A Wideband Self-consistent Disk-averaged Spectrum of Jupiter Near 30 GHz and Its Implications for NH₃ Saturation in the Upper Troposphere

Ramsey L. Karim¹ ², David DeBoer² ³, Imke de Pater², and Garrett K. Keating² ³ ⁴

¹Department of Astronomy, University of Maryland, College Park, MD 20742, USA; rkarim@astro.umd.edu
²Department of Astronomy, University of California, 501 Campbell Hall, Berkeley, CA 94720, USA
³Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Received 2017 November 15; revised 2018 January 22; accepted 2018 January 23; published 2018 February 26

Abstract

We present a new set of measurements obtained with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) of Jupiter’s microwave thermal emission near the 1.3 cm ammonia (NH₃) absorption band. We use these observations to investigate the ammonia mole fraction in the upper troposphere, near 0.3 < P < 2 bar, based on radiative transfer modeling. We find that the ammonia mole fraction must be \(~2.4 \times 10^{-4}\) below the NH₃ ice cloud, i.e., at 0.8 < P < 8 bar, in agreement with results by de Pater et al. We find the NH₃ cloud-forming region between 0.3 < P < 0.8 bar to be globally sub-saturated by ~55% on average, in accordance with the result in Gibson et al. Although our data are not very sensitive to the region above the cloud layer, we are able to set an upper limit of \(2.4 \times 10^{-4}\) on the mole fraction here, a factor of ~10 above the saturated vapor curve.

Key words: planetary systems: atmospheres – planets and satellites: individual (Jupiter) – radio continuum: planetary systems

Supporting material: data behind figure

1. Introduction

Microwave observations of Jupiter’s atmosphere are generally dominated by pressure-broadened spectral features of ammonia gas in the troposphere (Thornton & Welch 1963). The most notable feature in this region of the gas giant’s thermal spectrum is the 1.3 cm NH₃ inversion/absorption band, first reported as a single, broad line by Law & Staelin (1968) and found by Klein & Gulkis (1978) to be a “diagnostic of the pressure and temperature profiles in the cloud-forming region of the Jovian atmosphere.” As we continue to sample Jupiter’s thermal spectrum around this band, we can better characterize the shape of this spectral feature, which, through proper analysis, provides us with a deeper understanding of the planet’s vertical structure and improves Jupiter’s utility as a radio calibrator.

Decades of disk-averaged, and more recently, spatially resolved, observations as well as in situ probe measurements have contributed to our understanding of the planet’s atmospheric structure, initially revealing a relatively straightforward model involving an adiabatic atmosphere with roughly solar NH₃ mole fraction (hereafter, “abundance”) in the deep atmosphere, which is considered to be well-mixed. The detailed radiative transfer analysis presented in de Pater & Massie (1985) agrees, stating solar NH₃ abundance to within a factor of two until \(P < 0.5\) bar, above which NH₃ drops by \(\sim 10^3\). This depletion is consistent with NH₃ condensation following the saturated vapor curve.

Modern efforts to uncover more about the planet’s vertical structure have also raised new questions (de Pater et al. 2005). The Galileo probe mission of the 1990s presented in situ measurements of the NH₃ abundance that arguably conflict with models derived from ground-based observations, creating what was described in that paper as the “Galileo Ground-based Microwave Paradox.” Probe measurements suggest that NH₃ abundance should be nearly 4× solar. Given the previously accepted model, this result was jarring to our understanding of the atmosphere’s structure and dynamics. To improve this understanding, additional data sets are needed along with updated modeling using the latest measurements of the microwave properties of, primarily, ammonia gas.

This work presents new ground-based observations made over a very wide bandwidth with the Sunyaev–Zel’dovich Array (SZA), a subset of the CARMA interferometer in an array configuration that does not resolve the planet, so more accurate disk-averaged brightness temperatures may be determined. It provides a single systematically consistent data set over its band (27–35 GHz) that may be used in conjunction with the many decades of observations of our largest planet (e.g., Klein & Gulkis 1978; Page et al. 2003; Gibson et al. 2005; Weiland et al. 2011; de Pater et al. 2016a). Having a well-calibrated systematically consistent data set over this broad bandwidth complements the single absolutely calibrated point near 28.5 GHz in Gibson et al. (2005, hereafter JG). In addition to presenting their own absolutely calibrated data point from earlier work (Gibson 2003), JG corrects and discusses the 20–24 GHz observations from (Klein & Gulkis 1978), and the 22–94 GHz observations obtained with the Wilkinson Microwave Anisotropy Probe satellite (WMAP; Page et al. 2003; updated in Weiland et al. 2011); they conclude that NH₃ is globally subsolar between 0.6 < \(P < 2\) bar and sub-saturated by more than 50% between 0.4 < \(P < 0.6\) bar.

Based on these measurements we fine-tune the model presented in de Pater et al. (2001) and extended in de Pater et al. (2016a). Based on Galileo measurements, this model assumes the NH₃ abundance to be \(4.5 \times 10^{-4}\) in the deep (\(P > 8\) bar) atmosphere and then follows the saturated vapor curve within and above the cloud layers. This model, described in more detail in Section 3, is henceforth referred to as the solar model.
as the “nominal” model and serves as the base model for this work.

2. Data

One of the last studies conducted with CARMA was a CO power spectrum survey that aimed to measure the CO(1–0) transition in redshift \( \sim 3 \) galaxies (Keating et al. 2015; Keating et al. 2016, hereafter referred to as COPSS). The compact, eight-element Sunyaev–Zel’dovich Array (SZA) subset of CARMA was used to take various field scans between 27–35 GHz to measure the redshifted CO(1–0) \( \nu_0 = 115 \) GHz line. COPSS used Mars as the primary calibrator, and Jupiter as the secondary calibrator. It is these Jupiter observations, taken between 2014 December and the array’s decommission in 2015 April, that are used in this work.

The SZA is a set of eight 3.5 m elements sensitive to left circularly polarized radiation in a compact array (Keating et al. 2015). As it does not resolve the planet, the array is well-suited for accurate measurements of Jupiter’s total flux density. The calibration data from COPSS comprise flux densities spanning 15 channels from 27–35 GHz (0.8 to 1.1 cm) and 100 days between 2014 December and 2015 April. Thermal error estimates are typically of order 0.01 Jy for a single day’s worth of data on Jupiter. Uncertainty in the absolute flux calibration is preliminarily estimated at <5% according to COPSS, but we present our own thorough investigation in Section 2.1.1. CARMA in its entirety is a fairly spectrally stable instrument, so we expect relative uncertainty to be somewhat smaller than absolute uncertainty.

2.1. Determination of Jupiter’s Flux Densities

Reduction of these data converts a time series of flux densities to a single brightness temperature on channel-by-channel basis. The process also isolates and corrects for a variety of systematics throughout the process. The result is 15 time- and disk-averaged measurements of Jupiter’s brightness near the 1.3 cm ammonia absorption band.

The effects of Jupiter’s distance from Earth during the observational period are removed through distance normalization to the nominal value of 4.04 au, “flattening” each channel’s measurement as is made evident between the two panels in Figure 1. This step facilitates examination of antenna gain error, indicated by the variance in the normalized points as well as the cross-channel behavior during individual observations. Jackknife testing, discussed in more detail in Section 2.3, reveals an additional artifact at this stage. The series of flux

---

**Figure 1.** Flux density measurements by time, before (left) and after (right) distance adjustment. The data used to create this figure are available.

**Figure 2.** Indication of linear dependence of flux on elevation, and more importantly, linear dependence of flux-elevation slope on frequency. The left panel shows individual fits to each channel, sorted by Jupiter’s elevation at observation time. The right panel shows these fits set against channel frequency and demonstrates the frequency dependence.
densities for each channel show a positive linear correlation with Jupiter’s elevation in the sky at the time of observation, indicating some potential issue with airmass calibration in the original measurements. The slopes of each channel’s flux density are positive and linear with frequency and therefore relatively easy to correct for, as demonstrated in Figure 2; we assumed in this process that the measurements taken at higher elevations through thinner layers of atmosphere are more accurate.

The flux densities are averaged across time with weights corresponding inversely to the thermal error on each measurement. Averages are calculated as

\[ F_{\nu,\text{meas}} = \langle F_{\nu} \rangle = \frac{\sum_{i} w_{\nu,i} F_{\nu,i}}{\sum_{i} w_{\nu,i}} \]  

(1)

where

\[ w_{\nu,i} = 1/\sigma_{\nu,i}^2 \]

(2)

such that \( \sigma_{\nu,i} \) is the stated thermal error in Janskys on the \( i \)th measurement for a given channel. Averaging the flux densities themselves is fairly straightforward; the rest of this section will discuss the application of meaningful error estimates.

### 2.1.1. Absolute (\( \sigma_A \)) and Relative (\( \sigma_R \)) Uncertainty

We define two distinct error measurements for the data set: absolute uncertainty \( \sigma_A \) and relative uncertainty \( \sigma_R \). Absolute uncertainty quantifies our estimate of the overall calibration accuracy of the SZA, estimating how close the data are to the actual values. This is determined by the systematics of the instrument. An upper limit of \(<5\%\) on this calibration error is quoted in COPSS, which incorporates results from Sharp et al. (2010) in this estimate.

Relative uncertainty quantifies the stability of each channel with respect to the others, estimating internal consistency rather than absolute accuracy. CARMA has strong spectral stability and can observe this feature in the strongly correlated cross-channel behavior displayed in Figures 1 and 2, which suggests that the \( \sigma_R \) measurement, while allowing some independent uncertainty on points, is expected to be smaller than \( \sigma_A \) and so will not have as great an effect on the overall position of the ensemble. \( \sigma_R \) is useful in defending the use of the relative structure of the ensemble as a comparably reliable tool to the absolute position as well as quantifying a model’s match to this relative structure during the model-comparison process. \( \sigma_A \), by contrast, serves as a more conventional uncertainty estimate.

We approach the absolute uncertainty \( \sigma_A \) estimate using statistical properties of the flux density ensemble along with their stated thermal errors. The absolute uncertainty is the quadrature sum of the weighted average of the individual data and the thermal noise of each measurement and may be written

\[ \sigma_A^2(\hat{n}, \hat{n}) = \hat{\sigma}^2 + \hat{n}^2. \]

(3)

The first term is

\[ \hat{\sigma}^2 = \frac{\sum_{i} w_{i} (F_{\nu,i} - \langle F_{\nu} \rangle)^2}{\sum_{i} w_{i}}. \]

(4)

The second term, the thermal contribution \( \hat{n} \), is calculated as the reciprocal sum of thermal uncertainties for a given channel.

With \( w_i \) defined as in Equation (2), \( \hat{\sigma} \) is

\[ \frac{1}{\hat{\sigma}^2} = \sum_{i} w_{i}. \]

(5)

In this way, we merge statistical 1\( \sigma \) error on a channel’s flux ensemble with the thermal uncertainty of the points themselves and produce the value \( \sigma_A \), our estimate of uncertainty on the absolute calibration of the instrument. This we find to be closer to \( \sim\)2\% which falls under the upper limit stated in COPSS.

Relative uncertainty \( \sigma_R \) comprises both thermal contribution as well as the tendency of each channel to deviate from the others. A perfectly stable instrument should exhibit a consistent cross-channel response to small, day-to-day variation in observed flux; unexpected behavior should be reflected in \( \sigma_R \). We compare observations across channels by normalizing each channel with its average.5 The normalized measurements are denoted \( f_{\nu,i} \).

\[ f_{\nu,i} = \frac{F_{\nu,i}}{(\langle F_{\nu,i} \rangle_{\nu})}. \]

(6)

This fraction is averaged across each observation to find the daily mean deviation from each channel’s respective average. A stable instrument’s channel would exhibit minimal spread around this daily mean deviation, and any spread should be uncorrelated with channel. We isolate the residuals \( \delta_{\nu,i} \) from this daily average by subtracting the daily mean deviation from each observation set of normalized measurements, so as to exclude the daily deviation itself and examine each channel’s deviation from this deviation. These residuals are defractionalized by multiplying by the channel average.

\[ \delta_{\nu,i} = (f_{\nu,i} - \langle f_{\nu,i} \rangle_{i}) \cdot (F_{\nu,i})_{\nu}. \]

(7)

Each channel’s behavior is now quantified by its mean deviation from the daily average as well as the spread of these deviations, given by their variance across each channel. During this examination, it was noted that the channels had a tendency to vary together in time; they often would pivot around the 31.188 GHz measurement, which remained stable to within 0.5\% of the measurement value. The frequencies at either extreme (27.688 GHz and 34.688 GHz) varied by no more than 6\%. It is unclear what causes this linear variation, but it is worth mentioning that even though this estimate describes the uncertainty of these points relative to each other, it is an overestimate. There remains some unidentifiable cross-channel dependency.

We introduce a thermal component as well, calculated by fractionalizing each thermal error by its accompanying measurement, averaging across each channel, and denormalizing with the channel average.

\[ \sigma_{th} = \frac{\langle \sigma_{\nu,i} \rangle}{\langle F_{\nu,i} \rangle_{\nu}}. \]

(8)

The final relative uncertainty measurement contains the thermal component \( \sigma_{th} \) as well as the mean \( \langle \delta_{\nu,i} \rangle_{i} \) and standard

---

5 Until now, all averages have been across time, isolated to each channel. In this section, that will no longer be the case, so averages will be marked as either channel averages \( (i) \) summed across all observations as before, or “daily” averages \( (j) \) calculated with sums across all channels, isolated to each observation.
deviation \(\langle (\delta v_{i} - \langle \delta v_{i} \rangle)^2 \rangle_{\nu}^{1/2}\) of the daily deviations by channel. The third term, the variance of the channel’s daily deviations, dominates the entire measurement and gives each channel a relative uncertainty on the order of a jansky.

\[
\sigma_{R}^{2} = \sigma_{h}^{2} + \langle \delta v_{i} \rangle_{\nu}^{2} + \langle (\delta v_{i} - \langle \delta v_{i} \rangle)^2 \rangle_{\nu}. \tag{9}
\]

2.1.2. Correction for the Synchrotron Radiation

The relatively large SZA beam (\(\theta_{B} \approx 11^\circ\) full width at half max) contains flux from both thermal and non-thermal components. In this frequency regime, synchrotron radiation dominates the non-thermal emission. As we are interested only in the thermal component, we must subtract out the synchrotron radiation from the total observed flux density.

Jupiter’s dynamic synchrotron spectrum has been a subject of discussion since the 1970s when a series of observations suggested time variability in the low-frequency\(^6\) spectrum (Klein 1976). A survey of that spectrum from 74 MHz up to 8 GHz, described by de Pater et al. (2003), suggests that the synchrotron contribution to the planet’s radio spectrum drops off above 2 GHz, leading us to believe that, with frequencies around 30 GHz, our measurements contain negligible synchrotron-induced variability. Klein (1976) observes that fluctuations on the order of days did not exceed 10% and explores variability on timescales of several years using 1–3 month averages, which implies that our 5 month average should capture an approximately constant period of synchrotron activity. Under this assumption, we use a simplified and time-independent model to determine the contribution of synchrotron radiation on Jupiter’s thermal spectrum. The correction is purely arithmetic and thus does not propagate into uncertainties.

JG uses a value of 1.5 Jy for the synchrotron contribution to a 28.5 GHz measurement of the thermal spectrum, which has a value of about 145 Jy, based on work done by de Pater & Dunn (2003). In order to adjust extant data in the same frequency regime, JG adopts a relationship of \(F_{\nu,synch} \sim \nu^{-0.4}\), leading to the local model

\[
F_{\nu,synch} = (1.5 \text{ Jy}) \left(\frac{\nu}{28.5 \text{ GHz}}\right)^{0.4}, \tag{10}
\]

which we apply across our small frequency domain.

The synchrotron model (10) is subtracted from the time-averaged flux density at each channel (1), yielding thermal-only flux density measurements:

\[
F_{\nu,thermal} = F_{\nu,meas} - F_{\nu,synch}. \tag{11}
\]

2.2. Conversion to Brightness Temperature and Cosmic Microwave Background (CMB) Adjustment

The thermal radiation flux density, \(F_{\nu,thermal}\), is converted to brightness temperature, \(T_{b}\), via the Planck function. The resulting \(T_{b,meas}\) from a direct conversion is not yet indicative of the true temperature of the emitter—it is the contrast between the emitter and the microwave background. Correction for this is made during conversion, following a similar adjustment made by de Pater et al. (2014). Observed thermal flux density is set equal to a combination of thermal brightness temperature and CMB contribution by the Planck function, as

\[
\text{Table 1}
\]

| \(f (\text{GHz})\) | \(\lambda (\text{cm})\) | \(F_{\nu,meas} (\text{Jy})\) | \(F_{\nu,thermal} (\text{Jy})\) | \(T_{b} (\text{K})\) | \(\sigma_{A} (\text{K})\) | \(\sigma_{R} (\text{K})\) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 34.688          | 0.864           | 226.612         | 225.225         | 151.013         | 3.180           | 1.359           |
| 34.188          | 0.877           | 219.250         | 217.855         | 150.385         | 3.143           | 1.186           |
| 33.688          | 0.890           | 211.832         | 210.429         | 149.615         | 3.222           | 1.037           |
| 33.188          | 0.903           | 206.006         | 204.594         | 149.876         | 3.531           | 1.244           |
| 32.688          | 0.917           | 198.089         | 196.669         | 148.534         | 3.424           | 0.620           |
| 32.188          | 0.931           | 191.047         | 189.618         | 147.707         | 3.228           | 0.510           |
| 31.688          | 0.946           | 184.615         | 183.177         | 147.235         | 3.240           | 0.316           |
| 31.188          | 0.961           | 178.155         | 176.708         | 146.635         | 3.293           | 0.416           |
| 30.688          | 0.977           | 171.458         | 170.002         | 145.720         | 3.266           | 0.378           |
| 30.188          | 0.993           | 165.546         | 164.080         | 145.347         | 3.382           | 0.395           |
| 29.688          | 1.010           | 159.553         | 158.077         | 144.794         | 3.515           | 0.675           |
| 29.188          | 1.027           | 153.335         | 151.849         | 143.911         | 3.584           | 0.769           |
| 28.688          | 1.045           | 147.477         | 145.981         | 143.225         | 3.679           | 0.960           |
| 28.188          | 1.064           | 141.586         | 140.080         | 142.369         | 3.767           | 1.147           |
| 27.688          | 1.083           | 136.081         | 134.563         | 141.757         | 3.875           | 1.368           |

Note. \(F_{\nu,meas}\) and \(F_{\nu,thermal}\) are normalized to 4.04 au. \(T_{b}\) values include CMB correction. Error estimates are given for the final \(T_{b}\) values only.

below, allowing \(T_{\mathrm{cmb}} = 2.725\ K\).

\[
F_{\nu} = \frac{2\nu h^{3}}{c^{2}} \left(\frac{1}{e^{h\nu/kT_{b}} - 1} - \frac{1}{e^{h\nu/kT_{\mathrm{cmb}}} - 1}\right) \frac{\pi R_{p} R_{p}'}{D^{2}} \tag{12}
\]

where apparent polar radius is given by \(R_{p}' = \sqrt{R_{p}^{2} \sin^{2} \phi + R_{c}^{2} \cos^{2} \phi}\). Subearth latitude used here is \(\phi = 0^\circ.15\), which is the average over a tight cluster of small, similar \(\phi\) values over the four-month observation interval according to the JPL Horizons interface.

Working values at each major step as well as final measurements and associated error estimates are laid out in Table 1. The \(T_{b}\) values, along with some combination of the \(\sigma_{A}\) and \(\sigma_{R}\) uncertainties, are appropriate for reproduction in future work.

2.3. Jackknife Testing

In order to investigate whether identifiable systematics are present, we conducted a set of jackknife tests during which we run arbitrarily selected halves of the time-series data through the analysis pipeline and observe the average resulting change in brightness temperatures. The data are halved both on meaningless criteria as well as by criteria with more systematic potential. We applied arbitrary-parameter tests with the data split along odd versus even index, first versus second half, and first and last quarters versus central half. We applied the more meaningful test of sorting along Jupiter’s horizontal elevation at the time of observation.

It was mentioned earlier that what may be an airmass calibration error in the raw data was detected by one of these jackknife tests, specifically one using Jupiter’s elevation. After this correction, all subsequent jackknife tests amount to nothing more than noise at less than 2% variation from the full-range values, indicating that we have identified all major systematics about which we have information. The consistency of our measurements with the Gibson and WMAP points corroborates this, or at least suggests that we all suffer from the same unknown systematics.

---

\(^6\) Klein (1976) uses 11–13 cm and 21 cm, considerably longer wavelengths than our 1 cm.
3. Radiative Transfer Analysis

As briefly discussed in Section 1, the main source of radio opacity in Jupiter’s atmosphere is ammonia gas. The following subsections outline our methods to determine the NH₃ abundance in that part of the atmosphere to which our measurements are sensitive.

3.1. Nominal NH₃ Profile

Our calculations use the radiative transfer code most recently used by de Pater et al. (2016a); this code is based upon an atmosphere in thermochemical equilibrium, as described in detail by de Pater et al. (2005). As in de Pater et al. (2016a), we assume for our nominal model that all constituents (NH₃, H₂S, CH₄, and H₂O) are enhanced by a factor of 4.5 above solar in the deep atmosphere (P > 8 bar), as observed by the Galileo probe for NH₃, H₂S, and CH₄ (Folkner et al. 1998; Sromovsky et al. 1998; Mahaffy et al. 1999; Wong et al. 2004). At higher altitudes, NH₃ will be partially dissolved in the water cloud (~7.3 bar), will form the NH₄SH cloud (~2.5 bar, de Pater 1990), and at P < ~0.8 bar will condense into its own ice cloud and follow the saturated vapor curve. In our nominal model, we thus assume NH₃ abundance of 5.72 × 10⁻⁴⁴ in Jupiter’s deep atmosphere, which is diminished at altitudes at which clouds form. We adopt a 100% humidity within and above the NH₃ ice cloud in our nominal model. This results in a constant abundance of 1.20 × 10⁻⁷ near and above the tropopause. This NH₃ profile is shown by the blue curve in Figure 3(b), and the resulting spectrum is shown by the blue curves in Figures 4 and 5.

Note from the weighting functions in Figure 3(a) that our data are sensitive to P < ~3 bar. While our results should, strictly speaking, only apply down to a “deep atmosphere” cutoff defined by this sensitivity, we extend our results down to P < 8 bar in order to remain consistent with de Pater et al. (2016a) under the assumption that NH₃ abundance should remain roughly constant between 3 < P < 8 bar—it should only increase (with increasing pressure) at the clouds described above. Below P > 8 bar, we adopt the values as measured by the Galileo spacecraft (Wong et al. 2004).

3.2. Model Generation Through Perturbation

Starting with the nominal NH₃ abundance profile described above, we apply to it small, unity-order adjustments, which in turn gives us the ability to generate a range of theoretical spectra. These spectra are compared to the available measurements in order to isolate a NH₃ abundance profile in maximal agreement with observations. The spectra are generated using the radiative transfer software, pyplanet, described by de Pater et al. (2014) for its use on Neptune’s atmosphere and most recently updated with the NH₃ line profile from Bellotti et al. (2016). The software ignores potential opacities from clouds.

We begin this process by separating the atmosphere into regions of altitude based on their radiative contribution to our measurements, according to the nominal NH₃ abundance model. These contribution functions, shown in Figure 3(a), are most prevalent between 0.5 < P < 0.8 bar. This layer coincides with the NH₃ ice cloud-forming region, over which altitude range NH₃ follows the saturated vapor curve, as indicated by the nominal abundance profile (blue curve in Figure 3(b)). We apply to this region, defined by its plummeting NH₃ abundance, a constant humidity multiplier RH. Through this parameter, we will tune humidity in the NH₃ cloud-forming region to fit observations.

We similarly treat the regions of constant NH₃ abundance above and below this layer, granting them their own modifying constants. The sub-cloud region, defined as the region of approximately constant NH₃ abundance from the bottom of the NH₃ cloud down to P ~ 8 bar, is modified by the parameter αδ. As we consider our model not to apply below P > 8 bar, we jump the abundance below this point back to the nominal model, which is motivated by Galileo measurements sensitive to this deeper region. de Pater et al. (2016a) applies this same practice. The region of constant abundance above the tropopause is modified by the parameter αh.

These parameters, RH, αδ, and αh, form a three-parameter grid across which we create slightly modified versions of the nominal abundance model. Each element of the grid is run through the radiative transfer software to generate a spectrum, and each of these spectra is compared to the observations such...
that each point on the three-dimensional grid is associated with a $\chi^2$ value. We search the parameter space, bounded by a physically reasonable range of unity-order constants, for a global minimum. This minimum is explored to within 0.5% resolution of the nominal value. The abundance profile associated with this minimum is taken to be the profile in maximal agreement with observational evidence. Uncertainty for each parameter is approximated as the region in which the local $\chi^2$ value is less than $2 \times$ the minimum $\chi^2$ value.

4. Results

Our measurements of Jupiter’s atmospheric emission show a smoothly sloped curve on the short-wavelength side of the 1.3 cm NH$_3$ absorption band. We compare our data with the surrounding WMAP and Klein & Gulkis data sets, as adjusted in JG, as well as Gibson’s original point at 28.5 GHz. The CARMA observations are consistent to well within 1% with points from these existing measurements that fall between 27–35 GHz. In the 2–6 cm range, we use VLA measurements from de Pater et al. (2016a) that have since been recalibrated (de Pater et al. 2016b).

We implement the model-measurement comparison scheme discussed in the previous section and generate a grid of model spectra and corresponding $\chi^2$ comparison results. The $\chi^2$ grid fitting we implement compares models only to the CARMA, WMAP, and JG measurements. Comparisons to Klein & Gulkis and VLA data are made after best-fit values have been obtained in order to verify the results.

4.1. Sub-cloud Abundance $\alpha_d$

We examine the NH$_3$ abundance below the cloud-forming region relative to the nominal abundance value of $5.72 \times 10^{-4}$, and find a value of $2.40 \times 10^{-4}$ just above $P \sim 8$ bar, with uncertainty bounding it between $[2.26, 2.57] \times 10^{-4}$. Accounting for reductions at clouds, the $P \sim 0.8$ bar abundance is $1.89 \times 10^{-4}$. Figure 5 demonstrates the individual contribution of $\alpha_d$ (dashed cyan line) to the final model (red line). This contribution dominates far from the band center, where it fits especially well to the high-frequency WMAP and lower-frequency VLA points, both sensitive to the deeper atmosphere.

Considering that ours is a disk-averaged result, these measurements are consistent with results recently presented in Li et al. (2017) using data from the Microwave Radiometer (MWR) experiment on the Juno spacecraft. Latitudinally resolved abundance measurements from the MWR, shown in Figures 3 and 4 of Li et al. (2017), at all latitudes except the more ammonia-rich Equatorial Zone tend toward this same $2–2.4 \times 10^{-4}$ from the NH$_3$ cloud at $P \sim 0.8$ bar down to about 10 bar, a regime consistent with our sub-cloud partition.

4.2. Relative Humidity RH

Humidity is examined relative to the saturation curve region in the nominal model, roughly between $0.3 < P < 0.8$ bar. The nominal model follows 100% humidity, so our results will be considered relative to a fully saturated model. Best-fit results suggest a humidity of 56.5%, bounded between [50.0%, 63.5%]. The dotted cyan line in Figure 5 shows the individual contribution of $RH$, which dominates closer to the band center and produces model spectra that are consistent with the lower-frequency CARMA points and the Gibson point that are most sensitive to this pressure range.

JG states that the NH$_3$ abundance is, on average, sub-saturated by at least a factor of two at $P < 0.6$ bar. Our results corroborate this factor-of-two sub-saturation within our own pressure regime stated above but add a tighter bound based on three independent sets of measurements.

4.3. High-altitude Atmosphere Abundance $\alpha_h$

The high-altitude atmosphere abundance is examined relative to the nominal (saturated vapor curve) value of $1.2 \times 10^{-7}$. Our model fits suggest a value of about $2.8 \times 10^{-8}$, nearly one fifth of the original, but yield an upper
The relative-humidity-only and preferred atmosphere abundance is not shown here but when decreased raises the brightness temperature at the band center and accounts for the band center difference between well as their general independence to each other. The effects of relative humidity and deep atmosphere abundance are shown by the two cyan lines. High-altitude atmosphere abundance should be smaller than its value in the nominal model.

It is difficult to place any reasonable bound on the high-altitude atmosphere abundance due to the lack of data near the band center; the Klein & Gulkis measurements were deemed too uncertain for our comparison, but tend toward temperatures higher than the WMAP point. Higher brightness temperatures at the band center would indicate a lower pressure departure from the saturation curve and consequently a smaller high-altitude atmosphere abundance. There is no number found in our analysis that is likely to be meaningful—nevertheless, it is quite possible that the high atmosphere abundance should be smaller than its value in the nominal model.

Our final model is shown by the red dashed lines in Figures 4 and 5, with upper and lower bounds. In Figure 5, as mentioned above, we also show the spectra resulting from \( \alpha_d \) and RH only (cyan dashed and dotted lines, respectively).

5. Conclusion

We utilized data from the COPSS survey (Keating et al. 2015; Keating et al. 2016) at frequencies between 27–35 GHz to identify and extract observations of Jupiter, used as a secondary calibrator over the course of 5 months. These data were reduced into 15 frequency measurements of Jupiter’s disk-averaged thermal brightness temperature over a relatively unobserved \( \sim 10 \) GHz wide section of Jupiter’s thermal emission profile just short of the NH\(_3\) absorption band. CARMA’s strong spectral stability, and hence the observed slope in the spectrum, as well as the high precision in our absolute calibration, were key in deriving the disk-averaged NH\(_3\) profile by fitting the data using our radiative transfer models. We find that the NH\(_3\) abundance below the NH\(_3\) ice cloud, at \( P \sim 8 \) bar, is \( 2.40 \times 10^{-4} \), bounded between \([2.26, 2.57]\times 10^{-4}\), and carries up through the cloud reductions to \( 1.89 \times 10^{-4} \) at \( P \sim 0.8 \) bar. Relative humidity, within the NH\(_3\) cloud layer where the abundance follows the saturation curve, is found to be 56.5%, bounded between \([50\%, 63.5\%]\). At high altitudes, well above the NH\(_3\) cloud layer, the NH\(_3\) abundance is near \( 2 \times 10^{-8} \), with an upper bound of \( 2.4 \times 10^{-7} \). These results echo the conclusion made in JG, especially that of sub-saturation by a factor of two, and by de Pater et al. (2001, 2016a).

This measurement set will be useful in future explorations, as have WMAP, JG, and others been in ours. They will, in a sense, extend the Juno data, as they are at shorter wavelengths than the MWR experiment on Juno.

CARMA’s calibration is strong enough that these reduced thermal measurements may be useful as calibration information for interferometers lacking short baselines. The measurements produced in this work are believed to encompass all flux from the disk, so they may be treated as “single-dish” flux measurements to give calibration context to interferometer scans.
Norris Foundation, the University of Chicago, the Associates of the California Institute of Technology, and the National Science Foundation (NSF). Support for CARMA operations and analysis was provided in part by the National Science Foundation University Radio Observatories Program, including awards AST-1140019 (to the University of Chicago), AST-1140031 (University of California-Berkeley), AST-1140021 (California Institute of Technology), and by the CARMA partner universities. In addition, partial support to this particular research endeavor was provided by NASA Planetary Astronomy (PAST) Award NNX14AJ43G to the University of California, Berkeley.

Software: pyplanet (de Pater et al. 2014).

ORCID iDs
Ramsey L. Karim @ https://orcid.org/0000-0001-8844-5618
David DeBoer @ https://orcid.org/0000-0003-3197-2294
Garrett K. Keating @ https://orcid.org/0000-0002-3490-146X

References
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Bellotti, A., Steflès, P. G., & Chinsomboon, G. 2016, Icar, 280, 255
de Pater, I. 1990, AdSpR, 10, 79
de Pater, I., Butler, B. J., Green, D. A., et al. 2003, Icar, 163, 434
de Pater, I., DeBoer, D., Marley, M., Freedman, R., & Young, R. 2005, Icar, 173, 425
de Pater, I., Dunn, D., Romani, P., & Zahnle, K. 2001, Icar, 149, 66
de Pater, I., & Dunn, D. E. 2003, Icar, 163, 449
de Pater, I., Fletcher, L. N., Luszcz-Cook, S., et al. 2014, Icar, 237, 211
de Pater, I., & Massie, S. T. 1985, Icar, 62, 143
de Pater, I., Sault, R. J., Butler, B., DeBoer, D., & Wong, M. H. 2016a, Sci, 352, 1198
de Pater, I., Sault, R. J., Butler, B. J., DeBoer, D., & Wong, M. H. 2016b, in American Geophysical Union, Fall General Assembly 2016 (Washington, D.C.: AGU), P31D-08
Folkner, W. M., Woo, R., & Nandi, S. 1998, JGR, 103, 22847
Gibson, J., Welch, W. J., & de Pater, I. 2005, Icar, 173, 439
Gibson, J. L. 2003, PhD thesis, Univ. California
Keating, G. K., Bower, G. C., Marrone, D. P., et al. 2015, ApJ, 814, 140
Keating, G. K., Marrone, D. P., Bower, G. C., et al. 2016, ApJ, 830, 34
Klein, M. J. 1976, JGR, 81, 3380
Klein, M. J., & Gulkis, S. 1978, Icar, 35, 44
Law, S. E., & Staelin, D. H. 1968, ApJ, 154, 1077
Li, C., Ingersoll, A., Janssen, M., et al. 2017, GeoRL, 44, 5317
Mahaffy, P. R., Niemann, H. B., & Dickinson, J. E. 1999, BAAS, 31, 1154
Page, L., Barnes, C., Hinshaw, G., et al. 2003, ApJS, 148, 39
Sharp, M. K., Marrone, D. P., Carlstrom, J. E., et al. 2010, ApJ, 713, 82
Sromovsky, L. A., Collard, A. D., Fry, P. M., et al. 1998, JGR, 103, 22929
Thomton, D. D., & Welch, W. J. 1963, Icar, 2, 228
Weiland, J. L., Odegard, N., Hill, R. S., et al. 2011, ApJS, 192, 19
Wong, M. H., Mahaffy, P. R., Atreya, S. K., Niemann, H. B., & Owen, T. C. 2004, Icar, 171, 153