an ammonia distribution that produces the same brightness temperature anomaly ΔT_{model} as observed during

PJ4 $\Delta T_{\text{observation}}$. We use the same pressure nodes as we have done for the background atmosphere. For the error, we use the 0.1% of the observed temperature (Janssen et al. 2017). We minimize this cost function:

$$\ln(p(T|\sigma)) = -0.5 \left(\sum_1^6 \ln(2\pi\sigma_T) + \frac{\overbrace{(T_{\text{storm}} - \bar{T})^2}^{\text{Model}} - \overbrace{(T_{\text{storm}} - \bar{T})^2}^{\text{Observations}}}{\sigma_T^2} \right) + \lambda \left| \sum_1^8 \left(\frac{\delta N H_3}{\delta \ln(P)} \right)_i \right| \quad (3.5)$$

Our final results are the ammonia abundance anomaly or physical temperature anomalies in the form of a Gaussian temperature deviation, which matches the observed brightness temperature anomaly as shown in Figure 3.3. We parameterize the temperature anomaly as a Gaussian in the log pressure space, where we fit the depth, width, and magnitude, introducing three more variables to fit.

Temperature Structure

The observed brightness temperature variations can be ascribed to both variations in the trace gas abundances and variations in the physical temperature as a consequence of the ongoing storm complex. We tested this correlation by assuming various temperature profiles and determine its impact on the retrieved ammonia abundance.

Our nominal assumption is that everything follows a dry adiabat anchored to the 1-bar measurement of the Galileo probe ($166.1\text{K} \pm 0.8$) (Seiff et al. 1996). This temperature profile is a good representation when studying large-scale dynamics, as evaporation and condensation of trace gases are expected to act on much smaller scales and the result of the Galileo probe showed that within the $5 \mu\text{m}$ hot spot the atmosphere was close to a dry adiabat.

To quantify the impact of the storm on the temperature distribution, we employ non-hydrostatic simulations for Jupiter (Li et al. 2019a), which include the effect of condensable species on the dynamics of the atmosphere. The simulations captured a large-scale storm system at mid-latitudes, allowing us to capture the correlation between ammonia abundance and temperature variations. Based on the simulations we construct two temperature profiles: a domain-averaged temperature structure that is used to constrain the background atmosphere and individual profiles that represent the physical temperature variation during an ongoing storm.

For our updated background profile, we let everything at pressures below 12 bar follow our nominal dry adiabat, making 12 bar the anchor point where both profiles agree. The temperature structure below is highly dependent on the water content and could be significantly warmer than our assumptions (Leconte et al. 2017), however, this effect would only affect the absolute ammonia abundance and has less impact on our relative retrieval. At altitudes above 12 bar, the temperature profile is affected by the stabilizing effect of the

water cloud, causing a super-adiabicity around the water cloud condensation pressures. We compute the adiabatic lapse rate above 12 bar based on the simulations and propagated it upward until the 1-bar pressure. At 1-bar, the temperature reaches 166.9K, within the errors of the Galileo probe measurement (Seiff et al. 1996) and within a degree from our nominal profile. Higher in the atmosphere, the temperature structure follows the results from mid-infrared observations (Fletcher et al. 2009).

For the individual storm profiles, we match the retrieved ammonia profiles with the simulations that exhibit a similar topology. For each region, we selected 20 profiles from the simulated domain and computed the mean temperature deviation. All profiles share a strong subadiabatic region above 4 bars, leading to local heating of the troposphere.

Non-hydrostatic Simulations

We utilize the non-hydrostatic cloud-resolving model (based on Athena++ (Stone et al. 2008)) to study Jupiter’s atmosphere’s large-scale behavior (Li et al. 2019a). We conduct simulations on a beta plane using altitude coordinates in a Cartesian box to simulate the differential rotation at different latitudes on Jupiter. The domain is bounded by solid walls in latitude at 20° as the southern boundary and about 57° as the northern boundary. We adopt doubly-periodic boundary conditions in longitude. The size of the domain is 4.5×10^4 km in latitude, 6×10^4 km in longitude, and 340 km in altitude, in which the corresponding pressure range is about $2.5\text{E-}3$ to 90 bars. The resolution in longitude and latitude is 150 km, while it is about 2 km in the vertical. We initialize the simulation with three times solar water and ammonia and initialize the numerical experiment with the corresponding thermo-chemical equilibrium moist adiabat (Li et al. 2018a). The initial horizontal wind profiles are uniformly zero, but we implement a random and small vertical wind field, which is on the order of $1 \sim \text{cm s}^{-1}$ to break the initial asymmetry. Convection is driven by the spatially uniform and temporally constant cooling at the top and heating at the bottom, and their fluxes are fixed to 7.5 W m^{-2} , which is the recently corrected internal heat flux of Jupiter (Li et al. 2018b). The heating and cooling scheme was adopted for many numerical simulations to study the general behavior of moist convection on giant planets (Sugiyama et al. 2011; Sugiyama et al. 2014). We slightly overforce the model by amplifying the heat flux by a factor of four in the first 3,000 days and then reducing the heat flux to the normal Jupiter value so the simulation can reach the statistically steady state faster.

The simulation produces several self-organized mid-latitude jets, belts, and zones. It also produces storms that periodically occur every three to four years. In this study, we chose the storm that happened around 4,000 simulation days to best match the ammonia and temperature retrieval from the Juno data.

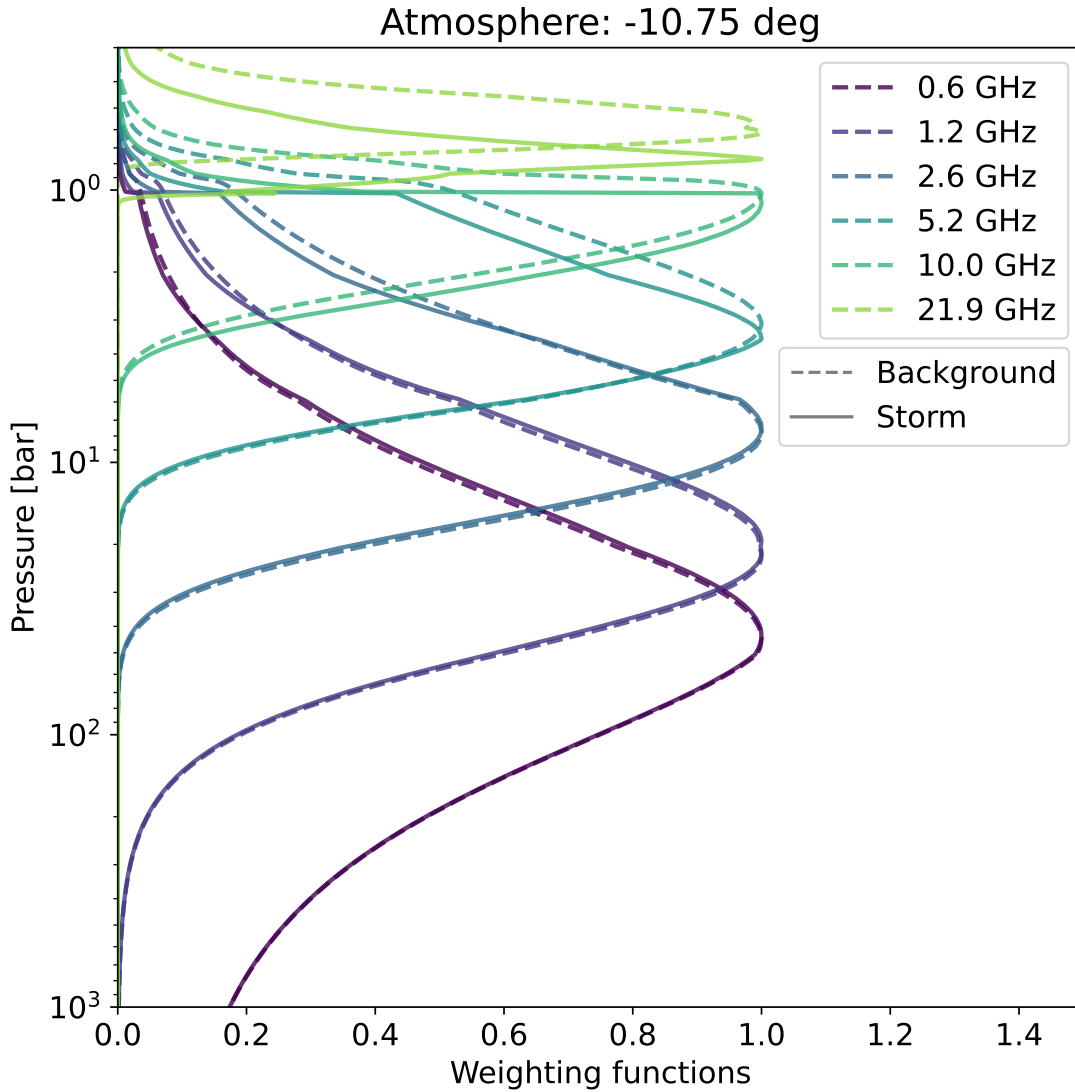


Figure 3.5: Radio signals record the opacity-weighted thermal emission by the atmosphere. Since the ammonia is the main factor controlling the opacity of the atmosphere, changes in the ammonia abundance will change the pressures from which the thermal signal is received. The dashed lines indicate the pressure from which the thermal emission is received for each frequency based upon the background ammonia profiles. The solid lines correspond to the storm profile that we retrieved. The depleted upper atmosphere allows to probe slightly deeper than compared to the background atmosphere.

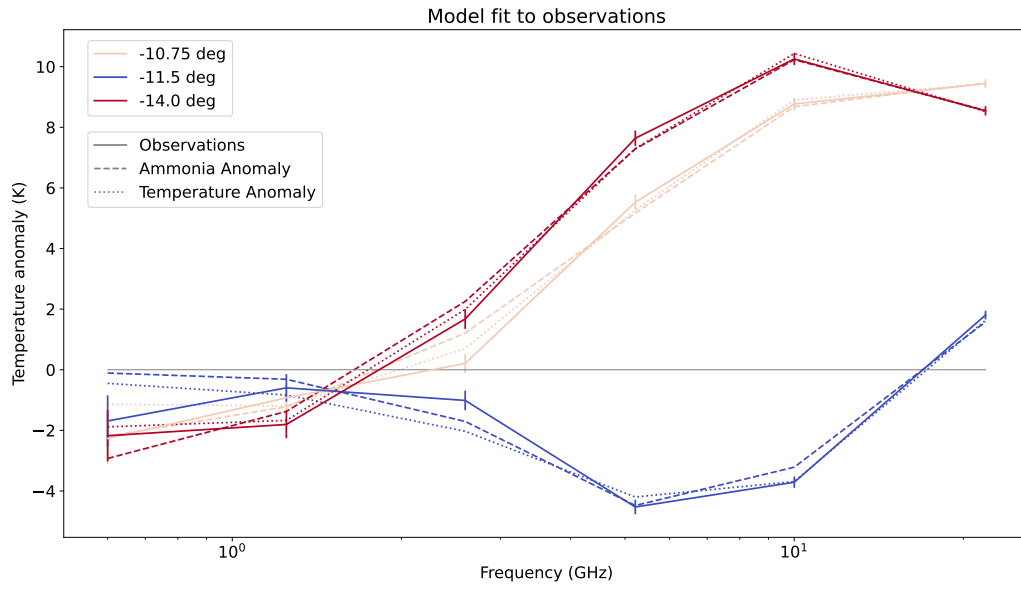


Figure 3.6: Comparison between the observed brightness temperature anomaly (solid lines) and the fitted brightness temperature anomaly for the three regions under consideration in Figure 3.3. The dashed line is the modeled brightness temperature difference between the background atmosphere and the storm atmosphere assuming a pure ammonia anomaly. The dotted line shows the result for keeping the ammonia abundance constant and instead showing a pure temperature anomaly. Both models, despite very different assumptions, fit the observations well.

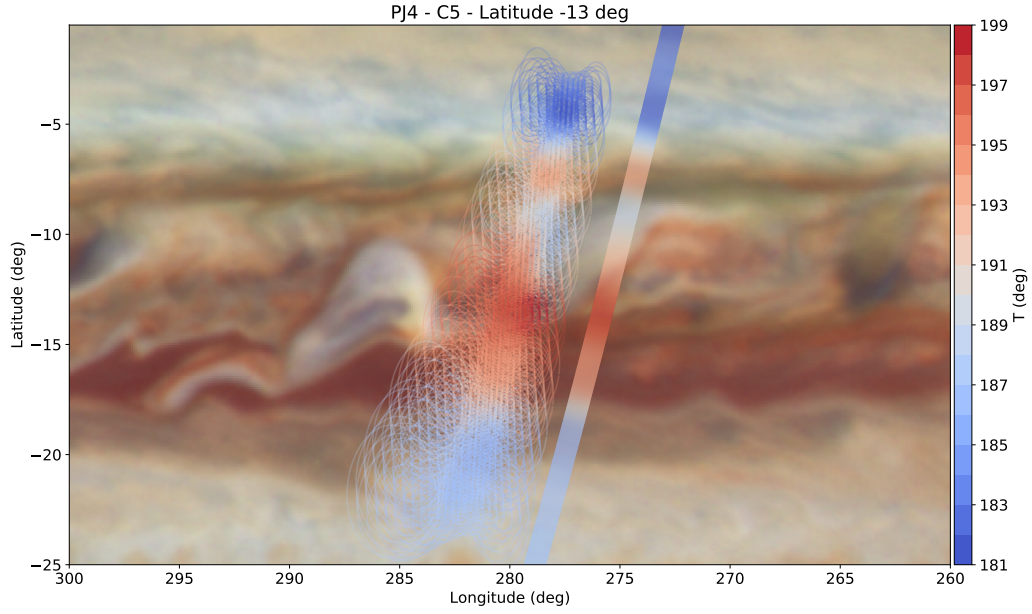


Figure 3.7: Example of the distribution of the available individual observations for the PJ4 flyby in the southern hemisphere, where each individual ellipse represents a single integration. For displaying purposes alone, we have converted each measurement into nadir brightness temperature, by assuming a limb-darkening coefficient. The bar on the right hand side indicates the zonally averaged brightness temperature, and the starting point for the deconvolution algorithm.

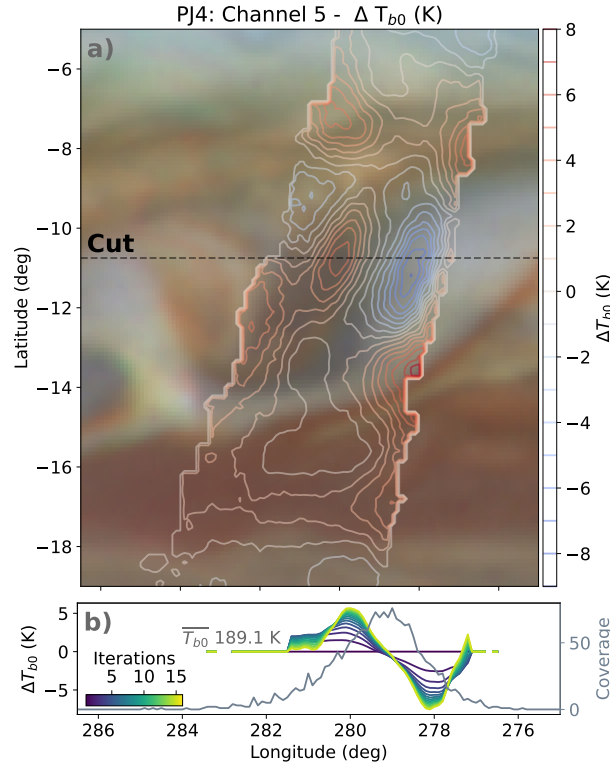


Figure 3.8: Example residual distribution for C5 during the PJ4 flyby. Panel shows shows the ΔT_{b0} distribution overlain on concurrent HST observations. The retrieved residuals are largest in regions where the HST observations show a localized white storm plumes next to a darker background. Panel b) is a cross cut through the ΔT_{b0} map where each line corresponds to the summed brightness residual after the number of indicated iterations, and the secondary axis indicates the number of observations for a given region of the map.

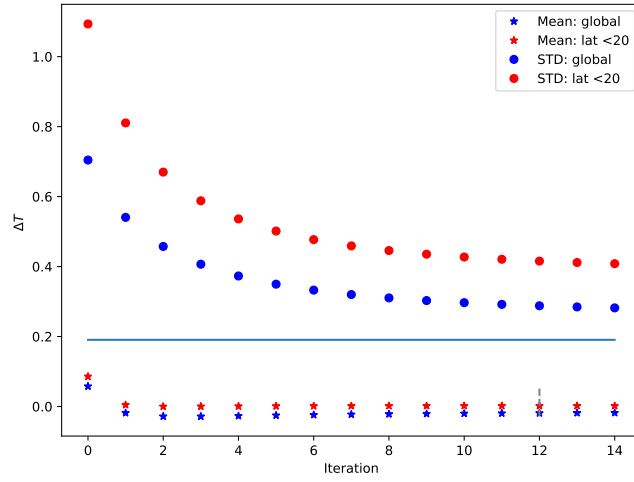


Figure 3.9: Convergence of the method by comparing the mismatch for PJ4 - C5 across all measurements with the theoretical measurement error approach 0.1% (Janssen et al. 2017) indicated by the horizontal line. We can see that within the first few iterations the standard deviations drops quickly until it slowly converges towards the theoretical limit. We track convergence in the tropical regions (lat < 20 deg) and globally, to look for possible contamination by synchrotron radiation.

Chapter 4

Effect of the Weather

Summary

Towering storms, swirling clouds, and vortices are the cloud tops manifestation of complex weather systems shaping the atmosphere of Jupiter. We use observations from Juno's MicroWave Radiometer (MWR), the Very Large Array (VLA) and the Hubble Space Telescope (HST) to probe the depth and impact of weather on Jupiter for the first time. We use ammonia, the main source of opacity at radio wavelengths on Jupiter, as the tracer for the weather by fitting ammonia anomalies to the MWR brightness temperature variations. We show that the majority of the weather on Jupiter is confined to regions where the clouds are forming. Both the South Equatorial Belt and the Equatorial Zone have surprisingly shallow weather systems ($P < 2$ bar), and even in the North Equatorial Belt most of the ammonia variations is above the water condensation level ($P \sim 6$ bar). This confirms that the water condensation layer plays a crucial role in controlling the dynamics and the weather on Jupiter. However, the shallow nature of the weather cannot explain the deep-seated depletion down to 30 bars that the Juno mission has revealed. Instead, we find three features that can extend below the water condensation layer: a vortex in the northern hemisphere reaching 30 bars, the tentative detection of an ammonia plume going down to 20-30 bars, and the signature of precipitation going down to 20 bars.

This work confirms that an interplay of large-scale processes (vortices, Rossby waves) and very small-scale processes (lightning storms) are responsible for shaping the atmospheric makeup of Jupiter.

4.1 Introduction

The Juno mission has challenged our understanding of the troposphere of Jupiter, by uncovering a distribution of material within the atmosphere that is inconsistent with our understanding of the dynamics. Before the Juno mission, the main driver of atmospheric distribution was assumed to be the global circulations, with Hadley and Ferrel cells dis-

tributing energy and material in the atmosphere. The more recent canonical view of the 2-layer shallow circulation (Showman et al. 2005; Fletcher et al. 2009; Fletcher et al. 2020b), where the lower cell extends from the tropopause to the layers at which the water condenses ($P \sim 6$ bar), was challenged by the realization that ammonia (Li et al. 2017a; Moeckel et al. 2023) and temperature effects (Li et al. 2024; Moeckel et al. 2024b) can be traced to much higher pressures ($P \geq 20$ bar). Instead, recent theoretical work (Guillot et al. 2020a) and observations (Moeckel et al. 2024b) support the idea that processes on the smallest scales could potentially explain the distribution by depleting the upper troposphere and enriching the lower troposphere through storms.

For this, processes of various scales have to interact to create these conditions. It requires a large-scale suppression of convection in order to build up convective available potential energy (CAPE) in the atmosphere, which is then violently released on intermittent time scales to form large-scale storms and localized thunderstorms. Inside these storms, the condensation and precipitation of water can be delayed, supercooling the water to a point where ammonia can much more effectively dissolve into water (Guillot et al. 2020a). Due to the supercooled nature of the water, the precipitates that form in this process can rapidly grow and obtain significant falling speeds, to reach pressures and temperatures much beyond their melting and evaporation points. This impact of storms on the middle and lower troposphere has been observed on both Jupiter (Moeckel et al. 2024b) and Saturn (Li et al. 2023), and could also play an important role for the ice giants (Guillot 2021).

In this paper, therefore, we aim our focus on intermediate scales - the weather patterns in the tropics of Jupiter. The turbulent cloud tops that dominate the tropical region of Jupiter offer us a glimpse of the dynamics that constantly shape the atmosphere. While we have a good understanding of the depths to which large-scale outbreaks (de Pater et al. 2019a; Moeckel et al. 2024b) and vortices can affect the atmosphere (Bolton et al. 2021), we lack an understanding of the role of these weather systems in affecting the atmosphere. In this work, we explore the link between the dynamics that play out at the cloud tops and trace these effects below the cloud tops.

We combine HST observations, with concurrent radio observations obtained with the MicroWave Radiometer (MWR) on board of Juno to map the three-dimensional structure of the ammonia distribution in the Jovian atmosphere and use observations with the Very Large Array to provide context and generalize these findings. We focus our analysis on the tropical region of Jupiter, where we see the majority of activity in the atmosphere based on visible and radio data. We first describe the three data sets that we are working with, then we explain our methodology for retrieving the three-dimensional weather based on the Juno observations. We conclude the paper with a comparison of the Juno observations with the VLA observations, and generalize the finding to the global atmosphere.

4.2 Data

Perijove 19 (PJ19) was dedicated to study the longitudinal structure of Jupiter, by aligning the spacecraft’s spin axis with the velocity vector, allowing the atmospheric instruments to scan the planet in an east-west manner. This specific focus on the longitudinal structure of the spacecraft motivated many scientists to support the campaign with (near)-simultaneous earth-based observations across a wide range of frequencies.

VLA data

We observed Jupiter with the VLA across 3 frequency bands in the B-configuration during Juno’s closest approach to provide a global snapshot of the Jovian sub-cloud structure down to pressures of ~ 4 bar (see Figure 4.1). To capture a global map for each frequency, we observed Jupiter over 4 nights, each night covering a Jovian hemisphere. The first two nights were used to observe Jupiter in X-band (8-12 GHz), interleaved with Ku-band (12-18 GHz); the two remaining nights were used for K-band (18-26 GHz). We detail the relevant details for each observation in Table 4.2. Each night was processed using the standard VLA CASA pipeline (Common Astronomy Software Applications) and then further processed in CASA (version 5.4.1-32). All four nights used the same amplitude and phase calibrator (3C286 and J1726-2258, resp.).

We first averaged the observations in time and frequency (10s, 16MHz) to increase the signal-to-noise ratio and reduce the size of the dataset for processing. We analyzed the difference between the expected and observed amplitudes as a proxy for the noise and interference in the system for each antenna pair. We flagged observations that showed spurious signals that were not picked up by the automatic radio frequency interference task in the pipeline. Once the data were flagged, we combined the two nights into a single combined dataset for the iterative inversion process. We split each night into two frequency bands for the self-calibration: The first two nights were split into X-band (8-12 GHz) and Ku-band (12-18 GHz) along their designated frequency band allocations, while the third and fourth nights were split in the middle (18-22 GHz, 22-26 GHz).

Variations in the atmospheric conditions above the antennas affect the phase of the incoming radio waves and increase the noise of the observations. The phase of the incoming radio waves is used in the Fourier transform to determine the location of the source on the sky. Therefore, phase delays blur the brightness distribution on the sky. Since we have a good understanding of the large-scale structure on the planet, we can correct for the phase-delays by correlating the signal between the various antenna pairs in a process called self-calibration. For the self-calibration procedure we build a model atmosphere that mimics the position and shape of Jupiter based on JPL horizons ¹ and flux from previous observations (de Pater et al. 2019a). Due to the high resolution of the observations and the wide spectral coverage, we included the zones and belts and their dependencies on the frequency in our model at-

¹<https://ssd.jpl.nasa.gov/horizons/>

mosphere. Within CASA we Fourier transform the model into the uv -plane, and performed two iterations of self-calibration. With increasing iterations we decrease the duration over which we obtain the phase delays starting with a solution interval of 5 min, and decreasing it to 2 min in the second iteration. These intervals represent the duration of the atmospheric fluctuations that we average over. We found that at shorter time intervals the signal was not strong enough to further solve for phase-delays. This concluded all the calibration efforts in CASA and we exported the calibrated dataset for the deprojection step in MIRIAD (Multichannel Image Reconstruction, Image Analysis and Display) (Sault et al. 1995).

We noticed that each observation of Jupiter appeared to be shifted from its ephemeris. The presence of these shifts probably points to unresolved phase-delays affecting the observations, potentially introduced by the self-calibration process. Or unaccounted timing-delays during the correlation steps. We, therefore, move the center of the data until they correspond well to the expected location of Jupiter for the given epoch. For the deprojection we remove the bulk of the emission by subtracting a limb-darkened disk and map these residuals using the method developed by Sault et al. (2004) to obtain global radio-residual maps. We produce maps that make use of the full frequency coverage for each band, where the increased frequency coverage fills in more of the uv space increasing the fidelity of the Fourier transform. The radio residuals highlight the atmospheric structure after removing the bulk emission as seen from Earth. As a consequence, the emission angle, that is the angle between the local zenith and the radio observatory, varies across the domain. Smaller emission angle, i.e. an increased angle between the zenith and the observer, increases the path lengths through the atmosphere. This increases the absorption along the line of sight and reduces the received brightness temperature. The emission angle varies across latitude due to the shape of the planet and varies with longitude due to the observation geometry during the observations. Therefore, the VLA residuals are the limb-darkened residuals as seen from an Earth-based observer. Without prior knowledge about the atmosphere, we cannot correct for this effect, since the limb-darkening is dependent on the distribution of radio-absorbing gases in the atmosphere.

HST data

Hubble Space Telescope observations (GO-#15665, PI: de Pater) were taken as part of the VLA observations campaign in support of PJ19. In total, they cover 4 rotations of Jupiter. The data are publicly available in the Mikulski Archive² and published by (Wong et al. 2020b); we refer the reader to this paper for the description for the data reduction. During the campaign HST took images at 225 nm, 275 nm, 395 nm, 631 nm, 727 nm, and 889 nm, however we only use the blue 395 nm and 631 nm to provide context for the radio observations.

²<https://archive.stsci.edu/hlsp/wfcj>

Juno/MWR

Juno hosts a set of six radiometers operating between 0.5 and 22 GHz, referred to as Channel 1 through 6 (C1-C6), to study the troposphere of Jupiter (Janssen et al. 2017). The six radiometers record the beam-convolved brightness temperature, that is the sky brightness temperature distribution with the instrument’s sensitivity pattern. The MWR beams sweep across the atmosphere as the satellite spins with 2 rpm, obtaining multiple measurements for a given location on the planet at different emission angles. The rotation vector of the spacecraft determines the number of overlapping observations. As mentioned, PJ19 was optimized for longitudinal coverage.

For our data reduction we obtain the antenna temperatures from the Planetary Data System ³ and first fit the nadir brightness temperature and limb-darkening coefficient to all the observations based on a parametric relationship between the brightness temperature and the emission angle (Moeckel et al. 2023). We choose a 2° bin size for this dataset, that is we consider all observations whose boresight fell within the bin size to fit the parameters. Based on this we obtain zonal brightness temperature and limb-darkening coefficient along with their uncertainties. We use this average as the starting point for the deconvolution that maps sub-beam size structure across the planet (Moeckel et al. 2024b). In an iterative approach, we convolve our best understanding of the atmospheric distribution with the beam pattern for each observation and update the maps based on the mismatch between observations and the best fit. Since we are convolving the brightness temperature structure with viewing geometry, we lose information about the limb-darkening coefficient, reducing our observables from 12 independent measurements (six frequencies sampling the nadir brightness temperature and limb-darkening coefficient) to just the 6 nadir brightness temperatures. We remove measurements where the beam is only partially on the planet to decrease the synchrotron contamination (Moeckel et al. 2023). The larger beamsize of C1 and C2 results in a much narrower domain, compared to the upper channels and limits longitude/latitude extent over which we have full frequency coverage.

We used all available measurements with their varying viewing geometries to construct maps. Closest to the center of the map we have the best resolution, steadily decreasing towards the edge of the domain due to the large footprint. The measurements at the lower frequencies closest to the edge of the domain appear to be affected by the synchrotron radiation, where extra emission seems to be picked up when the beam’s boresight is getting close to the limb of the planet. Instead of restricting the emission angle coverage we decided to remove the synchrotron radiation by running a moving median filter on the brightness temperature residuals for C1 - C3 (see Addendum A to the Chapter).

Radio Maps

In Figure 4.2 we show the observations from April 6 and 7 that coincided with Juno’s PJ19. The three panels show the HST observations, the VLA X-band observations, and

³<https://pds.nasa.gov/>

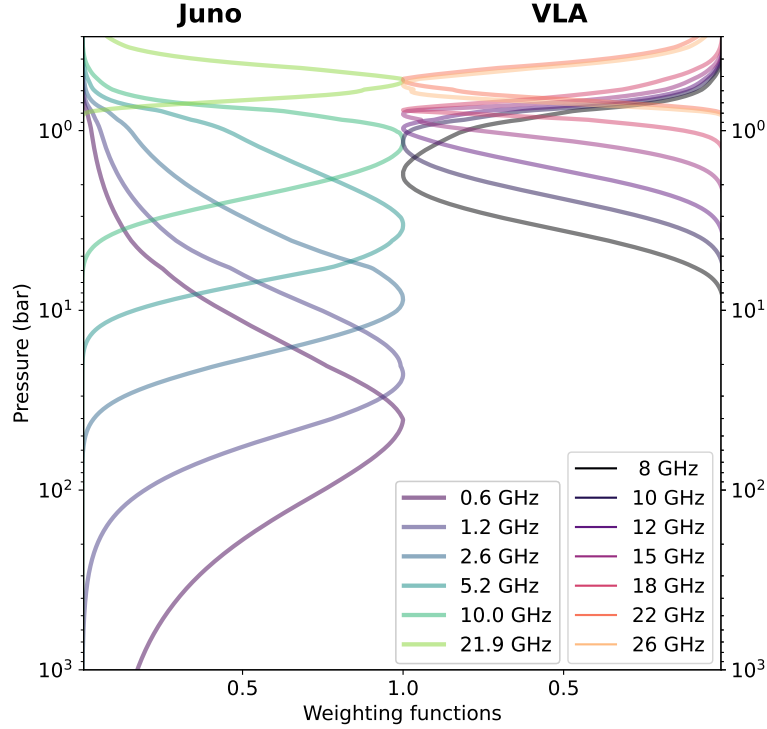


Figure 4.1: Weighting functions that indicate the pressure from which the thermal emission originates for a given frequencies. The Juno frequencies are presented on the left hand side, while the VLA frequencies are shown on the right hand side. The weighting functions are based on the mean tropical atmosphere of Jupiter coupled to a dry adiabat.

the VLA Ku-band observations, from top to bottom. The outline indicates where we have full frequency coverage of all 6 channels with MWR and denotes what small fraction of the planet MWR is able to scan during a single flyby. However, Juno's lower frequency measurements are able to provide information to much deeper part of the Jovian atmosphere (see Figure 4.1). The VLA X-band maps, probing deepest from all the VLA maps, show that Juno passed just west of an equatorial ammonia plume (90°W , 6°N , all latitudes are planetocentric in this paper), as seen by extremely low temperatures compared to their surroundings. Furthermore, the VLA maps show that the variability within the PJ19 region is typical for that part of the atmosphere. In the southern hemisphere, the Juno observations span two very narrow bright belts, whereas in the northern hemisphere the vortex structure at 15°N appears as a cold brightness temperature anomaly. Probing slightly higher in the atmosphere, the Ku-band maps show much more variability in the atmosphere. The ammonia plume anomaly just east of the flyby is less pronounced, but the slightly higher resolution

	Label	λ (nm)	Date	Time (UTC)	Resolution (km)
Hubble Space Telescope GO-#15665	HST - blue	395	2019-04-06	10:36:19	~180
	HST - red	631		10:39:57	
	HST - blue	395	2019-04-07	10:26:18	
	HST - red	631		10:29:56	
	HST - blue	395	2019-04-08	10:16:15	
	HST - red	631		10:19:53	
	HST - blue	395	2019-04-09	10:01:56	
	HST - red	631		09:58:31	
	Label	ν (GHz)	Observation date	Time (UTC)	Resolution (km)
Very Large Array VLA ID: 19A-001	X-band	8 - 12	2019-04-06	08:58:01 - 14:27:06	~4000
	Ku-band	12 - 18		08:58:01 - 14:27:06	~2500
	X-band	8 - 12	2019-04-07	08:54:05 - 14:23:09	~4000
	Ku-band	12 - 18		08:54:05 - 14:23:09	~2500
	K-band	18 - 26	2019-04-08	08:50:09 - 14:19:14.0	~1500
	K-band	18 - 26	2019-04-09	08:46:13 - 14:15:18	~1500
	Label	ν (GHz)	Observation date	Time (UTC)	Resolution (km)
Juno MWR	C1	0.6	2019-04-06	12:05:18 - 12:31:18	~2000
	C2	1.248			~2000
	C3	2.597			~1000
	C4	5.215			~1000
	C5	10.0			~1000
	C6	21.9			~1000

of the Ku-band observations shows that Juno covered an interesting region with significant brightness temperature variations at the EZ-NEB interface. In Figure 4.3 we show the observations for the next two days. The K-band observations probe the pressures around the ammonia ice cloud. The middle panel (centered around 20 GHz) shows that Juno observed a pretty calm part of the atmosphere for these pressures. The lower panel in Figure 4.3 is centered at 24 GHz, close to the center of the ammonia absorption band (23.5 GHz). At this frequency, the observations probe the highest in the atmosphere. These observations, being close to the water band, were the most challenging and had significant non-zonal features that appeared to be artifacts. Due to heavy filtering, we consider these maps only qualitative. The overall variability decreases in the maps as the observations probe altitudes at and above the NH_3 condensation level. The regions that Juno sampled appear mostly uniform.

For visualization purposes only, we combine the three of the four maps into a color composite image where the different colors indicate the depths from which we receive the signal. The red colors in Figure 4.4 correspond to radio-warm structure that has a deep root. Yellow corresponds to structure that is deep and cold in the planet, like the vortices at the northern edge of the NEB or the plumes at the northern edge of the EZ. The whiter/greenish

tones correspond to shallow structure extending just below the ammonia ice clouds, while blue/purple correspond to structure in and above the ammonia clouds.

The Juno deconvolved maps in Figure 4.5 show the nadir brightness temperature distribution for the 6 channels. Interpretation of the brightness temperatures alone is complicated by the fact that the weighting functions cover a wide range of pressures. Features visible across multiple frequency bands, however, are good indications of the vertical extent of these features. These maps reproduce the structure of the maps published before (Bolton et al. 2021). The most significant feature in these maps are the two large-scale features, an anticyclone and a barge in the northern hemisphere, that can be seen across most of the frequencies.

4.3 Methodology

The extended frequency and emission angle coverage, together with a high spatial resolution, allow Juno to constrain Jupiter’s tropical region to a much higher accuracy and greater depth than the VLA observations, albeit with a narrow longitudinal focus dictated by the orbit. Combining the VLA and Juno data in our retrievals would require us to deconvolve the Juno observations to the VLA resolution. Instead, we use the Juno observations to build up a 3D map of the temperature and NH_3 distribution in the tropical region of the atmosphere, and compare the results directly to the VLA observations.

We aim to map variations in atmospheric conditions with a lesser focus on the absolute abundances. Therefore, we utilize a multi-step method to obtain the atmospheric distribution of Jupiter. We first constrain the local atmospheric conditions by fitting a model atmosphere that matches the zonally averaged Juno observations, including both the nadir brightness temperature and the limb-darkening coefficient in the inversion (Moeckel et al. 2023). Figure 4.6 shows the PJ19 observables compared to the mean of the first 12 orbits including their standard deviations. The PJ19 signal in the southern hemisphere appears to be within the nominal atmosphere, while the atmosphere in the northern hemisphere shows more variations. We use radiobear⁴ (de Pater et al. 2005; de Pater et al. 2014; de Pater et al. 2019b; Moeckel et al. 2023) to model the effective brightness temperature for a given ammonia and/or temperature distribution in the atmosphere at the relevant frequencies. We parameterize the atmosphere by allowing the ammonia abundance to vary between various pre-set pressures until we reach the ammonia condensation pressure, above which the profile follows the saturated vapor pressure curve, modulated by the relative humidity Moeckel et al. (2023, Model 2). Figure 4.7 shows the ammonia distribution based on the averaged PJ19 observations assuming the atmosphere follows a dry adiabat (Moeckel et al. 2023) anchored to the Galileo 1 bar temperature of 166.1 K (Seiff et al. 1996). While in recent years there is growing evidence from theory (Guillot 1995; Leconte et al. 2017; Guillot et al. 2020a), from simulations (Li et al. 2018a; Ge et al. 2024), and from observations (Li et al. 2024; Moeckel et al. 2024b) that there are temperature variations below the clouds,

⁴<https://github.com/david-deboer/radiobear>

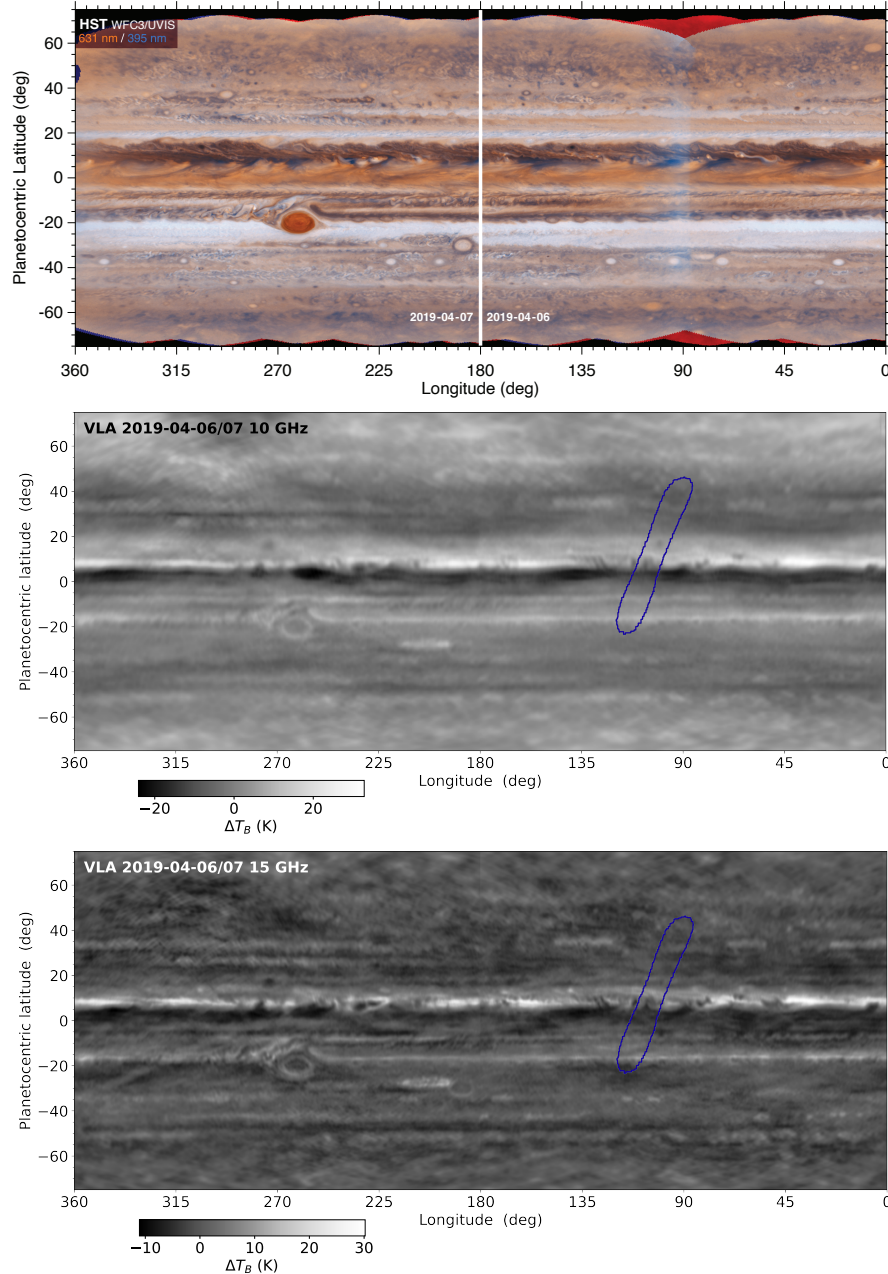


Figure 4.2: HST and VLA X- and Ku-band observations during 6th and 7th of April. The observing geometry from Earth only allowed hemispherical coverage of the planet, so that the both hemisphere are separated by 24 hours, or 2.5 Jovian rotation. The top row shows the red and blue composite of the HST observations, the middle row shows the VLA X-band observations, centered around 10 GHz with a 4 GHz bandwidth, and the lower row shows the VLA Ku-band observations centered around 15 GHz with a 6 GHz bandwidth. For the Ku-band data used a Gaussian filter to remove any non-zonal large scale structure (see Addendum B to the Chapter). The blue outline indicates where we have simultaneous coverage across all 6 Juno frequencies.

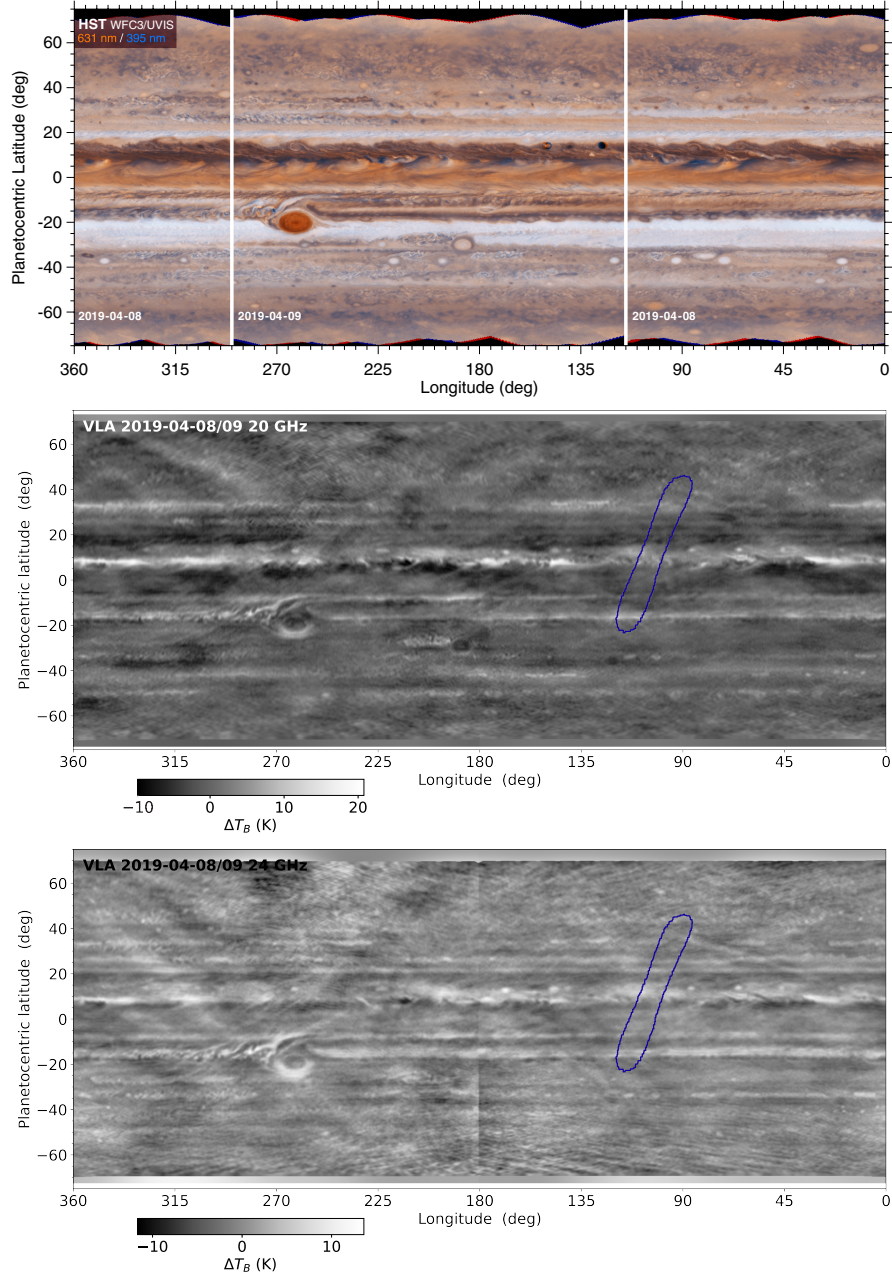


Figure 4.3: Same as Figure 4.2 but for the observations during 8th and 9th of April. The middle row shows the VLA K-band observations around 20GHz with a 4 GHz wide bandwidth, and the lower row shows the K-band observations around 24 GHz with a 4 GHz bandwidth. These lower panel was heavily filtered, and should be considered qualitative.

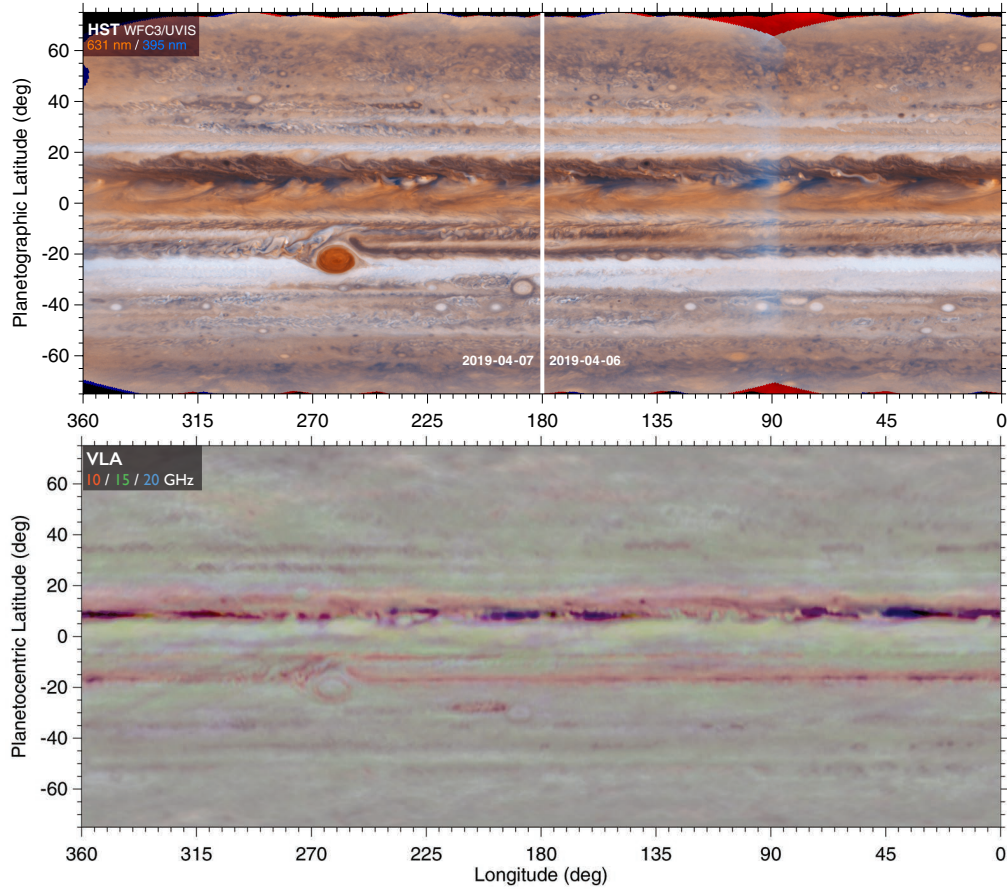


Figure 4.4: HST and VLA observations taken during Juno’s PJ19 encounter. The top panel shows the HST observations, while the lower contains a composite made of the three frequency bands corresponding to three color channels: red and yellow (X-band/10 GHz) show warm and cold brightness temperatures deepest in the planet, green/white colors (Ku-band/15-GHz) show the structure under the ammonia ice clouds, and blue colors (K-band/20-GHz) probe the pressures around the ammonia ice clouds.

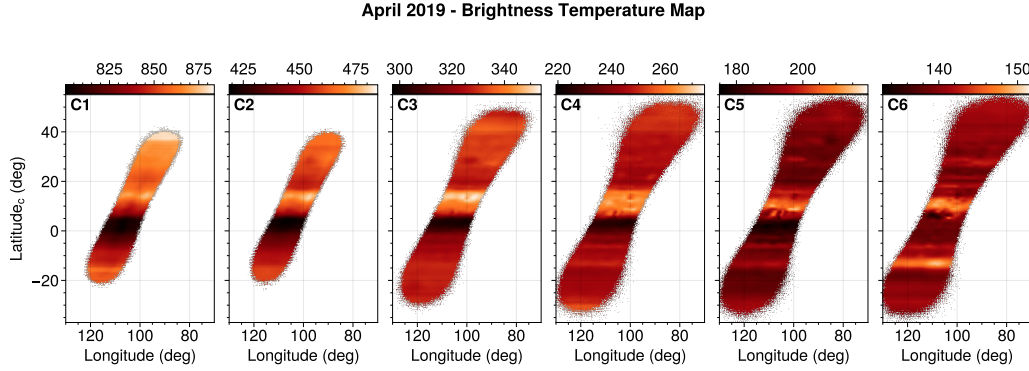


Figure 4.5: Deconvolved PJ19 Juno observations that map out the nadir brightness temperature distribution for the 6 channels. The channel numbers are increasing left to right. The colorbar for each panel is appended to the top of the plot. The resolution is set by the size of the individual beams and the the number of overlapping observations (Moeckel et al. 2024b). The lower frequencies cover less area due to the larger beams size and therefore dictate the region over which have full frequency coverage. These maps were independently produced, analyzed, and published by (Bolton et al. 2021).

we still have little information about their distribution. Although the exact temperature structure will affect the reference atmosphere (Li et al. 2024; Moeckel et al. 2024b), it will not affect the main conclusions of this paper, which is based on relative measurements in the brightness temperature. We used an optimizer that minimizes the difference between the observables (nadir brightness temperature T_B , limb-darkening coefficient p) and their modeled counterparts (T_m, p_m), while simultaneously regularizing the amount of vertical fluctuations using $\lambda = 1E4$ (Moeckel et al. 2023):

$$C_{fit} = \sum_1^6 \frac{(T_m - T_B)^2}{\sigma_{T_B}^2} + \sum_2^5 \frac{(p_m - p)^2}{\sigma_p^2} + \lambda \left| \sum_1^8 \left(\frac{\delta N H_3}{\delta \ln(P)} \right)_i \right| \quad (4.1)$$

Although working in a Markov Chain Monte Carlo framework (Li et al. 2017a; Li et al. 2024; Moeckel et al. 2024b) is preferable to determine parameters and their uncertainties, this was not possible due to the large computational costs incurred. Instead, we retrieve the zonally averaged ammonia abundance with 0.5° latitudinal resolution over the areal extent covered by Juno. Since optimizers have a higher likelihood to find local minima and produce large outliers, we apply a running median filter that is 2° wide to smooth out the data. Overall, the structure for PJ19 mirrors the topology we have seen before (Moeckel et al. 2023). We find an atmosphere that appears to be depleted in ammonia down to 30-40 bar

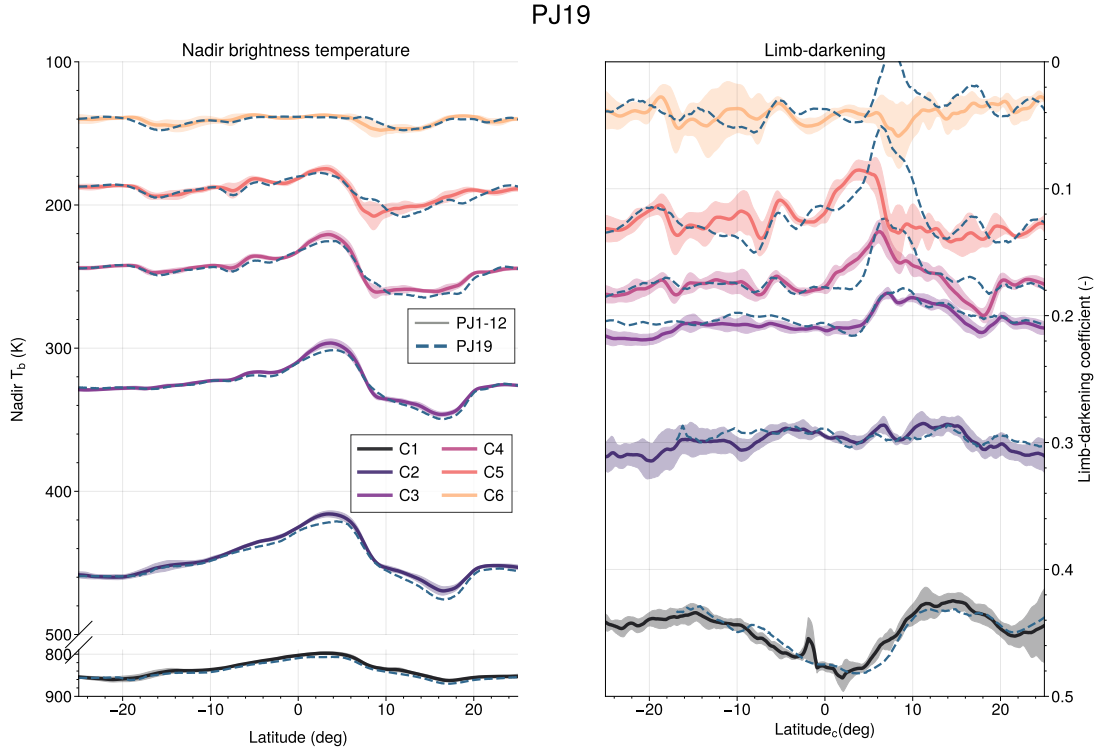


Figure 4.6: PJ19 observations compared to the mean atmosphere that we use to build up the reference atmosphere for our analysis.

in the southern hemisphere. The equator and northern hemisphere are dominated by the EZ and NEB signal, which have the lowest and highest brightness temperatures across the planet. We find a strong equatorial enhancement of the ammonia abundance especially at the northern edge of the EZ, with a highly depleted NEB that shows a characteristic depletion down to 40 bars, much deeper when compared to the equivalent latitudes in the southern hemisphere.

Next, we aim at retrieving residuals in the model atmosphere that mirror the brightness temperature residuals after subtracting the zonal mean, i.e. the longitudinal residual. The main disadvantage of this method over absolute retrievals is the fact that we lose information about the absolute abundance and our results are relative to a reference atmosphere. However, the advantage of a relative retrieval is that we can decrease the absolute calibration of 1.5% down to the $\sim 0.1\%$ measurement uncertainty for each observation (Janssen et al. 2017). The spatial variations within the maps are not affected by the absolute calibration error, which affects all data equally. By using this method, we drastically increase the reliability of our retrievals.

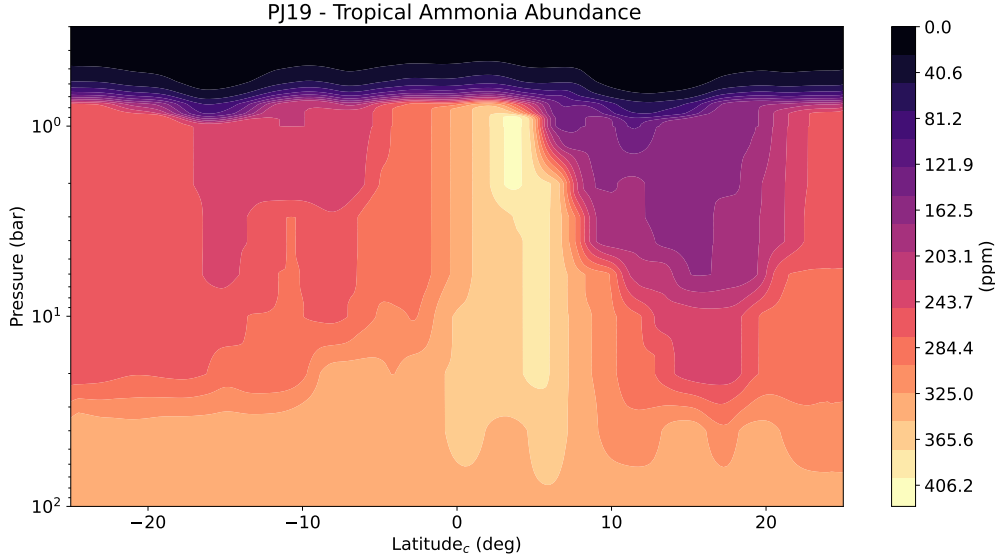


Figure 4.7: Retrieved ammonia abundance based all zonally averaged Juno observables (see Equation 4.1). We median filtered this map for visualization purposes only to remove small scale fluctuations.

To produce the anomaly map ($\Delta T(\theta, \phi)$), we first subtract the latitudinal (i.e., zonally averaged) brightness temperature profile ($\overline{T_B}(\theta)$) from the brightness temperature maps ($T(\theta, \phi)$ in Figure 4.5) to produce the residual map (4.8):

$$\Delta T_B(\theta, \phi) = T_B(\theta, \phi) - \overline{T_B}(\theta) \quad (4.2)$$

Additionally, we apply the synchrotron filter for Channel 1, 2, and 3 as explained in section 4.6 to remove the mild limb-brightening in the residuals.

Using this modeling framework, we retrieve an atmospheric model that mirrors the same residual structure as the observations. That is, we are no longer retrieving absolute ammonia abundances, but rather the ammonia anomaly with respect to our reference atmosphere, which would produce the same magnitude anomaly as we see in the observations. We note that the variations in the atmosphere could be caused by either temperature or ammonia, however the regions over which the atmosphere is affected remains comparable (Moeckel et al. 2024b). With this caveat addressed, we employ the following cost-function for the optimizer:

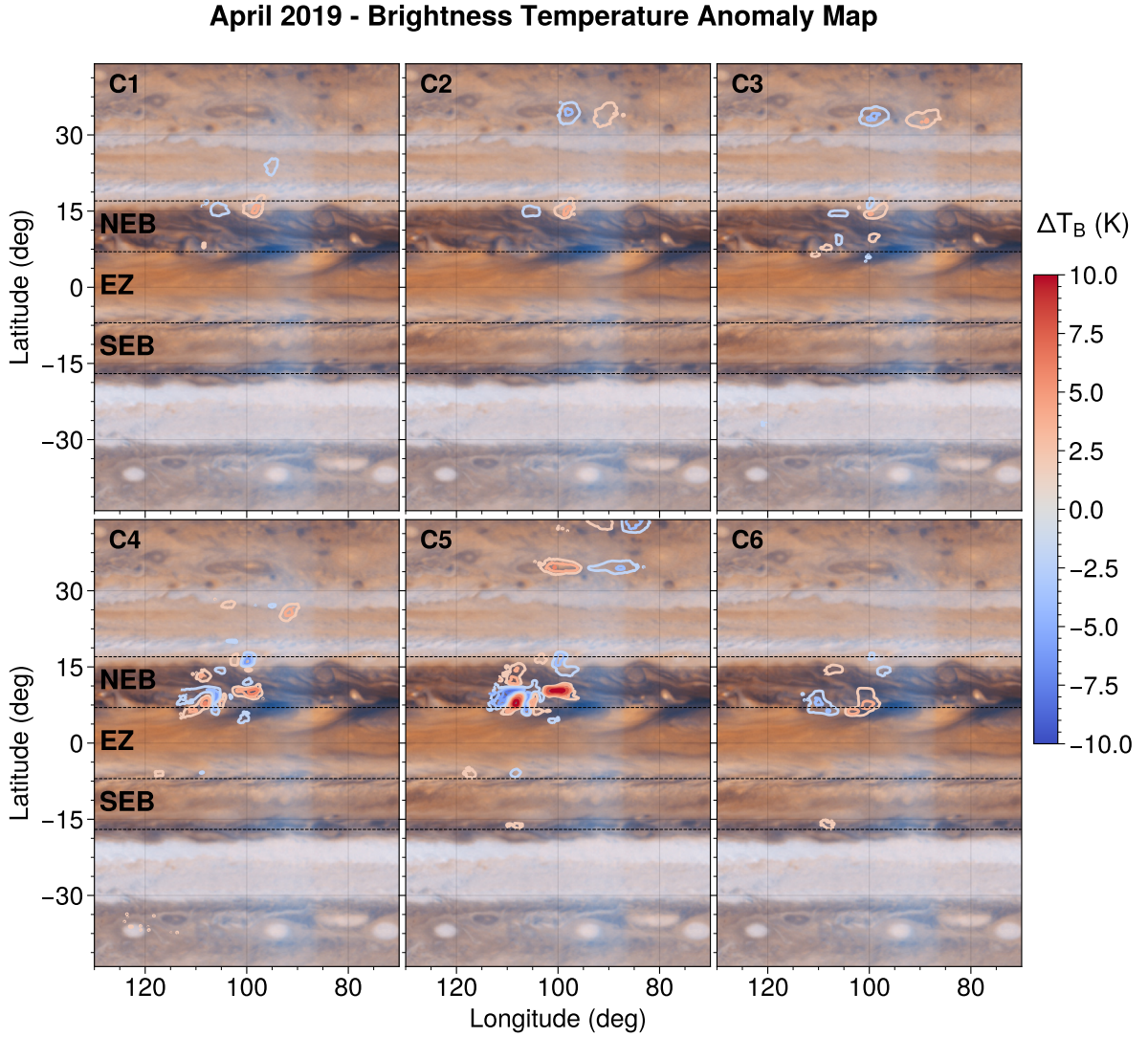


Figure 4.8: Longitudinal brightness temperature anomalies after subtracting the zonal atmospheric brightness temperature for a given frequencies overlayed on the concurrent HST observations. The contours lines show temperature anomalies that are larger than 2K for both cold and warm anomalies. We find the majority of the anomalies located in three distinct regions: At the locations of large scale vorticies, in the NEB, and at the locations of the jets at the zones and belts bondaries.

$$C_{fit} = \left(\sum_1^6 \frac{\overbrace{(T_{PJ19} - \bar{T})^2}^{Model} - \overbrace{(T_{PJ19} - \bar{T})^2}^{Observations}}{\sigma_T^2} \right) + \lambda \left| \sum_1^8 \left(\frac{\delta NH_3}{\delta \ln(P)} \right)_i \right| \quad (4.3)$$

The measurement error σ_T is 0.1% of the observed temperature, and thus increases with decreasing frequencies. We sampled the anomaly map at 0.5° resolution between -20° and 20° latitude. For each pixel, we fit the cost function in Equation 4.3. In total, we employed the retrieval on ~ 3500 individual locations on the planet to build up a three-dimensional structure of the tropical subcloud atmosphere on Jupiter.

Higher up in the atmosphere, in Channels 4-6, we see significant variations in the brightness temperature, much greater than the expected noise floor of the instruments, resulting in strong constraints on the NH_3 abundance retrieved values. Deeper in the atmosphere, the residuals decrease in magnitude and the measurement error increases, making the retrieval at these pressures less certain. Since the atmosphere represents a continuous field, we employ a median filter at constant pressure that operates on a $1.5^\circ \times 1.5^\circ$ grid to reduce the impact of outliers on the atmosphere.

4.4 Modeling Results

For our analysis of the subcloud structure of Jupiter, we make an important distinction between the climatological signal and the weather. Circulation cells tend to transport material across latitudes, and thus the latitudinal distribution, as shown in Figure 4.7, is composed of both local small-scale weather effects and the large-scale background circulation. In contrast, the distribution as a function of longitude is more indicative of local weather events, so for the purpose of this work, we refer to the longitudinal variations as weather.

VLA observations cover the pressure regions around and below the ammonia ice cloud (see Figure 4.1), with the K-band frequencies (18-26 GHz) probing the saturation vapor curve inside the ammonia ice cloud, and Ku- and X-band observations covering the subcloud structure. Comparing the distribution between the various VLA frequencies, we can already glean some important information about the weather patterns on Jupiter. The red colors in the radio-composite image (see Figure 4.4) show variations around a few bar. The overall lack of red-colors indicates that the majority of the atmospheric variability is happening around and below the ammonia clouds, but does not extend to much greater depths. Most of the cloud dynamics are surprisingly shallow. There are several features, however, that clearly show up in the red color scheme and can also be distinguished in the X-band maps themselves. The NEB and SEB both show up as distinct features that wrap around the planet, and

embedded within the belts we see variations. The NEB is disrupted by the repeated pattern of the 5 micron hotspots, and cold ammonia plume that shape much of the interface between the EZ and NEB. The SEB is dominated by the Great Red Spot (GRS), especially the wake in the southern hemisphere appears to extend to several bars at least based on the VLA data. The most consistent signal is a narrow band of warm brightness temperature, with variations that correlate well with the location of vortices on the southern edge of the SEB. The last category of features that appears to have large vertical extent in the atmosphere of Jupiter are the barges, such as the one just west of Oval BA in the southern hemisphere. Similarly, longitude extended features can be identified in the northern hemisphere in the radio images (e.g. 140° - 125° W, 40° N, or 70° - 60° W, 40° N). In the HST maps, these features appear as regions with a lot of substructure and a higher degree of turbulence as opposed to the more continuous cloud deck seen at other longitudes.

The visible images and the brightness distribution maps (Figures 4.2 and 4.3) are anti-correlated because of the different sources of flux. Radio-cold regions are enhanced in traces gases, where the enhanced gases produce bright clouds to scatter off. Contrary regions that are darker in the visible indicate low cloud coverage, that is light is scattered at higher pressures within the planet. The low cloud coverage also implies less trace gases and thus radio-warm regions.

Next, we focus on the tropical region that was sampled by MWR. From the longitudinal brightness temperature anomaly maps in Figure 4.8 we can already discern some important distinctions. The southern hemisphere shows much less spatial variability compared to the northern hemisphere. The SEB shows a surprising lack of structure, with only very few shallow features at the edges of the SEB. For example, on the southern edge around 110° W, 16° S or at the northern edge around 115° W, 7° S. We, therefore, find only structures at the locations for the zonal wind jets peak.

The equatorial structure is also remarkably homogeneous, showing no significant variations with longitude, with the only exception of a localized cold feature at the northern edge of the EZ around 100° W, 6° N. This localized cold feature can be traced from Channel 3 to Channel 5.

The most significant variability is seen in the NEB with the strongest anomalies in Channel 5, i.e., just below the ammonia ice clouds. The majority of the signal is contained in the upper 4 channels but decreases deeper in the planet. North of the NEB, the spatial variability is again reduced with the exception of two distinct characteristics that are present in the northern hemisphere. There is a vortex at 15° N at the boundary of NEB and NTrZ, and a barge-like feature at 34° N (Bolton et al. 2021). The vortex can be identified across all 6 channels, indicating that it has a substantial depth to it, while the barge-like features only appears in the upper 5 channels.

Using Equation 4.3, we can fit ammonia anomalies to the brightness temperature anomalies. Figure 4.9 visualizes the retrieved ammonia anomaly at several pressures. The southern hemisphere, including the equatorial zone, shows remarkably little variation, with most of the variability restricted to the upper 2 bars. The large residuals in the NEB can be traced down to the 6 bar levels.

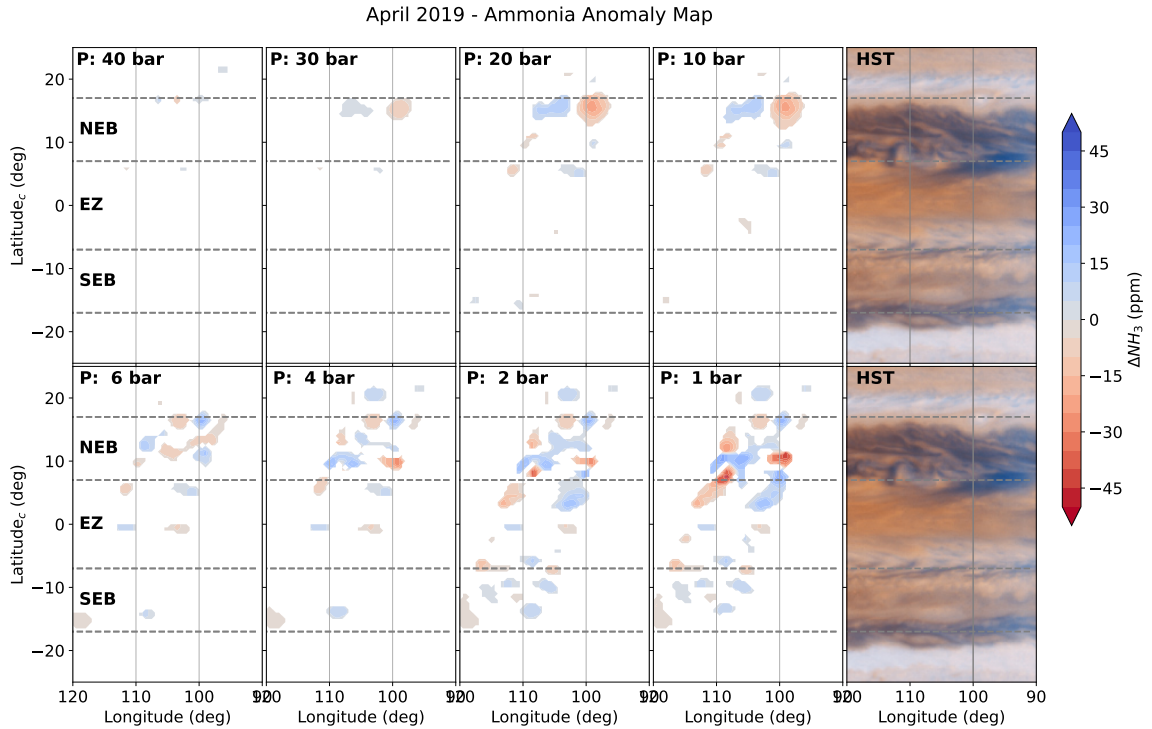


Figure 4.9: Ammonia abundance anomalies that fit the brightness temperature anomalies shown in Figure 4.8. The right-most panel shows the (near) simultaneous HST observations, and the panels to the left show slices in pressure, with the pressure indicated in the upper left corner. The ammonia variability peaks just below the clouds, and decrease with depths. Most features extend down to about 6 bars, where the water is expected to condense out, with the anticyclone in the northern hemisphere and the ammonia plume at the interface between the NEB and EZ the two notable exceptions. The dynamics in the SEB and EZ appear to be mostly located at altitudes above 2 bar, while the NEB shows significant variations down to 6 bar.

Next, we focus on some remarkable features in Figure 4.9. Most of the variations in ammonia abundance, up to 50ppm, is near the 1 bar level, just under the ammonia ice clouds; the signal decays in magnitude with depth. Around the water condensation level (~ 6 bar), the variability has decreased considerably. There are a few exceptions to this trend.

Precipitation

We find evidence for precipitation and evaporation in the form of dipolar structures in the ammonia anomalies. We find a depletion at low pressures high up in the atmosphere and enhancement of ammonia below. For example the depletion around (100°W , 10°N), turns into an enhancement around 6 bar, indicative of material being rained out and later evaporated to create the anomalies.

Plume

The one noticeable exception to this is an extended column of ammonia enhancement at the interface of the NEB and EZ, that appears just west of the dark region in the HST images. These dark regions in HST maps are normally associated with hot spots (Allison 1990; Friedson 2005). The VLA X-band maps that provide context for these observations show an extended cold region east of the flyby, just overlapping with the edge of the MWR domain. Both these observations taken together are a strong indicator that it is the location of an ammonia plume as suggested by Wong et al. (2020b). The MWR observations are able to trace this ammonia plume to at about 30 bar.

Vortex

The second most interesting structure in the northern hemisphere is the vortex at 15°N , at the interface of the NEB and North Tropical Zone (NTrZ). We find that higher up in the atmosphere the ammonia is enhanced causing the cold brightness temperature anomaly. Around the pressure where the water is condensing out, the anomalies change sign and can be traced down to 40 bars. This finding is in line with the finding by Bolton et al. (2021) for the depth of the anticyclone, however, we can rule out variations that go deeper than 40 bar. Additionally we find that the ammonia depletion below the vortex appears to be shifted towards the south. As shown in Figure 4.1, most of the signal at $P > 10$ bar originates from Channel 1 and 2, which have about twice the beamsizes compared to the upper four channels. Therefore, the increased size of the anomaly can at least partially be explained by resolution effects.

To further illustrate the dynamics in the tropical region we render the anomaly with the "Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers" (VAPOR) (Li et al. 2019b). In Figure 4.10 we show a visualization of the anomaly, where blue regions indicate ammonia enhancement, and the orange / red shades show ammonia

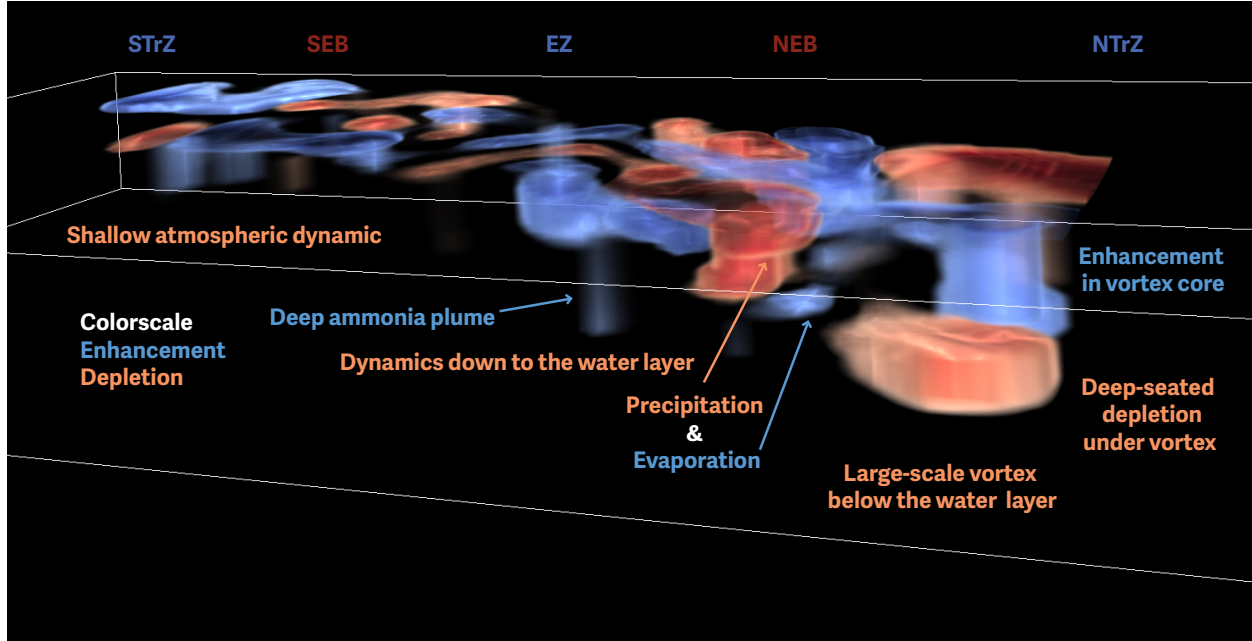


Figure 4.10: 3D rendering of the longitudinal ammonia anomaly (Figure 4.9) in the Jovian tropics, where red shades are ammonia depletion causing warm brightness temperature anomalies, while blue shades correspond to ammonia enhancements. The relative shallow atmospheric of the SEB can be found in the upper left corner, the EZ in the center, and the NEB and the vortex at its northern boundary can be found in the bottom right corner. We annotated the render to highlight processes that shape the atmosphere of Jupiter and indicated approximated pressure levels.

depletion. On the left-hand side, the SEB and EZ show very little spatial variability, except for the ammonia plume. As we approach the NEB the ammonia variations increase drastically. In this region there is evidence for precipitation in the form of depletion higher up in the atmosphere as ammonia is being removed, and the subsequent evaporation and enhancement around the water condensation level. At the northern edge of the rendering, the dipolar vortex structure is apparent, characterized by an enhanced ammonia core above a deep-seated ammonia depletion.

4.5 Discussion

The ammonia anomaly distribution that we have found gives us a first glimpse of the effect of the weather on Jupiter. There are several processes that can modify the ammonia distribution, such as the background circulation (Showman et al. 2005; Duer et al. 2021), to local dynamical effects (Ingersoll et al. 2004; de Pater et al. 2016; Ingersoll et al. 2017; Ge

et al. 2024), microphysics (Sugiyama et al. 2011; Sugiyama et al. 2014; Guillot et al. 2020a) and temperature effects (Palotai et al. 2014). Regardless of the mechanisms modulating the ammonia distribution, we find some remarkable weather signatures in the atmosphere of Jupiter. Both the SEB and EZ appear well-mixed with shallow weather signatures that only extend to about 2 bar, indicating that most of the ammonia variability is contained within the region where ammonia should precipitate and evaporate (Ingersoll et al. 2017). The difference in dynamical activity between the NEB and SEB has been observed in the brightness temperature distribution of VLA and MWR observations before (Hardesty et al. 2024), but we extend this analysis by showing that the activity in the EZ and SEB is really limited to the upper few bars of pressures. We find that the EZ is surprisingly homogeneous and very similar to the SEB in terms of activity. When looking at the general activity in the EZ in the X-band images, we see that much of the dynamical activity is driven by strong ammonia plumes, which show up predominantly at the lower frequencies (C-band, X-band) but not at the higher frequencies (de Pater et al. 2016).

An intriguing feature of the MWR inversion is a deep-rooted ammonia enhancement of a few parts per million at the east end of the domain (101°W , 6°N). While the interpretation of the brightness temperature favored the shallow nature of the feature, we can trace the feature down to at about 30 bars, and it is the only feature that does not appear to change signs around the water condensation level. The context maps provided by the VLA in Figure 4.11 show that the C5 domain appears to grace the tail end of an extended cold region, which we associate with ammonia plumes (de Pater et al. 2016). We can clearly distinguish the plumes in the X-band observations; however, higher up in the atmosphere their signal fades away in the Ku- and K-band maps, which suggests that these are deep-seated features that have significant vertical structure. Looking at the hotspot-plume cloud top manifestation in Figure 4.11, we see a dark region at the cloud top (96°W , 6°N), and light-brown region east of that (90°W , 6°N). Indeed, Wong et al. (2020b) suggested the presence of an ammonia plume in the observations based on Gemini-Near Infrared Observations and the HST observations. The MWR observations show that the plume extends much further west than the cloud top observations reveal, and show that the plume extends into the MWR domain.

This shows the crucial role that ammonia plumes play in enriching the northern part of the EZ in the atmosphere by dredging up material from well below the water cloud. Although previous observations have interpreted the shallow nature of the plumes by interpreting only brightness temperatures (Fletcher et al. 2020a), we use ammonia variations to show that the plumes have a much deeper root.

Further north in the domain, we enter the NEB, the region that shows the strongest brightness temperature anomalies, both for the zonal (see Figure 4.6) and for the meridional brightness temperature distribution (see Figure 4.8). Even in this highly dynamical region, we find that the major dynamical activity in the NEB happens within the cloud-forming region of the planet. Contrasts of up to 20K were observed in Channel 5 in the brightness temperature anomalies, and yet we can explain most of the signal by strong ammonia depletions and enhancements around 1-2 bar. Using the VLA observations (see Figures 4.2 and 4.11), we see that the structure probed by Juno is among the most extremes for this latitude.

This allows us to generalize these findings that even in the most turbulent regions of the NEB, the majority of the variability is restricted to the weather layer (upper 6 bar), as also suggested by de Pater et al. (2016). The VLA observations further show that the variability indeed peaks around 1 bar (C5/X-band), with the observation probing slightly higher in the atmosphere (Ku-band) already showing a much reduced brightness temperature contrast.

The only small-scale structure that we see in the NEB that extends below the water layer appears to switch signs below the 4 bar level, similar to the signature seen during the SEB outbreak (Moeckel et al. 2024b). Ammonia condenses above 0.7 bar level and precipitates in the form of ammonia rain. The depths to which the droplet can fall is dependent on the size and temperature (Loftus et al. 2021), but around 4 bar the ammonia is expected to boil (Li et al. 2019a). This is the pressure at which we find that the ammonia depletion around 100°W and 10°N turns into an enhancement consistent with the evaporation of ammonia droplets. However, the enhancements in ammonia can be traced deeper into the planet, which requires precipitation to penetrate the water condensation layer (Sugiyama et al. 2014; Guillot et al. 2020a) and subsequent cold downdrafts to reach deeper into the atmosphere (Markham et al. 2023).

Regardless of this, we find that the majority of the weather on Jupiter is very shallow and that much of the brightness temperature variability in the upper channels from MWR and VLA observations can be explained by both local and global shallow atmospheric circulation models (Showman et al. 2005; de Pater et al. 2016; Ingersoll et al. 2017; Fletcher et al. 2020b; Ge et al. 2024).

The depth of the vortex has already been established by Bolton et al. (2021). Our results are mostly consistent with the finding that the vortex appears to have a denser upper core, above lighter/warmer region that appears to be shifted slightly southward compared to the upper core.

The weather that we see in the atmosphere appears too shallow to explain the depletion of ammonia down to 30-40 bar (Li et al. 2017a; Moeckel et al. 2023). This requires processes that cause the global depletion of ammonia to either be much smaller than the resolution that we capture here (Showman et al. 2005), or require much more energy (Li et al. 2023; Moeckel et al. 2024b).

4.6 Conclusion

The distribution of ammonia anomalies offers valuable insights into Jupiter’s atmospheric dynamics. Leveraging data from Juno’s MWR, VLA, HST, we conducted a groundbreaking study of Jupiter’s tropical regions, generating a three-dimensional rendering of its weather for the first time. We define weather as the longitudinal variations in the atmosphere after removing the latitudinal mean. Initially, we fitted a reference atmosphere based on various observables: nadir brightness temperature and limb-darkening effects. Subsequently, we extracted ammonia anomalies relative to this reference, enabling us to discern weather patterns beneath the cloud tops and investigate their vertical extent.

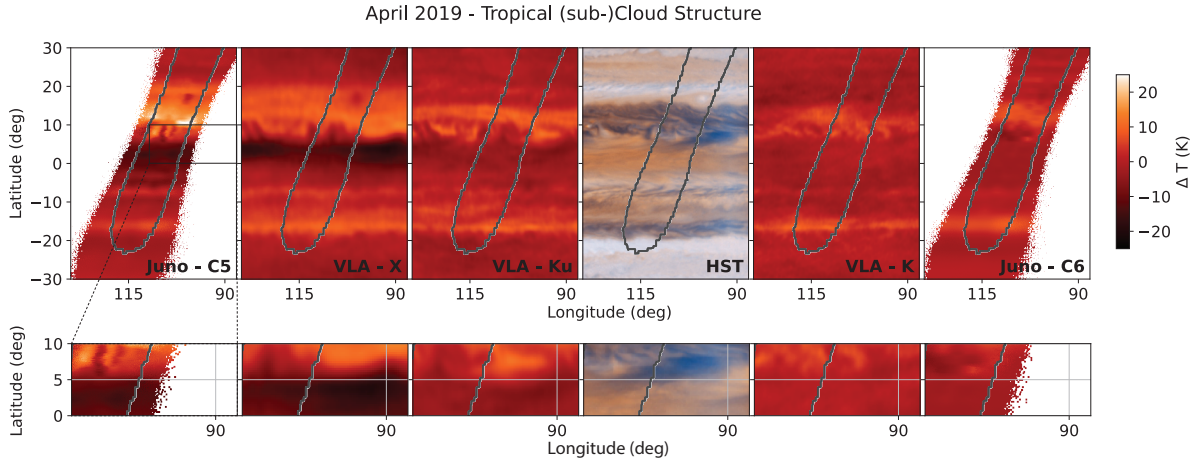


Figure 4.11: Zoom in on the cloud and sub-cloud structure captured during the flyby. Comparing Channel 5 with the VLA observations that probe the same depths we can see that Juno passed just east of an extended cold region that appears to be part of the plume-hotspot system at the northern edge of the EZ. Furthermore we can see that Juno flew over a particularly variable region in the NEB. The VLA observations also show that variability indeed peaks around 1 bar, with observations probing a bit higher in the atmosphere showing much less contrast (Ku-, and K-band).

Combining VLA and MWR observations, we found that Jupiter’s weather is primarily confined to the uppermost layers of its atmosphere, suggesting a shallow weather system. Specifically, our analysis of MWR data revealed that while there are few variations within the North Equatorial Belt (NEB) that extend to greater depths, the majority of variability occurs at altitudes above 6 bars, indicating that Jupiter’s weather occurs predominantly between the water and ammonia cloud layers (Showman et al. 2005; Fletcher et al. 2020b; Ge et al. 2024). The absence of significant structures at higher latitudes in both previous VLA maps (de Pater et al. 2016) and our findings are a strong indication that these results are valid beyond the tropics. Moreover, this underscores the critical role of water condensation in Jupiter’s atmospheric dynamics, serving as a key energy source through latent heat release (Ingersoll et al. 2000) and acting as a stabilizing agent to limit the dynamics to above the water layer (Guillot 1995; Showman et al. 2005; Ge et al. 2024; Moeckel et al. 2024b).

Among the few features extending below the water layer, we observed an ammonia enhancement at the NEB-EZ boundary, consistent with an ammonia plume reaching depths exceeding 30 bars — far deeper than previously interpreted (Fletcher et al. 2020a). This deep-rooted plume suggests continuous upwelling of material from the lower troposphere, explaining the ammonia enrichment in the equatorial zone compared to other regions (Li et al. 2017a; de Pater et al. 2019a; Moeckel et al. 2023). Additionally, we identified an

intriguing anticyclone at the NEB-NTrZ interface, characterized by a dense ammonia core above the water layer and ammonia depletion beneath it.

Our study underscores that conventional weather patterns observed at Jupiter’s upper atmosphere do not fully account for the ammonia depletion down to 30 bars. Large-scale features such as plumes and vortices likely play pivotal roles in enriching and depleting Jupiter’s atmosphere. Alternatively, the discrepancy may stem from storm-scale phenomena beyond the resolution of current observations (Guillot et al. 2020a).

Future research, incorporating mid-infrared observations, holds promise for refining our understanding by resolving temperature ambiguities at the upper atmosphere. Additionally, integrating temperature structure retrievals, as proposed by Li et al. (2024), could enhance the accuracy of the reference atmosphere, although the main findings regarding ammonia anomalies would remain unaffected.

Addendum A

After analyzing the residuals, we observed a near-symmetric increase in brightness temperature towards the edges of the Juno domain in Channel 1. Despite our method being restricted to observations where 99% of the emission originates from the planet, uncertainties in the beam shape may pick up extra-planetary emission from the synchrotron radiation belts. Given that non-thermal emission is several times stronger than the thermal emission from the planet for Channel 1 (Santos-Costa et al. 2017), even minor uncertainties can manifest prominently.

During normal operations, Juno scans the planet from north to south, optimized to acquire multiple measurements for a given latitude at different emission angles. For PJ19, however, the spacecraft is scanning the planet from west to east, resulting in a distinct distribution where the emission angle varies with longitude. Larger emission angles correspond to the edges of the domain, while the smallest angles are found towards the map’s center. Although synchrotron radiation is expected to vary with latitude, the effect should be relatively consistent within approximately 100° . We, therefore, initially centered the observations around the minimum emission angle and then applied a median filter with a width of 20° to the data (twice the width of a typical zone or belt). Increasing the window size beyond this threshold would fail to capture variations in synchrotron strength with latitude, while reducing the window size risked removing genuine atmospheric structures.

The leftmost panel of Figure 4.12 displays the shifted data, revealing the residual temperature after subtracting the mean zonal brightness temperature. Notably, the increase in brightness temperature residual with distance from the map’s center is evident in Channel 1. The center panel showcases the median-filtered residual, with the strongest residual observed around the equator, consistent with the distribution of synchrotron emission. Finally, the right panel displays the residual after removing the median-filtered data, where the deep-rooted vortex at 15°N remains visible, indicating that genuine structure persists in our residual maps even after filtering. We applied a similar filter to Channels 2 and 3

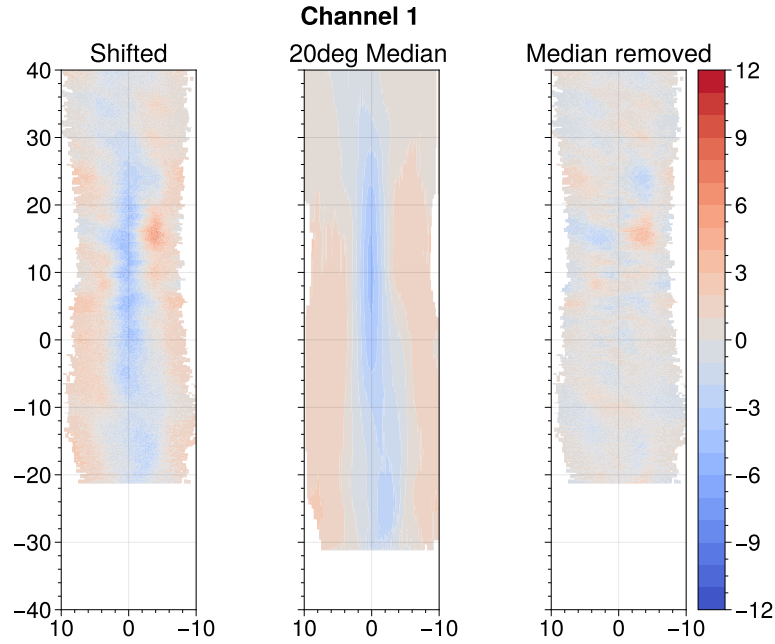


Figure 4.12: The left panel displays the residuals after subtracting the mean of the PJ19 observations. We re-mapped the structure to be centered around the minimum emission angle to highlight its dependence on the emission angle and longitude. We calculated the running median over 20 degrees latitude to reveal the systematic brightening towards the limb, attributed to the increased synchrotron contribution. We chose a window size of 20 degrees to ensure it was twice as large as the typical extent of the zones and belts. In the right panel, the residual structure after removing the median is depicted. Although the majority of the atmospheric signal is attenuated, the structure at 15°N persists, indicating a deep-seated origin for this feature.

but observed minimal effects on Channel 3, as expected due to the decreased strength of synchrotron emission with increasing frequency.

Addendum B

Radio observations come with two inherent resolution limits. The largest separation between antennas indicates the highest achievable resolution for the radio maps, while the shortest baseline indicates the largest resolvable structure for radio observations. The VLA B-configuration strikes a good balance between these two resolution limits. However, after subtracting a limb-darkened disk, we identified large-scale structures in the VLA maps that

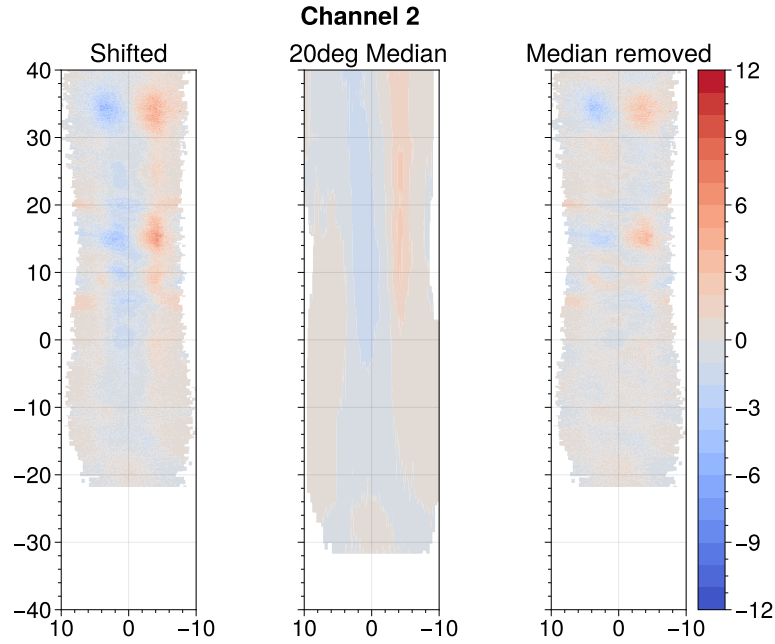


Figure 4.13: Same as Figure 4.12 but for Channel 2

seemed superimposed on the residual structure. This residual, on the order of a few Kelvins, manifested as a large sinusoidal structure particularly affecting the mid-latitudes. Since this large-scale structure must originate from observations at the shorter baselines, we restricted the mapping to observations above 15, 15, and 20 $\text{kilo}\lambda$ for the X-, Ku-, and K-band observations, respectively. Although we managed to reduce the magnitude of the residual, we were unable to fully eliminate it. The most likely cause is a slight misalignment between the our model and the actual observations caused by the self-calibration processes. Instead, we applied a Gaussian filter (i.e., a high-pass filter) on the image plane, targeting the removal of the largest-scale structure. We selected a Gaussian kernel size that specifically targeted the large sinusoidal structure while preserving the smaller-scale structures of interest for our study. By subtracting the filtered image from the image plane, we reduced the amplitude of the residual, rendering our filtered maps an upper limit. The following images display the removed structure for the maps presented in Figures 4.2 and 4.3.

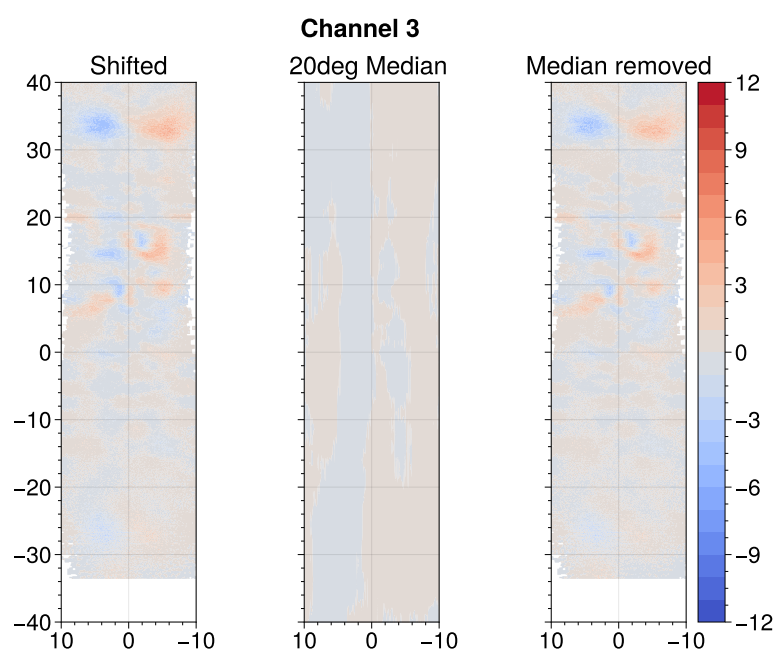


Figure 4.14: Same as Figure 4.12 but for Channel 3

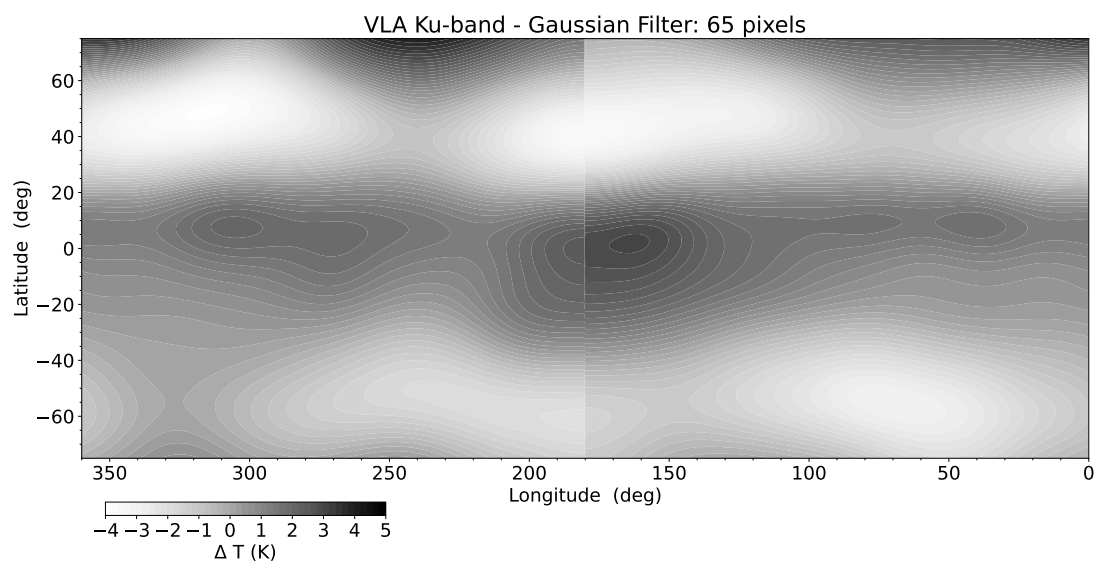


Figure 4.15: Residual structure due to misalignment during the deprojection process that was removed for the Ku-band observations with a Gaussian filter of 65 pixels.

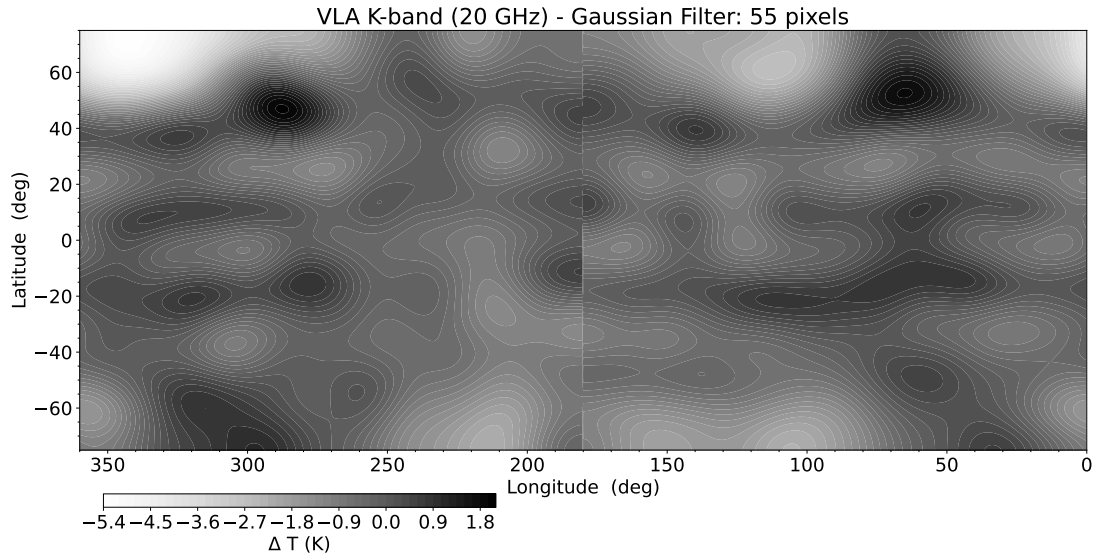


Figure 4.16: Same as Figure 4.15 but for K-band observations around 20 GHz.

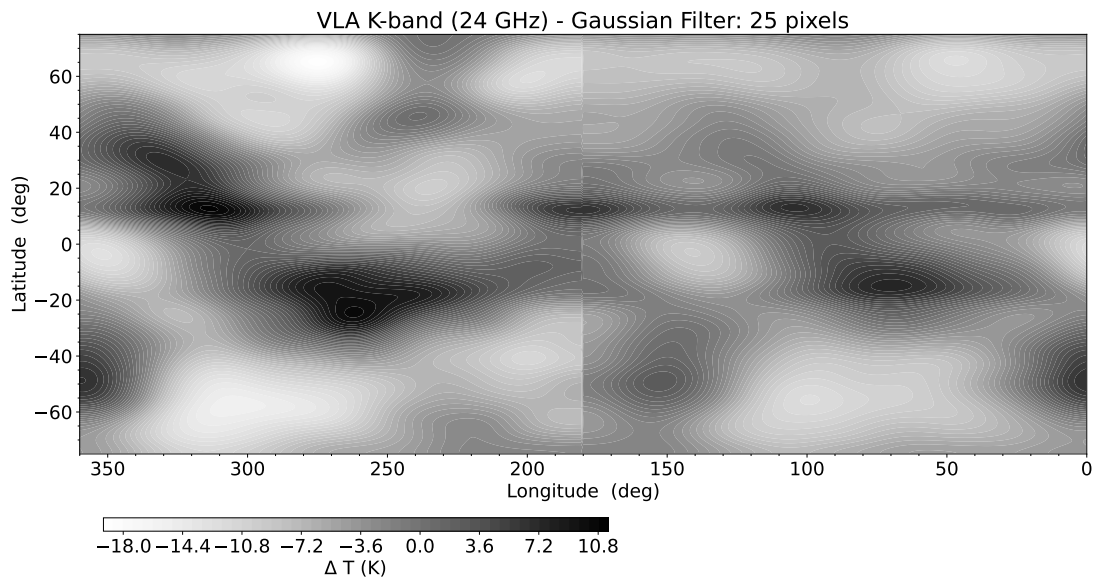


Figure 4.17: Same as Figure 4.15 but for K-band observations around 24 GHz.

Chapter 5

Conclusions

Over the course of my PhD, I have observed Jupiter with various radio-telescopes to refine and advance our understanding of the Jovian atmosphere. We used these radio observations to observe first the climate, then the effects of storms, and finally the weather. To achieve this goal, I ended up developing a pipeline for Juno-MWR observations that is completely independent from the Juno team (Chapter 2). This effort was partially motivated by obtaining uncertainties along with the observable to understand how measurement uncertainties propagate into our understanding of the Jovian atmosphere. The more honest reason was the fact that the Juno team never made the reduced MWR data publicly available, controlling access to the data through the good will of the PI of the mission. It took me three years to convert the raw data into actual usable quantities, validating both our results and making the pipeline and their products publically available to the community.

The representation of trace gases in the atmosphere can be approached through different parameterization schemes. I developed a model that incorporates perturbed thermo-chemical equilibrium computations, reflecting the expected behavior of trace gases within the large-scale circulation. For localized effects, I also developed a model with stochastic variations in the atmosphere to capture non-hydrostatic effects (see Chapter 2.3). I applied both models to longitudinally averaged data to retrieve the latitudinal distribution of ammonia on Jupiter. The two models exhibited good agreement validating our findings, which revealed an atmosphere that defies our expectations and assumptions. Jupiter appears to be depleted in ammonia to much greater depths than could be explained by either dynamics (Showman et al. 2005; Sugiyama et al. 2014) or conventional microphysics (Li et al. 2019a; Loftus et al. 2021).

The MWR observations confirm earlier VLA findings, indicating that the zones and belts of Jupiter exhibit enrichment and depletion in ammonia, respectively, extending below the cloud tops. Near the water layer, this contrast changes sign, suggesting a reversal in the inferred circulation (see Chapter 2.6). The tropical zone of Jupiter also showed a drastic difference between the NEB and SEB, uncoupled from seasonal effects on Jupiter.

The solution to the depletion conundrum may not lie solely in a better understanding of the global circulation but rather in the dynamics of the atmosphere. Observations of Saturn’s ammonia distribution with the VLA (Li et al. 2023) and new theoretical work on the microphysics of Jupiter (Guillot et al. 2020a) both highlighted storms as possible culprits. On Saturn, we observed ammonia anomalies that correlate with the locations of past global-scale storms, which deplete the upper atmosphere and enrich the lower atmosphere. These anomalies represent the scars left by storms of days gone by and remain visible for possibly centuries. In Chapter 3, I was able to discern the impact of storms on Jupiter by observing a giant outbreak in the SEB. Indeed, this observation revealed that these large storms impact the deep troposphere of Jupiter. My findings demonstrate that storms deplete the upper atmosphere and deposit material well below the water layer. Regardless of the interpretation of the source of the anomaly—whether temperature or ammonia—both interpretations are consistent with ammonia hail (Guillot et al. 2020a).

Chapter 4 explored the role of weather on Jupiter. The cloud tops provide only a glimpse of the ever-changing weather that shapes Jupiter, disrupting its zones and belts. Surprisingly, I discovered that most of the weather is confined to the upper 2-3 bars of the atmosphere. Only in the NEB can we trace weather patterns down to the water condensation layer, as predicted by dynamics. The NEB also stands out as the only region where I find evidence of “hail out” similar to those observed during the SEB outbreak. Two notable structures extend below the water condensation layer: the tail-end of an ammonia plume, which we trace down to about 30 bar, and a vortex at the northern border of the NEB, extending even deeper, beyond 30 bar.

Over the past decade, our understanding of the processes governing Jupiter’s atmosphere has undergone a profound transformation. Previously believed to be a highly convective planet, we now realize that convection on Jupiter must be sluggish. The depletion of ammonia to such great depths, along with the deep extent of vortices, contradicts the expectations for a highly convective lower troposphere. Instead, we observe signs of intermittent and small-scale convection, manifested in outbreaks and smaller thunderstorms. Paradoxically, while studying the circulation using ammonia as a tracer, we discovered its depletion. This depletion may be attributed to microphysical processes, such as ammonia hail, which could potentially compromise its reliability as a tracer.

This work, however, underscores the significance of interactions between climate and weather on Jupiter, where processes across vastly different scales shape the planet. The climate sets the stage for convective inhibition, while storm outbreaks disrupt the atmosphere locally. Hail, on the scale of a few centimeters, depletes the upper troposphere, cooling and enhancing the lower troposphere in turn. The cloud tops, often the only accessible layer in visible and near-infrared observations, provide a limited view of the planet’s interior and radio observations provide the crucial link in tracing dynamics deeper into the planet.

Atmospheric temperature not only influences our inversions for atmospheric and interior models but also would provide crucial information on microphysical processes in the atmosphere. Furthermore, temperature serves as a more reliable indicator of circulation and dynamics compared to ammonia. Recent advances have begun to address the degeneracy between temperature and opacity (Li et al. 2024, & Chapter 3 of this work), yet temperature information is extremely hard to extract from observations. Temperature constraints for the atmosphere, therefore, remain paramount for our understanding of Jupiter’s atmosphere. Observations in the mid-infrared, in conjunction with radio observations, can begin to break the degeneracies between temperature and ammonia at least around the ammonia cloud and with that within the convectively controlled region of the atmosphere.

The abundance of water and its distribution on Jupiter remain elusive, despite MWR observations placing some moderate constraints on the water abundance in the equatorial zone (Li et al. 2020; Li et al. 2024). Simulations and theories have revealed the role of water in shaping the dynamics (Ingersoll et al. 2000; Showman 2007; Li et al. 2018a; Ge et al. 2024) of the planet; however, very little is known about its distribution and the corresponding water cycle. Better constraints on the temperature environment and the effect of clouds on radiation will allow tighter bounds on the water distribution on Jupiter.

Simulations of the Jovian system are slowly catching up with the wealth of information collected throughout the Juno era at Jupiter. Their biggest challenge will be reproducing the countless observations and deciding which observations to favor when trying to constrain the model. Current models are still attempting to reproduce large-scale structures such as the jets; however, local models are starting to focus on the effects of the observed weather, which we are starting to observe with high spatial and spectral resolution.

Lastly, this work was made possible thanks to the dedicated work of the MWR team and in spite of the Juno leadership. Drastic changes are needed to ensure that science becomes open-source and open-data. Hiding models, data, and discussions behind closed doors creates a toxic environment only rivaled by the very atmosphere that I studied. Our best ideas will come through collaboration, not competition, and retaining curiosity and talent is crucial for the existence of the field, planetary science, and science in general. After all, science is conducted by humans, with all our imperfections and biases. But I believe that science can be better: be kind, share your data, respect individuals and their diverse backgrounds. In essence, approach science not only with an open mind, but also with an open heart.

Bibliography

- Allen, John T. et al. (2020). “Understanding Hail in the Earth System”. In: *Reviews of Geophysics* 58.1. DOI: <https://doi.org/10.1029/2019RG000665>.
- Allison, M. (Feb. 1990). “Planetary waves in Jupiter’s equatorial atmosphere”. In: *Icarus* 83.2, pp. 282–307. DOI: 10.1016/0019-1035(90)90069-L.
- Asay-davis, Xylar S et al. (2011). “Changes in Jupiter ’ s zonal velocity between 1979 and 2008 ”. In: *Icarus* 211, pp. 1215–1232. DOI: 10.1016/j.icarus.2010.11.018.
- Asplund, Martin et al. (2009). “The Chemical Composition of the Sun”. In: *Annual Review of Astronomy and Astrophysics* Vol. 47, pp. 481–522. DOI: 10.1146/annurev.astro.46.060407.145222.
- Atreya, S. K. and P. N. Romani (1985). “Photochemistry and clouds of Jupiter, Saturn and Uranus.” In: *Recent Advances in Planetary Meteorology*. Ed. by G. E. Hunt, pp. 17–68.
- Baines, Kevin H., Robert W. Carlson, and Lucas W. Kamp (Sept. 2002). “Fresh Ammonia Ice Clouds in Jupiter. I. Spectroscopic Identification, Spatial Distribution, and Dynamical Implications”. In: *Icarus* 159.1, pp. 74–94. DOI: 10.1006/icar.2002.6901.
- Becker, Heidi N. et al. (Aug. 2020). “Small lightning flashes from shallow electrical storms on Jupiter”. In: *Nature* 584.7819, pp. 55–58. DOI: 10.1038/s41586-020-2532-1.
- Bellotti, Amadeo (2018). “Jupiter: A study of atmospheric composition, structure, and dynamics using microwave techniques”. PhD thesis. Georgia Institute of Technology.
- Bellotti, Amadeo, Paul G Steffes, and Garrett Chinsomboon (2016). “Ammonia , Water vapor , and Methane under Simulated Conditions for the Deep Jovian Atmosphere”. In: *Icarus* 284, pp. 1–13. DOI: 10.1016/j.icarus.2016.07.013.
- Bellotti, Amadeo, Paul G Steffes, and Garrett Chinsomboon (2017). “Corrigendum to “ Laboratory measurements of the 5 – 20 cm wavelength opacity of ammonia , water vapor , and methane under simulated conditions for the deep jovian atmosphere ” ”. In: *Icarus* 284, pp. 2016–2017. DOI: 10.1016/j.icarus.2016.11.006.
- Berge, G L and S Gulkis (Jan. 1976). “Earth-based observations of Jupiter: millimeter to meter wavelengths”. In: URL: <https://www.osti.gov/biblio/7346847>.
- Bhattacharya, Ananyo et al. (Aug. 2023). “Highly Depleted Alkali Metals in Jupiter’s Deep Atmosphere”. In: *ApJ* 952.2, L27, p. L27. DOI: 10.3847/2041-8213/ace115. arXiv: 2306.12546 [astro-ph.EP].

- Bjoraker, Gordon L. et al. (Sept. 2022). “The Spatial Variation of Water Clouds, NH₃, and H₂O on Jupiter Using Keck Data at 5 Microns”. In: *Remote Sensing* 14.18, p. 4567. DOI: 10.3390/rs14184567.
- Bolton, S. J. et al. (Nov. 2021). “Microwave observations reveal the deep extent and structure of Jupiter’s atmospheric vortices”. In: *Science* 374.6570, pp. 968–972. DOI: 10.1126/science.abf1015.
- Braude, Ashwin S. et al. (Mar. 2020). “Colour and tropospheric cloud structure of Jupiter from MUSE/VLT: Retrieving a universal chromophore”. In: *Icarus* 338, 113589, p. 113589. DOI: 10.1016/j.icarus.2019.113589. arXiv: 1912.00918 [astro-ph.EP].
- Brown, Shannon et al. (June 2018). “Prevalent lightning sferics at 600 megahertz near Jupiter’s poles”. In: *Nature* 558.7708, pp. 87–90. DOI: 10.1038/s41586-018-0156-5.
- Busse, F. H. (Oct. 1976). “A Simple Model of Convection in the Jovian Atmosphere”. In: *Icarus* 29.2, pp. 255–260. DOI: 10.1016/0019-1035(76)90053-1.
- Carlson, Barbara E., Andrew A. Lacis, and William B. Rossow (July 1994). “Belt-zone variations in the Jovian cloud structure”. In: *J. Geophys. Res.* 99.E7, pp. 14623–14658. DOI: 10.1029/94JE01222.
- Carlson, R. W. et al. (Aug. 2016). “Chromophores from photolyzed ammonia reacting with acetylene: Application to Jupiter’s Great Red Spot”. In: *Icarus* 274, pp. 106–115. DOI: 10.1016/j.icarus.2016.03.008.
- Dahl, Emma K. et al. (Feb. 2021). “Vertical Structure and Color of Jovian Latitudinal Cloud Bands during the Juno Era”. In: *PSJ* 2.1, 16, p. 16. DOI: 10.3847/PSJ/abd400. arXiv: 2012.06740 [astro-ph.EP].
- de Pater, I. (Nov. 1986). “Jupiter’s zone-belt structure at radio wavelengths. II. Comparison of observations with model atmosphere calculations”. In: *Icarus* 68.2, pp. 344–365. DOI: 10.1016/0019-1035(86)90027-8.
- de Pater, Imke (1981). “A comparison of the radio data and model calculations of Jupiter’s synchrotron radiation, 1. The high energy electron distribution in Jupiter’s inner magnetosphere”. In: *Journal of Geophysical Research: Space Physics* 86.A5, pp. 3397–3422.
- (1990). “Radio Images of the Planets”. In: *Annual Review of Astronomy and Astrophysics* 28.347-99. DOI: 10.1146/annurev.aa.28.090190.002023.
- de Pater, Imke and Steven T Massie (1985). “Models of the millimeter-centimeter spectra of the giant planets”. In: *Icarus* 62.1, pp. 143–171.
- de Pater, Imke, Edward M. Molter, and Chris M. Moeckel (Feb. 2023). “A Review of Radio Observations of the Giant Planets: Probing the Composition, Structure, and Dynamics of Their Deep Atmospheres”. In: *Remote Sensing* 15.5, 1313, p. 1313. DOI: 10.3390/rs15051313.
- de Pater, Imke, Paul N. Romani, and Sushil K. Atreya (June 1991). “Possible microwave absorption by H₂S gas in Uranus’ and Neptune’s atmospheres”. In: *Icarus* 91.2, pp. 220–233. DOI: 10.1016/0019-1035(91)90020-T.
- de Pater, Imke and R J Sault (1998). “An intercomparison of three-dimensional reconstruction techniques using data and models of Jupiter’s synchrotron radiation”. In: *Journal of Geophysical Research: Planets* 103, pp. 973–984.

- de Pater, Imke et al. (1997). “The evolution of Jupiter’s radiation belts after the impact of Comet D/Shoemaker–Levy 9”. In: *Icarus* 129.1, pp. 21–47.
- de Pater, Imke et al. (Jan. 2001). “Reconciling Galileo Probe Data and Ground-Based Radio Observations of Ammonia on Jupiter”. In: *Icarus* 149.1, pp. 66–78. DOI: 10.1006/icar.2000.6527.
- de Pater, Imke et al. (2005). “Retrieval of water in Jupiter ’ s deep atmosphere using microwave spectra of its brightness temperature”. In: *Icarus* 173, pp. 425–438. DOI: 10.1016/j.icarus.2004.06.019.
- de Pater, Imke et al. (July 2014). “Neptune’s global circulation deduced from multi-wavelength observations”. In: *Icarus* 237, pp. 211–238. DOI: 10.1016/j.icarus.2014.02.030.
- de Pater, Imke et al. (June 2016). “Peering through Jupiter’s clouds with radio spectral imaging”. In: *Science* 352.6290, pp. 1198–1201. DOI: 10.1126/science.aaf2210.
- de Pater, Imke et al. (Oct. 2019a). “First ALMA Millimeter-wavelength Maps of Jupiter, with a Multiwavelength Study of Convection”. In: *AJ* 158.4, 139, p. 139. DOI: 10.3847/1538-3881/ab3643. arXiv: 1907.11820 [astro-ph.EP].
- de Pater, Imke et al. (Apr. 2019b). “Jupiter’s ammonia distribution derived from VLA maps at 3-37 GHz”. In: *Icarus* 322, pp. 168–191. DOI: 10.1016/j.icarus.2018.11.024. arXiv: 1902.07294 [astro-ph.EP].
- Devaraj, Kiruthika, Paul G Steffes, and Danny Duong (2014). “The centimeter-wavelength opacity of ammonia under deep jovian conditions”. In: *ICARUS* 241.2014, pp. 165–179. ISSN: 0019-1035. DOI: 10.1016/j.icarus.2014.06.017. URL: <http://dx.doi.org/10.1016/j.icarus.2014.06.017>.
- Dowling, T. E. and P. J. Gierasch (June 1989). “Cyclones and Moist Convection on Jovian Planets”. In: *Bulletin of the American Astronomical Society*. Vol. 21, p. 946.
- Dowling, T. E. et al. (Apr. 1998). “The Explicit Planetary Isentropic-Coordinate (EPIC) Atmospheric Model”. In: *Icarus* 132.2, pp. 221–238. DOI: 10.1006/icar.1998.5917.
- Dressel, Linda and Mariarosa Marinelli (2023). “WFC3 Instrument Handbook for Cycle 31 v. 15.0”. In: *WFC3 Instrument Handbook for Cycle 31 v. 15.0*. Vol. 15, p. 15.
- Duer, Keren et al. (Dec. 2021). “Evidence for Multiple Ferrel-Like Cells on Jupiter”. In: *Geophys. Res. Lett.* 48.23, e95651, e95651. DOI: 10.1029/2021GL095651. arXiv: 2110.07255 [astro-ph.EP].
- Emanuel, Kerry A., J. David Neelin, and Christopher S. Bretherton (July 1994). “On large-scale circulations in convecting atmospheres”. In: *Quarterly Journal of the Royal Meteorological Society* 120.519, pp. 1111–1143. DOI: 10.1002/qj.49712051902.
- Fegley B., Jr. and R. G. Prinn (Dec. 1985). “Equilibrium and nonequilibrium chemistry of Saturn’s atmosphere - Implications for the observability of PH₃, N₂, CO, and GeH₄.” In: *ApJ* 299, pp. 1067–1078. DOI: 10.1086/163775.
- Fletcher, L. N. et al. (Aug. 2009). “Phosphine on Jupiter and Saturn from Cassini/CIRS”. In: *Icarus* 202.2, pp. 543–564. DOI: 10.1016/j.icarus.2009.03.023.
- Fletcher, L. N. et al. (Aug. 2020a). “Jupiter’s Equatorial Plumes and Hot Spots: Spectral Mapping from Gemini/TEXES and Juno/MWR”. In: *Journal of Geophysical Re-*

- search (Planets)* 125.8, e06399, e06399. DOI: 10.1029/2020JE00639910.1002/essoar.10502118.1.
- Fletcher, L. N. et al. (2021). “Jupiter’s Temperate Belt/Zone Contrasts Revealed at Depth by Juno Microwave Observations”. In: *Journal of Geophysical Research: Planets* 126.10, pp. 1–28. ISSN: 21699100. DOI: 10.1029/2021JE006858. arXiv: 2110.14620.
- Fletcher, Leigh N. et al. (Nov. 2016). “Mid-infrared mapping of Jupiter’s temperatures, aerosol opacity and chemical distributions with IRTF/TEXES”. In: *Icarus* 278, pp. 128–161. DOI: 10.1016/j.icarus.2016.06.008. arXiv: 1606.05498 [astro-ph.EP].
- Fletcher, Leigh N. et al. (Apr. 2017). “Moist convection and the 2010-2011 revival of Jupiter’s South Equatorial Belt”. In: *Icarus* 286, pp. 94–117. DOI: 10.1016/j.icarus.2017.01.001. arXiv: 1701.00965 [astro-ph.EP].
- Fletcher, Leigh N. et al. (Mar. 2020b). “How Well Do We Understand the Belt/Zone Circulation of Giant Planet Atmospheres?” In: *Space Sci. Rev.* 216.2, 30, p. 30. DOI: 10.1007/s11214-019-0631-9. arXiv: 1907.01822 [astro-ph.EP].
- Folkner, W. M., R. Woo, and S. Nandi (1998). “Ammonia abundance in Jupiter’s atmosphere derived from the attenuation of the Galileo probe’s radio signal”. In: *Journal of Geophysical Research E: Planets* 103.E10, pp. 22847–22855. ISSN: 01480227. DOI: 10.1029/98JE01635.
- Foreman-Mackey, Daniel et al. (2013). “emcee : The MCMC Hammer ”. In: *Publications of the Astronomical Society of the Pacific* 125.925, pp. 306–312. ISSN: 00046280. DOI: 10.1086/670067. eprint: 1202.3665.
- Friedson, A. James (Sept. 2005). “Water, ammonia, and H₂S mixing ratios in Jupiter’s five-micron hot spots: A dynamical model”. In: *Icarus* 177.1, pp. 1–17. DOI: 10.1016/j.icarus.2005.03.004.
- Ge, Huazhi, Cheng Li, and Xi Zhang (Feb. 2024). “A stable and superadiabatic weather layer in Jupiter induced by moist convection”. In: *In review - Nature Astronomy* 7.
- Gierasch, P. J. (Dec. 1976). “Jovian meteorology: Large-scale moist convection”. In: *Icarus* 29.4, pp. 445–454. DOI: 10.1016/0019-1035(76)90064-6.
- Gierasch, P. J. et al. (Feb. 2000). “Observation of moist convection in Jupiter’s atmosphere”. In: *Nature* 403.6770, pp. 628–630. DOI: 10.1038/35001017.
- Gierasch, Peter J., Barney J. Conrath, and Julio A. Magalhães (Sept. 1986). “Zonal mean properties of Jupiter’s upper troposphere from voyager infrared observations”. In: *Icarus* 67.3, pp. 456–483. DOI: 10.1016/0019-1035(86)90125-9.
- Guillot, Tristan (Sept. 1995). “Condensation of Methane, Ammonia, and Water and the Inhibition of Convection in Giant Planets”. In: *Science* 269.5231, pp. 1697–1699. DOI: 10.1126/science.7569896.
- (Sept. 2021). “Mushballs and the lack of Ammonia in Uranus and Neptune”. In: *European Planetary Science Congress*, EPSC2021-422, EPSC2021-422. DOI: 10.5194/epsc2021-422.
- Guillot, Tristan et al. (2004). “The interior of Jupiter”. In: *Jupiter. The Planet, Satellites and Magnetosphere*. Ed. by Fran Bagenal, Timothy E. Dowling, and William B. McKinnon. Vol. 1, pp. 35–57.

- Guillot, Tristan et al. (Aug. 2020a). “Storms and the Depletion of Ammonia in Jupiter: I. Microphysics of “Mushballs””. In: *Journal of Geophysical Research (Planets)* 125.8, e06403. DOI: 10.1029/2020JE00640310.1002/essoar.10502154.1.
- Guillot, Tristan et al. (Aug. 2020b). “Storms and the Depletion of Ammonia in Jupiter: II. Explaining the Juno Observations”. In: *Journal of Geophysical Research (Planets)* 125.8, e06404. DOI: 10.1029/2020JE00640410.1002/essoar.10502179.1.
- Gulkis, S., M. A. Janssen, and E. T. Olsen (Apr. 1978). “Evidence for the depletion of ammonia in the Uranus atmosphere”. In: *Icarus* 34.1, pp. 10–19. DOI: 10.1016/0019-1035(78)90120-3.
- Gupta, Pranika et al. (July 2022). “Jupiter’s Temperature Structure: A Reassessment of the Voyager Radio Occultation Measurements”. In: *PSJ* 3.7, 159, p. 159. DOI: 10.3847/PSJ/ac6956. arXiv: 2205.12926 [astro-ph.EP].
- Hanel, R. et al. (Sept. 1981). “Albedo, internal heat, and energy balance of Jupiter: preliminary results of the voyager infrared investigation”. In: *Journal of Geophysical Research* 86.A10, pp. 8705–8712. DOI: 10.1029/JA086iA10p08705.
- Hanley, Thomas R., Paul G. Steffes, and Bryan M. Karpowicz (2009). “A new model of the hydrogen and helium-broadened microwave opacity of ammonia based on extensive laboratory measurements”. In: *Icarus* 202.1, pp. 316–335. ISSN: 00191035. DOI: 10.1016/j.icarus.2009.02.002. URL: <http://dx.doi.org/10.1016/j.icarus.2009.02.002>.
- Hardesty, Joanna, Chris Moeckel, and Imke de Pater (Jan. 2024). “Investigating Temporal and Spatial Variation of Jupiter’s Atmosphere with Radio Observations”. In: *In review - Planetary Science Journal*.
- Heimpel, Moritz, Jonathan Aurnou, and Johannes Wicht (Nov. 2005). “Simulation of equatorial and high-latitude jets on Jupiter in a deep convection model”. In: *Nature* 438.7065, pp. 193–196. DOI: 10.1038/nature04208.
- Hess, S. L. and H. A. Panofsky (1951). “The Atmospheres of the Other Planets”. In: *Compendium of Meteorology: Prepared under the Direction of the Committee on the Compendium of Meteorology*. Ed. by Thomas F. Malone. Boston, MA: American Meteorological Society, pp. 391–398. ISBN: 978-1-940033-70-9. DOI: 10.1007/978-1-940033-70-9_34. URL: https://doi.org/10.1007/978-1-940033-70-9_34.
- Hueso, R. et al. (Oct. 2009). “The jovian anticyclone BA. II. Circulation and interaction with the zonal jets”. In: *Icarus* 203.2, pp. 499–515. DOI: 10.1016/j.icarus.2009.05.004.
- Iess, L et al. (2018). “Measurement of Jupiter ’ s asymmetric gravity field”. In: *Nature Publishing Group*. ISSN: 0028-0836. DOI: 10.1038/nature25776.
- Ingersoll, A. P. et al. (May 1975). “Pioneer 11 Infrared Radiometer Experiment: The Global Heat Balance of Jupiter”. In: *Science* 188.4187, pp. 472–473. DOI: 10.1126/science.188.4187.472.
- Ingersoll, A. P. et al. (Feb. 2000). “Moist convection as an energy source for the large-scale motions in Jupiter’s atmosphere”. In: *Nature* 403.6770, pp. 630–632. DOI: 10.1038/35001021.

- Ingersoll, Andrew P. et al. (1981). “Interaction of eddies and mean zonal flow on Jupiter as inferred from Voyager 1 and 2 images”. In: *Journal of Geophysical Research: Space Physics* 86.A10, pp. 8733–8743. DOI: 10.1029/ja086ia10p08733.
- Ingersoll, Andrew P. et al. (2004). “Dynamics of Jupiter’s atmosphere”. In: *Jupiter. The Planet, Satellites and Magnetosphere*. Ed. by Fran Bagenal, Timothy E. Dowling, and William B. McKinnon. Vol. 1, pp. 105–128.
- Ingersoll, Andrew P. et al. (Aug. 2017). “Implications of the ammonia distribution on Jupiter from 1 to 100 bars as measured by the Juno microwave radiometer”. In: *Geophys. Res. Lett.* 44.15, pp. 7676–7685. DOI: 10.1002/2017GL074277.
- Ingersoll, Andrew P. et al. (Dec. 2021). “Jupiter’s Overturning Circulation: Breaking Waves Take the Place of Solid Boundaries”. In: *Geophys. Res. Lett.* 48.23, e95756, e95756. DOI: 10.1029/2021GL095756.
- Irwin, P. G. J. et al. (Apr. 2008). “The NEMESIS planetary atmosphere radiative transfer and retrieval tool”. In: *J. Quant. Spec. Radiat. Transf.* 109, pp. 1136–1150. DOI: 10.1016/j.jqsrt.2007.11.006.
- Irwin, Patrick G. J. et al. (Mar. 2019). “Probable detection of hydrogen sulphide (H₂S) in Neptune’s atmosphere”. In: *Icarus* 321, pp. 550–563. DOI: 10.1016/j.icarus.2018.12.014. arXiv: 1812.05382 [astro-ph.EP].
- Janssen, M A et al. (2005). “Microwave remote sensing of Jupiter’s atmosphere from an orbiting spacecraft”. In: *Icarus* 173.2, pp. 447–453.
- Janssen, M. A. et al. (2017). “MWR: Microwave radiometer for the Juno mission to Jupiter”. In: *Space Sci. Rev.* 213, pp. 139–185. DOI: 10.1007/s11214-017-0349-5.
- Jonathan, Aurnou et al. (June 2008). “Convective heat transfer and the pattern of thermal emission on the gas giants”. In: *Geophysical Journal International* 173.3, pp. 793–801. ISSN: 0956-540X. DOI: 10.1111/j.1365-246X.2008.03764.x. eprint: <https://academic.oup.com/gji/article-pdf/173/3/793/5895750/173-3-793.pdf>. URL: <https://doi.org/10.1111/j.1365-246X.2008.03764.x>.
- Kaspi, Yohai et al. (June 2020). “Comparison of the Deep Atmospheric Dynamics of Jupiter and Saturn in Light of the Juno and Cassini Gravity Measurements”. In: *Space Sci. Rev.* 216.5, 84, p. 84. DOI: 10.1007/s11214-020-00705-7. arXiv: 1908.09613 [astro-ph.EP].
- Klein, M.J. and S. Gulkis (1978). “Jupiter’s atmosphere: Observations and interpretation of the microwave spectrum near 1.25-cm wavelength”. In: *Icarus* 35.1, pp. 44–60. ISSN: 0019-1035. DOI: [https://doi.org/10.1016/0019-1035\(78\)90059-3](https://doi.org/10.1016/0019-1035(78)90059-3). URL: <https://www.sciencedirect.com/science/article/pii/0019103578900593>.
- Leachman, J.W. et al. (2009). “Fundamental Equations of State for Parahydrogen, Normal Hydrogen, and Orthohydrogen”. In: *Journal of Physical and Chemical Reference Data* 38.3. DOI: 10.1063/1.3160306.
- Leconte, Jérémy et al. (Feb. 2017). “Condensation-inhibited convection in hydrogen-rich atmospheres. Stability against double-diffusive processes and thermal profiles for Jupiter, Saturn, Uranus, and Neptune”. In: *A&A* 598, A98, A98. DOI: 10.1051/0004-6361/201629140. arXiv: 1610.05506 [astro-ph.EP].

- Lee, Sukyoung and Yohai Kaspi (July 2021). “Toward an Understanding of the Structure of Jupiter’s Atmosphere Using the Ammonia Distribution and the Transformed Eulerian Mean Theory”. In: *Journal of the Atmospheric Sciences* 78.7, pp. 2047–2056. DOI: 10.1175/JAS-D-20-0342.1.
- Lewis, John S. (1969). “The clouds of Jupiter and the $\text{NH}_3\text{H}_2\text{O}$ and $\text{NH}_3\text{H}_2\text{S}$ systems”. In: *Icarus* 10.3, pp. 365–378. ISSN: 10902643. DOI: 10.1016/0019-1035(69)90091-8.
- Li, Cheng and Xi Chen (Feb. 2019a). “Simulating Nonhydrostatic Atmospheres on Planets (SNAP): Formulation, Validation, and Application to the Jovian Atmosphere”. In: *ApJS* 240.2, 37, p. 37. DOI: 10.3847/1538-4365/aafdaa. arXiv: 1901.02955 [astro-ph.EP].
- Li, Cheng and Andrew P. Ingersoll (May 2015). “Moist convection in hydrogen atmospheres and the frequency of Saturn’s giant storms”. In: *Nature Geoscience* 8.5, pp. 398–403. DOI: 10.1038/ngeo2405.
- Li, Cheng, Andrew P. Ingersoll, and Fabiano Oyafuso (Apr. 2018a). “Moist Adiabats with Multiple Condensing Species: A New Theory with Application to Giant-Planet Atmospheres”. In: *Journal of the Atmospheric Sciences* 75.4, pp. 1063–1072. DOI: 10.1175/JAS-D-17-0257.1. arXiv: 1801.05529 [astro-ph.EP].
- Li, Cheng et al. (2017a). “The distribution of ammonia on Jupiter from a preliminary inversion of Juno microwave radiometer data”. In: *Geophysical Research Letters* 44.11, pp. 5317–5325. ISSN: 19448007. DOI: 10.1002/2017GL073159.
- (2017b). “The distribution of ammonia on Jupiter from a preliminary inversion of Juno microwave radiometer data”. In: *Geophysical Research Letters* 44.11, pp. 5317–5325. ISSN: 19448007. DOI: 10.1002/2017GL073159.
- Li, Cheng et al. (2020). “The water abundance in Jupiter’s equatorial zone”. In: *Nature Astronomy*. ISSN: 2397-3366. DOI: 10.1038/s41550-020-1009-3. URL: <http://dx.doi.org/10.1038/s41550-020-1009-3>.
- Li, Cheng et al. (Aug. 2023). “Long-lasting, deep effect of Saturn’s giant storms”. In: *Science Advances* 9.32, eadg9419. DOI: 10.1126/sciadv.adg9419.
- Li, Cheng et al. (May 2024). “Super-adiabatic temperature gradient at Jupiter’s equatorial zone and implications for the water abundance”. In: *Icarus* 414, 116028, p. 116028. DOI: 10.1016/j.icarus.2024.116028. arXiv: 2403.05363 [astro-ph.EP].
- Li, Liming et al. (Sept. 2018b). “Less absorbed solar energy and more internal heat for Jupiter”. In: *Nature Communications* 9, 3709, p. 3709. DOI: 10.1038/s41467-018-06107-2.
- Li, Shaomeng et al. (Aug. 2019b). “VAPOR: A Visualization Package Tailored to Analyze Simulation Data in Earth System Science”. In: *Atmosphere* 10.9, 488, p. 488. DOI: 10.3390/atmos10090488.
- Lindal, G. F. et al. (Sept. 1981). “The atmosphere of Jupiter: an analysis of the Voyager radio occultation measurements”. In: *J. Geophys. Res.* 86.A10, pp. 8721–8727. DOI: 10.1029/JA086iA10p08721.
- Little, Blane et al. (Dec. 1999). “Galileo Images of Lightning on Jupiter”. In: *Icarus* 142.2, pp. 306–323. DOI: 10.1006/icar.1999.6195.

- Liu, Junjun, Peter M. Goldreich, and David J. Stevenson (Aug. 2008). “Constraints on deep-seated zonal winds inside Jupiter and Saturn”. In: *Icarus* 196.2, pp. 653–664. DOI: 10.1016/j.icarus.2007.11.036. arXiv: 0711.3922 [astro-ph].
- Loftus, Kaitlyn and Robin D. Wordsworth (Apr. 2021). “The Physics of Falling Raindrops in Diverse Planetary Atmospheres”. In: *Journal of Geophysical Research (Planets)* 126.4, e06653. DOI: 10.1029/2020JE006653. arXiv: 2102.09570 [astro-ph.EP].
- Markham, S., T. Guillot, and C. Li (June 2023). “Rainy downdrafts in abyssal atmospheres”. In: *A&A* 674, A177, A177. DOI: 10.1051/0004-6361/202245609. arXiv: 2303.10604 [astro-ph.EP].
- Mironova, Irina A. et al. (Nov. 2015). “Energetic Particle Influence on the Earth’s Atmosphere”. In: *Space Sci. Rev.* 194.1-4, pp. 1–96. DOI: 10.1007/s11214-015-0185-4.
- Moeckel, Chris and Imke de Pater (Feb. 2024a). “Jupiter’s tropical atmosphere: Shallow Weather, Deep Plumes and Vortices”. In: *In prep - Planetary Science Journal*.
- Moeckel, Chris, Imke de Pater, and David DeBoer (Feb. 2023). “Ammonia Abundance Derived from Juno MWR and VLA Observations of Jupiter”. In: *PSJ* 4.2, 25, p. 25. DOI: 10.3847/PSJ/acaf6b. arXiv: 2209.03513 [astro-ph.EP].
- Moeckel, Chris, Huazhi Ge, and Imke de Pater (Feb. 2024b). “Tempest in the Troposphere - Mapping the Impact of Giant Storms on Jupiter’s Deep Atmosphere”. In: *In review - Science Advances* 0.
- Moeckel, Chris et al. (2019). “Tracking Temporal Changes below the Jovian Clouds using the VLA and Juno”. In: *EPSC-DPS Joint Meeting 2019* 13, pp. 0–1.
- Molter, Edward M. et al. (Feb. 2021). “Tropospheric Composition and Circulation of Uranus with ALMA and the VLA”. In: *PSJ* 2.1, 3, p. 3. DOI: 10.3847/PSJ/abc48a. arXiv: 2010.11154 [astro-ph.EP].
- Moore, K M et al. (2019). “Time variation of Jupiter’s internal magnetic field consistent with zonal wind advection”. In: *Nature Astronomy* 3.August, pp. 730–735. ISSN: 2397-3366. DOI: 10.1038/s41550-019-0772-5. URL: <http://dx.doi.org/10.1038/s41550-019-0772-5>.
- Niemann, H. B. et al. (Sept. 1998). “The composition of the Jovian atmosphere as determined by the Galileo probe mass spectrometer”. In: *J. Geophys. Res.* 103.E10, pp. 22831–22846. DOI: 10.1029/98JE01050.
- Niemann, Hasso B. et al. (May 1996). “The Galileo Probe Mass Spectrometer: Composition of Jupiter’s Atmosphere”. In: *Science* 272.5263, pp. 846–849. DOI: 10.1126/science.272.5263.846.
- Orton, Glenn S. et al. (Sept. 1998). “Characteristics of the Galileo probe entry site from Earth-based remote sensing observations”. In: *J. Geophys. Res.* 103.E10, pp. 22791–22814. DOI: 10.1029/98JE02380.
- Orton, Glenn S. et al. (Feb. 2023). “Unexpected long-term variability in Jupiter’s tropospheric temperatures”. In: *Nature Astronomy* 7, pp. 190–197. DOI: 10.1038/s41550-022-01839-0. arXiv: 2211.04398 [astro-ph.EP].

- Oyafuso, F et al. (2020). “Angular Dependence and Spatial Distribution of Jupiter ’ s Centimeter-Wave Thermal Emission from Juno ’ s Microwave Radiometer”. In: *Journal of Geophysical Research* July 2016, pp. 1–50. DOI: 10.1029/2020EA001254.
- Palotai, Csaba, Timothy E. Dowling, and Leigh N. Fletcher (Apr. 2014). “3D Modeling of interactions between Jupiter’s ammonia clouds and large anticyclones”. In: *Icarus* 232, pp. 141–156. DOI: 10.1016/j.icarus.2014.01.005.
- Peek, Bertrand M (1959). *The Planet Jupiter*. 2nd ed. Faber & Faber Limited.
- Pirraglia, J. A. (Aug. 1984). “Meridional energy balance of Jupiter”. In: *Icarus* 59.2, pp. 169–176. DOI: 10.1016/0019-1035(84)90020-4.
- Porco, C. C. et al. (Feb. 2005). “Cassini Imaging Science: Initial Results on Saturn’s Atmosphere”. In: *Science* 307.5713, pp. 1243–1247. DOI: 10.1126/science.1107691.
- Ragent, B. et al. (May 1992). “Galileo Probe Nephelometer experiment”. In: *Space Sci. Rev.* 60.1-4, pp. 179–201. DOI: 10.1007/BF00216854.
- Read, Peter L. et al. (July 2006). “Mapping potential-vorticity dynamics on Jupiter. I: Zonal-mean circulation from Cassini and Voyager 1 data”. In: *Quarterly Journal of the Royal Meteorological Society* 132, pp. 1577–1603. DOI: 10.1256/qj.05.34.
- Roberts, J A (1976). “The pitch angles of electrons in Jupiter’s radiation belt”. In: *Proceedings of the Astronomical Society of Australia*. Vol. 3, pp. 53–55.
- Sánchez-Lavega, A. et al. (Jan. 2008). “Depth of a strong jovian jet from a planetary-scale disturbance driven by storms”. In: *Nature* 451.7177, pp. 437–440. DOI: 10.1038/nature06533.
- Sánchez-Lavega, A. et al. (2017). “A planetary-scale disturbance in the most intense Jovian atmospheric jet from JunoCam and ground-based observations”. In: *Geophysical Research Letters* 44.10, pp. 4679–4686. ISSN: 19448007. DOI: 10.1002/2017GL073421.
- Santos-Costa, D. et al. (2017). “First look at Jupiter’s synchrotron emission from Juno’s perspective”. In: *Geophysical Research Letters* 44.17, pp. 8676–8684. ISSN: 19448007. DOI: 10.1002/2017GL072836.
- Sault, R J et al. (1997). “The first three-dimensional reconstruction of a celestial object at radio wavelengths: Jupiter’s radiation belts.” In: *Astronomy and Astrophysics* 324, pp. 1190–1196.
- Sault, R. J., Chermelle Engel, and Imke de Pater (Apr. 2004). “Longitude-resolved imaging of Jupiter at $\lambda=2$ cm”. In: *Icarus* 168.2, pp. 336–343. DOI: 10.1016/j.icarus.2003.11.014. arXiv: astro-ph/0612769 [astro-ph].
- Sault, R. J., P. J. Teuben, and M. C. H. Wright (Jan. 1995). “A Retrospective View of MIRIAD”. In: *Astronomical Data Analysis Software and Systems IV*. Ed. by R. A. Shaw, H. E. Payne, and J. J. E. Hayes. Vol. 77. Astronomical Society of the Pacific Conference Series, p. 433. DOI: 10.48550/arXiv.astro-ph/0612759. arXiv: astro-ph/0612759 [astro-ph].
- Schneider, Tapio and Junjun Liu (Jan. 2009). “Formation of Jets and Equatorial Superrotation on Jupiter”. In: *Journal of the Atmospheric Sciences* 66.3, p. 579. DOI: 10.1175/2008JAS2798.1. arXiv: 0809.4302 [astro-ph].

- Seiff, Alvin et al. (May 1996). “Structure of the Atmosphere of Jupiter: Galileo Probe Measurements”. In: *Science* 272.5263, pp. 844–845. DOI: 10.1126/science.272.5263.844.
- Showman, Adam P. (Jan. 2007). “Numerical Simulations of Forced Shallow-Water Turbulence: Effects of Moist Convection on the Large-Scale Circulation of Jupiter and Saturn”. In: *Journal of the Atmospheric Sciences* 64.9, p. 3132. DOI: 10.1175/JAS4007.1.
- Showman, Adam P. and Imke de Pater (Mar. 2005). “Dynamical implications of Jupiter’s tropospheric ammonia abundance”. In: *Icarus* 174.1, pp. 192–204. DOI: 10.1016/j.icarus.2004.10.004.
- Showman, Adam P. and Timothy E. Dowling (Sept. 2000). “Nonlinear Simulations of Jupiter’s 5-Micron Hot Spots”. In: *Science* 289.5485, pp. 1737–1740. DOI: 10.1126/science.289.5485.1737.
- Showman, Adam P., Peter J. Gierasch, and Yuan Lian (June 2006). “Deep zonal winds can result from shallow driving in a giant-planet atmosphere”. In: *Icarus* 182.2, pp. 513–526. DOI: 10.1016/j.icarus.2006.01.019.
- Simon-Miller, Amy A., Don Banfield, and Peter J. Gierasch (Jan. 2001). “An HST Study of Jovian Chromophores”. In: *Icarus* 149.1, pp. 94–106. DOI: 10.1006/icar.2001.6473.
- Simon-Miller, Amy A. et al. (Jan. 2006). “Jupiter’s atmospheric temperatures: From Voyager IRIS to Cassini CIRS”. In: *Icarus* 180.1, pp. 98–112. DOI: 10.1016/j.icarus.2005.07.019.
- Sromovsky, L. A. and P. M. Fry (June 2002). “Jupiter’s Cloud Structure as Constrained by Galileo Probe and HST Observations”. In: *Icarus* 157.2, pp. 373–400. DOI: 10.1006/icar.2002.6844.
- Sromovsky, L. A. et al. (July 2017). “A possibly universal red chromophore for modeling color variations on Jupiter”. In: *Icarus* 291, pp. 232–244. DOI: 10.1016/j.icarus.2016.12.014. arXiv: 1706.02779 [astro-ph.EP].
- Stone, James M. et al. (Sept. 2008). “Athena: A New Code for Astrophysical MHD”. In: *ApJS* 178.1, pp. 137–177. DOI: 10.1086/588755. arXiv: 0804.0402 [astro-ph].
- Strycker, Paul D. et al. (Oct. 2011). “Jovian chromophore characteristics from multispectral HST images”. In: *Icarus* 215.2, pp. 552–583. DOI: 10.1016/j.icarus.2011.08.004.
- Sugiyama, K. et al. (July 2011). “Intermittent cumulonimbus activity breaking the three-layer cloud structure of Jupiter”. In: *Geophys. Res. Lett.* 38.13, L13201, p. L13201. DOI: 10.1029/2011GL047878.
- Sugiyama, K. et al. (Feb. 2014). “Numerical simulations of Jupiter’s moist convection layer: Structure and dynamics in statistically steady states”. In: *Icarus* 229, pp. 71–91. DOI: 10.1016/j.icarus.2013.10.016.
- Thomson, Stephen I. and Michael E. McIntyre (Mar. 2016). “Jupiter’s Unearthly Jets: A New Turbulent Model Exhibiting Statistical Steadiness without Large-Scale Dissipation*”. In: *Journal of the Atmospheric Sciences* 73.3, pp. 1119–1141. DOI: 10.1175/JAS-D-14-0370.1. arXiv: 1412.4684 [astro-ph.EP].
- Thornton, D. D. and W. J. Welch (1963). “8.35 mm Radio Emission from Jupiter and Venus”. In: *Icarus* 2.

- Tibshirani, Robert (1996). “Regression Shrinkage and Selection Via the Lasso”. In: *Journal of the Royal Statistical Society: Series B (Methodological)* 58.1, pp. 267–288. DOI: <https://doi.org/10.1111/j.2517-6161.1996.tb02080.x>. eprint: <https://rss.onlinelibrary.wiley.com/doi/pdf/10.1111/j.2517-6161.1996.tb02080.x>. URL: <https://rss.onlinelibrary.wiley.com/doi/abs/10.1111/j.2517-6161.1996.tb02080.x>.
- Tollefson, Joshua et al. (June 2021). “Neptune’s Spatial Brightness Temperature Variations from the VLA and ALMA”. In: *PSJ* 2.3, 105, p. 105. DOI: 10.3847/PSJ/abf837. arXiv: 2104.06554 [astro-ph.EP].
- Trenberth, Kevin E. and Julie M. Caron (Aug. 2001). “Estimates of Meridional Atmosphere and Ocean Heat Transports.” In: *Journal of Climate* 14.16, pp. 3433–3443. DOI: 10.1175/1520-0442(2001)014<3433:EOMAAO>2.0.CO;2.
- Vallis, Geoffrey K. (2017). *Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation*. DOI: 10.1017/9781107588417.
- Vasavada, Ashwin R. and Adam P. Showman (Aug. 2005). “Jovian atmospheric dynamics: an update after Galileo and Cassini”. In: *Reports on Progress in Physics* 68.8, pp. 1935–1996. DOI: 10.1088/0034-4885/68/8/R06.
- Weidenschilling, S.J. and J.S. Lewis (1973). “Atmospheric and cloud structures of the Jovian planets”. In: *Icarus* 20.4, pp. 465–476. ISSN: 0019-1035. DOI: [https://doi.org/10.1016/0019-1035\(73\)90019-5](https://doi.org/10.1016/0019-1035(73)90019-5). URL: <https://www.sciencedirect.com/science/article/pii/0019103573900195>.
- Welch, W. J., D. D. Thornton, and R. Lohman (1966). “Observations of Jupiter, Saturn, and Mercury at 1.53 Centimeters”. In: *The Astrophysical Journal* 146, pp. 799–810.
- West, R. A., A. J. Friedson, and J. F. Appleby (Nov. 1992). “Jovian large-scale stratospheric circulation”. In: *Icarus* 100.1, pp. 245–259. DOI: 10.1016/0019-1035(92)90033-4.
- Wicht, J. et al. (Sept. 2019). “Dynamo action of the zonal winds in Jupiter”. In: *A&A* 629, A125, A125. DOI: 10.1051/0004-6361/201935682. arXiv: 1906.09061 [astro-ph.EP].
- Wicht, Johannes and Thomas Gastine (June 2020). “Numerical simulations help revealing the dynamics underneath the clouds of Jupiter”. In: *Nature Communications* 11, 2886, p. 2886. DOI: 10.1038/s41467-020-16680-0.
- Wong, Michael H. et al. (Sept. 2004). “Updated Galileo probe mass spectrometer measurements of carbon, oxygen, nitrogen, and sulfur on Jupiter”. In: *Icarus* 171.1, pp. 153–170. DOI: 10.1016/j.icarus.2004.04.010.
- Wong, Michael H. et al. (Apr. 2020a). “High-resolution UV/Optical/IR Imaging of Jupiter in 2016-2019”. In: *Astrophysical Journal Supplement Series* 247.2, 58, p. 58. DOI: 10.3847/1538-4365/ab775f.
- (Apr. 2020b). “High-resolution UV/Optical/IR Imaging of Jupiter in 2016-2019”. In: *ApJS* 247.2, 58, p. 58. DOI: 10.3847/1538-4365/ab775f.
- Wong, Michael H. et al. (Jan. 2023). “Deep Clouds on Jupiter”. In: *Remote Sensing* 15.3, 702, p. 702. DOI: 10.3390/rs15030702.
- Wrixton, G. T., W. J. Welch, and D. D. Thornton (1971). “The Spectrum of Jupiter at Millimeter Wavelengths”. In: *The Astrophysical Journal* 169, pp. 171–183.

- Yadav, Rakesh Kumar, Moritz Heimpel, and Jeremy Bloxham (Nov. 2020). “Deep convection-driven vortex formation on Jupiter and Saturn”. In: *Science Advances* 6.46, eabb9298. DOI: 10.1126/sciadv.abb9298. arXiv: 2011.07263 [astro-ph.EP].
- Young, Roland M. B. and Peter L. Read (Nov. 2017). “Forward and inverse kinetic energy cascades in Jupiter’s turbulent weather layer”. In: *Nature Physics* 13.11, pp. 1135–1140. DOI: 10.1038/nphys4227.
- Young, Roland M. B., Peter L. Read, and Yixiong Wang (July 2019a). “Simulating Jupiter’s weather layer. Part I: Jet spin-up in a dry atmosphere”. In: *Icarus* 326, pp. 225–252. DOI: 10.1016/j.icarus.2018.12.005.
- (July 2019b). “Simulating Jupiter’s weather layer. Part II: Passive ammonia and water cycles”. In: *Icarus* 326, pp. 253–268. DOI: 10.1016/j.icarus.2018.12.002.
- Zarka, Philippe (1998). “Auroral radio emissions at the outer planets: Observations and theories”. In: *Journal of Geophysical Research: Planets* 103.3339, pp. 20159–20194. ISSN: 01480227. DOI: 10.1029/98je01323.
- Zhang, Zhimeng et al. (Sept. 2020). “Residual Study: Testing Jupiter Atmosphere Models Against Juno MWR Observations”. In: *Earth and Space Science* 7.9, e01229. DOI: 10.1029/2020EA001229.