THE SOURCE OF WIDESPREAD 3-µm ABSORPTION IN JUPITER’S CLOUDS: CONSTRAINTS FROM 2000 CASSINI VIMS OBSERVATIONS

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ABSTRACT

The Cassini flyby of Jupiter in 2000 provided spatially resolved spectra of Jupiter’s atmosphere using the Visual and Infrared Mapping Spectrometer (VIMS). A prominent characteristic of these spectra is the presence of a strong absorption at wavelengths from about 2.9 µm to 3.1 µm, previously noticed in a 3-µm spectrum obtained by the Infrared Space Observatory (ISO) in 1996. While Brooke et al. (1998, Icarus 136, 1-13) were able to fit the ISO spectrum very well using ammonia ice as the sole source of particulate absorption, Sromovsky and Fry (2010, Icarus 210, 211-229), using significantly revised NH₃ gas absorption models, showed that ammonium hydrosulfide (NH₄SH) provided a better fit to the ISO spectrum than NH₃, but that the best fit was obtained when both NH₃ and NH₄SH were present in the clouds. Although the large FOV of the ISO instrument precluded identification of the spatial distribution of these two components, the VIMS spectra at low and intermediate phase angles show that 3-µm absorption is present in zones and belts, in every region investigated, and both low- and high-opacity samples are best fit with a combination of NH₄SH and NH₃ particles at all locations. The best fits are obtained with a layer of small ammonia-coated particles (r ~ 0.3 µm) overlaying but often close to an optically thicker but still modest layer of much larger NH₃ particles (r ~ 10 µm), with a deeper optically thicker layer, which might also be composed of NH₄SH. Although these fits put NH₃ ice at pressures less than 500 mb, this is not inconsistent with the lack of prominent NH₃ features in Jupiter’s longwave spectrum because the reflectivity of the core particles strongly suppresses the NH₃ absorption features, at both near-IR and thermal wavelengths. Unlike Jupiter, Saturn lacks the broad 3-µm absorption feature, but does exhibit a small absorption near 2.965 µm, which resembles a similar Jovian feature and suggests that both planets contain upper tropospheric clouds of sub-micron particles containing ammonia as a minor fraction.

Subject headings: Jupiter; Jovian Atmosphere; Jupiter, Clouds

1. INTRODUCTION

Analysis of Pioneer and groundbased observations of Jupiter, summarized by West et al. (1984), led to an expected Jovian cloud structure that included an upper ammonia cloud layer starting near 700-mb and a putative NH₄SH cloud top near 2 bars, which was thought to be optically thick outside the hot spot regions. The putative ammonia cloud was thought to have two particle populations: a vertically compact layer of large particles (of 3 to 100 µm in radius) and a vertically diffuse component of small particles (r ~ 1µm) extending up to 200-300 mb in low latitude regions. However, the more diffuse component should have produced prominent spectral signatures at 9.4 µm and 26 µm, which were not observed (Orton et al. 1982). After considering possible masking of these features by the likely tetrahedral shapes of these particles, West et al. (1983) concluded that these particles could not be primarily composed of ammonia ice. It was also the case that neither Voyager Infrared Interferometer Spectrometer (IRIS) observations (Carlson et al. 1993), nor microwave observations (de Pater 1984), ever found an ammonia vapor profile that would support a 700-mb condensation level. Carlson’s derived condensation pressure was closer to 500 mb, while a later analysis of microwave observations (de Pater et al. 2001) suggested NH₃ condensation near 600 mb.

Only in the last decade or so has there been even a hint of the spectral signatures expected of NH₃ ice clouds. From an analysis of a 3-µm absorption anomaly in a central-disk spectrum of Jupiter, Brooke et al. (1998) inferred the existence of a layer of ammonia ice particles of 10 µm in radius, beginning at 550 mb with a scale height of 30% of the gas scale height. The wide field of view covered by the observation (roughly a quarter of the Jovian disk) suggested that the ammonia ice was widely distributed. Irwin et al. (2001) found a similar absorption anomaly in analysis of observations by the Galileo Near Infrared Mapping Spectrometer (NIMS), but concluded that it was not due to NH₃ ice because a key spectral signature at 2.0 µm was missing. The subsequent Baines et al. (2002) detection of spectrally identifiable ammonia clouds (SIACs) in other NIMS observations was based on depressed reflectivity at 2.7 µm as well as at 2.0 µm, but these detections covered a very tiny fraction (< 1%) of Jupiter’s cloud features. On the other hand, Wong et al. (2004) inferred more widely distributed ammonia ice, at least in some latitude bands, from a detection of a 9.4-µm spectral feature in Jovian spectra obtained from the Cassini Composite Infrared Spectrometer (CIRS). The model calculations of Wong et al. (2004) implied that the 9.4-µm ice feature could only be detected when the aerosols were at pressures ≤500 mb and the particle effective radius was within a factor of two of...
New band models for NH$_3$ absorption developed by Bowles et al. (2008) and recent additions to the HITRAN line data base motivated Sromovsky and Fry (2010) to update exponential sum models for NH$_3$ absorption. They found substantial changes relative to the absorption models used in the analysis by Brooke et al. (1998) and undertook a reanalysis of the ISO spectrum. They found that the best fit to the 3-$\mu$m absorption feature was obtained not with NH$_3$ as the sole absorber, but instead when particles of NH$_2$SH and NH$_3$ were both present, with the predominant opacity provided by NH$_2$SH. Two types of solutions were found to provide good fits to the ISO spectrum: one had relatively large NH$_3$ and NH$_2$SH particles at nearly the same pressure, near 500 mb, and the other had small NH$_3$-coated particles closer to 350 mb, with large NH$_2$SH particles again near 500 mb. The large FOV of the ISO measurement did not permit any conclusions concerning the spatial distribution of these two components, i.e. whether some clouds had only NH$_2$SH particles, and others had only NH$_3$ particles, or whether the two types existed in the same physical location.

In the following analysis we present new results based on near-IR spatially resolved spectral observations of the Cassini Visual and Infrared Mapping Spectrometer (VIMS). Our analysis takes advantage of recently improved models of methane and ammonia gas absorption, and uses refractive index properties of putative cloud materials in constraining model structures and composition. We first describe the VIMS observations, then the radiation transfer methods, the modeling results, how they compare with other models based on other observations at visible, near-IR, and thermal wavelengths, and finally summarize their implications for Jovian cloud structure. We show that VIMS observations display a widely distributed strong absorption in the 3.1-$\mu$m region of the spectrum, and evidence for a much weaker absorption near 2-$\mu$m, both of which are qualitative features expected from a cloud consisting of ammonia ice particles. However, it is only the darker cloud features, with smaller optical depths, that can be well fit with ammonia ice as the sole absorber. We find that brighter clouds require more absorption at 3-$\mu$m without increased absorption at 2-$\mu$m and that this can be provided by NH$_2$SH.

2. OBSERVATIONS.

2.1. VIMS Overview

For constraining models of low-latitude Jovian cloud structure we used spectra acquired by VIMS during Cassini’s flyby of Jupiter in December 2000. The VIMS instrument and investigation are described by Miller et al. (1996) and Brown et al. (2004). The instrument’s spectral range is 0.35-5.1 $\mu$m, with an effective pixel size of 0.5 milliradians on a side and a near-IR spectral resolution of approximately 15 nm (sampled at intervals of approximately 16 nm). Our analysis focuses on the 1-3.2 $\mu$m interval where scattering by aerosols predominates over Rayleigh scattering and where a wide range of atmospheric pressures can be sampled and discriminated by means of variations in gas absorption with wavelength (Fig. 1). In this wavelength range the contribution of Jupiter’s thermal emission is everywhere less than 0.1% of the observed I/F. To provide an approximate comparison with prior low phase angle observations we chose VIMS data cube CM$_{1355256529}$, obtained on 11 December 2000 at a phase angle of 2.5$^\circ$. This provides a pixel size of 9925 km at the spacecraft point. In Fig. 2 VIMS images extracted from this cube at 4.798 $\mu$m, 1.864 $\mu$m and 1.997 $\mu$m are compared to a Cassini ISS (Imaging Science Subsystem) image obtained at 0.451 $\mu$m. The encircled pixels in the figure are locations from which we extracted VIMS spectra, taking samples from the North Equatorial Belt (NEB), and from the Equatorial Zone (EZ). The pixel labeled 12x16y, which is brightest at 4.798 $\mu$m, is located in a region where deep cloud opacity is at a relative minimum, corresponding to a relatively low reflectivity at 1.864 $\mu$m. To obtain samples at higher spatial resolution and less sensitive to details of backscatter phase functions, we also selected data cube CM$_{1356976257}$, obtained on 31 December 2000 at a phase angle of 67.8$^\circ$, with a spacecraft pixel size of 4887 km, which is about twice the resolution obtained from the low phase angle cube. Sample images and target selections from this cube are shown in Fig. 3.

2.2. Image Processing and Navigation

VIMS image cubes were processed using the pipeline processing code downloaded from the Planetary Data System, described by McCord et al. (2004). The cubes were navigated by manual adjustments of planet center coordinates using visual comparisons of model and image limbs at window wavelengths to find an approximate best fit, which is estimated to be within a fraction of a pixel. This provided sufficient definition of view angles and latitudes near the disk center to allow a meaningful comparison of spectral characteristics in broad latitude regions, as appropriate for the relatively low spatial resolution of these observations.

2.3. Photometry

The VIMS calibration obtained by the pipeline processing has an uncertainty that has not yet been documented, but is at least as large as the near-IR solar spectral irradiance uncertainty of $\sim$3%-5% (Colima et al. 1996). It appears to be less than 10% uncertain, based on window-region comparisons with independent spectra of Jupiter, shown in Fig. 4. In the 0.9-0.98 $\mu$m region the disk-integrated VIMS spectrum is $\sim$8% brighter than that of Karkoschka (1998). In the 0.9-2.2 $\mu$m region we computed a central-disk VIMS spectrum to compare with the ground-based central-disk spectrum of Clark and McCord (1979). In the brighter window regions, where thin upper-level hazes and low-level artifacts have much reduced impact, the VIMS observations are within $\sim$5% of the Clark and McCord (1973) spectrum, except near 1.6 $\mu$m, where an order-sorting filter joint in the VIMS detector array apparently results in poor response corrections. The VIMS spectrum averaged over the same angular FOV as a 1996 ISO spectrum (Brooke et al. 1998) is found to be about 20% brighter, which might be entirely due to temporal variations or even phase angle variations (the VIMS and ISO phase angles in this comparison are 2.5$^\circ$ and 11$^\circ$ respectively). Another possible contribution to the VIMS - ISO difference is the ISO calibration uncertainty, which could
Fig. 1.— Penetration depth of photons in a clear Jovian atmosphere, indicated by pressures at which a unit change in albedo of a reflecting layer results in an external I/F change of $1/e$, $1/e^2$, and $1/e^4$ (three solid curves), for NH$_3$ mixing ratios typical of the NEB. The sloping dotted lines define the location at which 2-way optical depths for Raleigh scattering reach 0.1 and 0.01.

Fig. 2.— Cassini VIMS images from 11 December 2000 at 4.798 $\mu$m (A), 1.864 $\mu$m (B), and 1.997 $\mu$m (C) compared to an ISS image acquired roughly one month earlier (D). Circles in A–C, locate pixels from which we extracted spectra for analysis. These are located at 6$^o$N, 290$^o$E (12x16y), 1.2$^o$S, 306$^o$E (11x14y), and 14$^o$N, 306$^o$E (13x14y). An additional spectrum (not shown) was extracted from 1.5$^o$S, 298$^o$E (11x15y). Here y increases to the left and x upward.

Fig. 3.— Cassini VIMS images from 31 December 2000 at 4.798 $\mu$m (A), 1.864 $\mu$m (B), and 1.997 $\mu$m (C). Circles in A–C, locate pixels from which we extracted spectra for analysis. These are located at 9.9$^o$ N (centric), 298$^o$E (25x35y), 2.4$^o$N, 295$^o$E (27x34y), and 1.8$^o$S, 280$^o$E (28x31y). An additional spectrum was extracted at 6.3$^o$N, 280$^o$E (26x31y). Here y increases to the right and x downward.

be as large as 12% for wavelengths less than 3.8 $\mu$m (Schaeidt et al. 1996). Overall, there seems to be a tendency for the VIMS spectra to be on the high side, but how much of the differences are due to calibration errors
as opposed to temporal variation or phase-angle differences is uncertain.

2.4. VIMS artifacts.

There are two important artifacts that need to be considered in the interpretation of VIMS spectra. The first has to do with responsivity corrections at wavelengths in close proximity to joints between order sorting filters overlaid on the VIMS linear detector arrays. The joints of concern here appear at wavelengths of 1.64 µm and 2.98 µm. The required responsivity correction factors to compensate for shading effects are very large for the former (∼300) and relatively small for the latter (∼2). To test the correction near 2.98 µm we used a comparison between the ISO 3-µm spectrum of Brooke et al. (1998) and a central disk VIMS spectrum covering approximately the same field of view. When the ISO spectrum is empirically scaled by a factor of 1.2, the two spectra are in generally excellent agreement (Fig. 4), including the region of the filter joint near 2.98 µm. However, we do see a significant disagreement near 2.58 µm, where the ISO spectrum reaches a deeper minimum. This may be related to the second kind of artifact, which is discussed later. There is also a small discrepancy near 2.52 µm, where the ISO spectrum has a local minimum that is not seen in the VIMS spectrum. A similar discrepancy is also seen between model spectra and the VIMS observations in this region. The rather large responsivity correction near 1.64 µm does have significant errors, which can be seen from a comparison between a groundbased spectrum of Banfield et al. (1998a) and a VIMS spectrum from a nearby latitude region (Fig. 5). The discrepant region is from about 1.60 to 1.68 µm. This can also be seen from a comparison to the Clark and McCord (1978) spectrum shown in Fig. 4C. It is also apparent in the striking disagreement between model and observations in this region, as discussed in later sections.

The second type of artifact is evident in the 2.3-µm spectral region where the groundbased spectrum in Fig. 6 has a minimum that is a factor of 10 lower than that of the VIMS spectrum. This cannot be attributed to local variations because the latitude difference is small and the I/F disagreement is typical of several comparisons. To resolve which of these two measurements is more believable we used 1997 NICMOS observations (HST Program 7445, Reta Beebe PI), selecting an image (n49o01mvs) made with the F237M filter, which heavily weights the spectral region of the filter joint near 2.98 µm evident in Fig. 5. In any case, the defect in the VIMS measurements near 2.3 µm has the effect of distorting our model fits in the stratosphere, suggesting far more particulate reflectivity than is actually present.

2.5. VIMS noise characteristics.

For most applications at moderate signal levels, the random noise level of VIMS is very small, nominally less than one digital quantization number (DN) (Kevin Baines, personal communication, January 2010). As there is no published equation defining how VIMS measurement noise depends on signal level, exposure time, and wavelength, we tried to better characterize the noise by comparing spectra in cubes that imaged the same region of Jupiter with as small a time difference as possible. We chose CM_{1355309574} and CM_{1355309697} cubes, which were exposed only two minutes apart. These results were consistent within about 1.2 DN RMS for a single measurement, even for signal levels up to 2000 DN or more. For the cubes we used in our detailed spectral analysis, which had exposures much shorter than these comparison cubes, the noise level would still be only 0.14% at 2.7 µm and thus not a significant error source. However, at signals 100 times smaller, as found near 2.3 µm, the noise becomes a much larger fraction of the total signal. This is evident from the rapid variations with wavelength observed in that region of the spectrum, which are up to 50% or more of the signal level. This can be roughly characterized as an offset noise in I/F, which we crudely estimated as ∼5×10^{-4} from the on-disk spectra. Other possible sources of uncertainty, though not strictly random noise, are scattered light inside the spectrometer, wavelength errors, line-spread uncertainties, and variable absolute calibration and wavelength calibration errors. We lumped all these potential uncertainties into a somewhat arbitrary 2.5% error proportional to signal, and an I/F offset error of ∼5×10^{-4}. We did look into the possibility of wavelength errors by making fits with shifted wavelength scales, and determining χ^2 as a function of shift. We found that the minimum χ^2 was within 1 µm of the nominal wavelength scale and that no revision was needed.

3. RADIATION TRANSFER CALCULATIONS

3.1. Atmospheric structure and composition

We followed the same approach described by Sromovsky and Fry (2010). In summary, we used the tabulated results of Seiff et al. (1998) for Jupiter’s temperature structure down to the 22-bar level, and assumed an atmospheric composition of He/H_2=0.157±0.003 (von Zahn et al. 1998) and CH_4/H_2=2.1E-3±0.4E-3 (Niemann et al. 1998), which are expressed as number density ratios. We used model mixing ratio profiles (Fig. 8) ranging from what should be typical of the equatorial zone to hot-spot values. The basis for these models is discussed by Sromovsky and Fry (2010). The deep mixing ratio is from Folkner et al. (1998), while the upper level Probe result is from Sromovsky et al. (1998). The EZ (Equatorial Zone, ±7° latitude), NEB (North Equatorial Belt, ∼8°N-18°N), Hot Spot (∼7°N), and EZG (±7° latitude) profiles were based on combinations of NH_3 mixing ratios inferred from ISO observations by Fouchet et al.
Jupiter's 3-µm absorber

Fig. 4.— VIMS I/F spectra (solid lines) compared to the Karkoschka (1998) 1995 geometric albedo spectrum of Jupiter (A), the Brooke et al. (1998) ISO 1996 spectrum (B), and the 1976 Clark and McCord (1979) central-disk spectrum (C). In (A) and (B) the reference spectra (dot-dash) are averaged to VIMS resolution. In (C) the VIMS spectrum (solid) is averaged to the resolution of the reference spectrum (dot-dash). Ratio plots are dotted, except where heavy black lines are used in low-absorption regions that are not much affected by upper level aerosols.

Fig. 5.— Comparison of central-disk I/F spectra from VIMS (solid) and ISO×1.2 (dot-dash) with comparable fields of view covering about 1/4 of the disk. The ISO spectrum was converted from the flux spectrum of Brooke et al. (1998). Vertical dotted lines mark the locations of an absorption feature of NH₃ ice at 2.95 µm and the VIMS filter joint at 2.98 µm.

Upper level mixing ratios were also guided by results of Edgington et al. (1999), Lara et al. (1998), and Achterberg et al. (2006).

3.2. Gas absorption models

We used the k-distribution models of hydrogen-broadened methane absorption described by Irwin et al. (2006), which employ new two-term models of temperature dependence (Sromovsky et al. 2006). For ammonia we used the combined correlated-k absorption model described by Sromovsky and Fry (2010), which is based on the Goody-Lorentz band model of Bowles et al. (2008), and also makes use of 1996 and 2004 (or equivalently, 2008) HITRAN spectral line compilations. The basis for and details of how these results were combined are described by Sromovsky and Fry (2010). Collision-induced absorption (CIA) for H₂ and H₂-He was calculated using programs downloaded from the Atmospheres Node of the Planetary Data System, which are documented by Borovsky (1991, 1993) for the H₂-H₂ fundamental band, Zheng and Borovsky (1995) for the first H₂-H₂ overtone band, and by Borovsky (1992) for H₂-He bands. We fol-
Fig. 6.— Top: Comparison of VIMS 6° N spectrum (solid) with a 7° N ground-based spectrum (dot-dash) from Banfield et al. (1998a). Vertical dotted lines at 1.6 and 1.68 µm bound the region in which VIMS spectra are in significant error. Lower: transmission spectrum of the NICMOS F237M filter.

Fig. 7.— Comparison of NICMOS F237M central meridian I/F vs latitude (solid) with synthetic photometry band-pass results computed from VIMS spectra and a 7° N spectrum from Banfield et al. (1998a). The plus symbols are for a central meridian latitude scan with a 3-pixel longitudinal average. Offset (dashed) and scaled (dotted) versions of the NICMOS scan are also shown.

followed the Birnbaum et al. (1996) parameter recommendations to avoid sudden drops in wing absorption in the 1.58-µm window. We assumed equilibrium mixing ratios of ortho and para hydrogen in all our model fitting calculations and later show that the resulting errors are not significant to our main conclusions.

3.3. Reflecting layer methods

3.3.1. Linear combination equations

If all the cloud layers were composed of broken cloud fields of opaque elements, a linear combination of reflecting layer contributions would be an ideal model for representing the combined I/F of the vertical cloud structure. By fitting parameters of such a model to obtain agreement with the observed I/F spectra or variation of I/F with angle, it can also be used to obtain a rough idea of the distribution of scatterers when the cloud layers are optically thin. Its main virtue is the great speed of the inversion, because it makes use of precomputed arrays.

Our model equations for a multilayer atmosphere are based on Eq. 4 of Sromovsky and Fry (2007), which can be written in the following form in a three-layer model:

\[
I(\vec{\theta}) = I_0(P, \vec{\theta}) + f_1 \times [I_1(P_1, \vec{\theta}) - I_0(P_1, \vec{\theta})] \\
+ I_0(P_2, \vec{\theta}) - I_0(P_1, \vec{\theta}) + f_2 \times [I_1(P_2, \vec{\theta}) - I_0(P_2, \vec{\theta})] \times T_1(\vec{\theta}) \\
+ I_0(P_3, \vec{\theta}) - I_0(P_2, \vec{\theta}) + f_3 \times [I_1(P_3, \vec{\theta}) - I_0(P_3, \vec{\theta})] \times T_1(\vec{\theta})T_2(\vec{\theta}) \\
+ I_0(\vec{\theta}) - I_0(P_3) \times T_1(\vec{\theta})T_2(\vec{\theta})T_3(\vec{\theta}) \tag{1}
\]

where \(I_0(P, \vec{\theta})\) is the I/F observed at the top of the atmosphere for viewing geometry \(\vec{\theta}\) when a zero-albedo surface is placed at pressure \(P\) and \(I_1(P, \vec{\theta})\) is the top-of-atmosphere I/F for a unit-albedo surface placed at the same level. Here \(\vec{\theta}\) denotes the viewing geometry vector \([\theta, \theta_0, \phi]\), which refer to viewer and solar zenith angles and azimuth angle, respectively.

The first line in the above equation contains one contribution from the atmosphere above the first reflecting
layer \( I_0 \) and a second differential contribution from the reflecting layer itself \( (f \times I_1 - I_0) \), where \( f \) can be interpreted as the fraction of area covered by the reflecting layer, for a pure broken cloud model, or as the reflectivity of the cloud, for models approximating translucent clouds. Successive lines have a similar structure, except that the atmospheric contribution is only from scattering between a layer and the next highest layer, and the contributions from both cloud and atmosphere are attenuated by a transmission factor \( T_1 T_2 \ldots T_i \). In the pure broken cloud model this is just the fraction that is not blocked by the opaque elements in the previous layers, i.e. \((1 - f_{1})(1 - f_{2}) \ldots (1 - f_i)\). In the translucent approximation we use \( T_i \approx \exp[-\tau'_i (1/\mu + 1/\mu_0)] \), where \( \mu \) and \( \mu_0 \) are cosines of observer and solar zenith angles, \( \tau'_i = (1 - 1/\mu)(1 + g_i)\tau_i \), \( g_i \) is the scattering asymmetry parameter for the \( i \)th layer, and \( \varpi_i \) is the corresponding single-scattering albedo.

The formula for the effective attenuation optical depth for each layer \( (\tau'_i) \) is an empirical result optimized for low opacity layers considered by Sromovsky and Fry (2007). Here, we make the simplifying assumption that the overlying layers are conservative \( (\varpi = 1) \) and symmetric scatterers \( (g = 0) \), so that \( \tau'_i = \tau_i/2 \). Under the same approximation we have \( \tau_i \approx 4 \times f_i \) Sromovsky and Fry (2007), so that \( \tau'_i \approx 2 \times f_i \). Because our analysis of each spectrum is at a fixed viewing geometry, we ignore possible angular variation in effective cloud fractions. However, we do need to parameterize variations with wavelength, which is accomplished by setting \( f_i = f_0 \times (\varpi/\varpi_0)^{n_i} \), where large particle clouds would likely have exponents near zero, and very small particles would likely approach the Rayleigh limit of \( n_i = -4 \).

3.3.2. Reflecting layer I/F computations

A comparison of single-scattering and multiple-scattering reflecting layer calculations shows that atmospheric multiple scattering is insignificant over the range \( 1.1 < \lambda < 4 \ \mu m \), and even the 1.05 \( \mu m \) window adds no more than a few percent to the I/F obtained from single-scattering. The computed clear-atmosphere I/F values throughout this range are well below the observed values by 1-3 orders of magnitude, and thus particulate scattering is the dominant influence at all wavelengths considered in this analysis. For our reflecting layer calculations, atmospheric scattering plays a minor role that is adequately modeled with single scattering.

We computed reflecting layer I/F values for unit-albedo and zero-albedo reflecting layers placed at 91 pressures logarithmically distributed between 0.5 mb and 40 bars, using the single-scattering equations

\[
P_R(\theta_S) = \frac{3}{2} \left[ 1 + \delta + (1 - \delta) \cos^2(\theta_S) \right] (6)
\]

\[
\cos(\theta_S) = \cos(\phi) \sqrt{1 - \mu^2} \sqrt{1 - \mu_0^2 - \mu \mu_0} (7)
\]

where \( \mu \) and \( \mu_0 \) are observer and solar zenith angle cosines, \( \phi \) is the azimuth angle between incident and scattered directions, \( \varpi_i \) is the effective single-scattering albedo of the gas between pressures \( p_i \) and \( p_{i-1} \) denotes normal albedo of the reflecting layer (both 0 and 1 are used), \( K \) defines the limb darkening character of the layer (assumed to have the Minnaert form in which reflected radiance at zenith cosine \( \mu \) is proportional to incident irradiance times \( \mu^{K-1} \mu_0^K \)), \( P_R(\theta_S) \) is the scalar Rayleigh phase function for anisotropic randomly oriented molecules, evaluated at depolarization factor \( \delta = 0.020 \) (Sromovsky 2005), and scattering angle \( \theta_S \), \( \tau_i \) is the vertical extinction optical depth from the top of the atmosphere to pressure \( p_i \), and \( \tau_{i,\text{scat}} \) is the corresponding scattering optical depth. Our calculations cover the spectral range from 1.05 \( \mu m \) to 3.3 \( \mu m \) with a uniform step size of 5 cm\(^{-1} \), the sampling interval of the \( CH_4 \) absorption model. For wavelengths where both methane and ammonia absorptions are important, opacities are computed 100 times for each wavelength (for each of the 10 terms of the correlated-k model of \( CH_4 \), the calculation is done for each of the 10 terms of the correlated-k model of \( NH_3 \)). The most accurate I/F is obtained by solving the radiative transfer problem for each opacity combination and then computing the weighted sum of the 10 or 100 calculations per wavelength.

3.4. Multiple scattering methods

For multiple scattering calculations, which are needed to accurately model translucent clouds, we followed Sromovsky and Fry (2010). In brief, we used the doubling and adding code described by Sromovsky (2005b,a). We used a grid of 44 pressure levels from 0.5 mb to 10 bars, distributed roughly in equal log increments, except with finer spacing in the ammonia condensation region. We generally used 10 zenith angle quadrature points per hemisphere (NQUAD) and handled the sharp forward scattering peak of larger particles using the \( \delta \)-Fit procedure of Hu et al. (2000). The backscatter phase function of larger particles is not well characterized with NQUAD of 10, so that calculations for low phase angles are subject to errors, as shown in Section 5A1. However, it is unlikely that these larger particles are spherical in any case, so that a truncation of the spherical backscatter peak may actually be more realistic than keeping it. Reduced backscatter (relative to spheres) is characteristic of aggregate particles West (1991), and many randomly ordered crystals and spheroids (Yang et al. 2000), including the prolates spheroidal shapes favored by Wong et al. (2004).

The most significant difference between the approach we used and that of Sromovsky and Fry (2010) is that in modeling VIMS spectra we made an additional approximation to account for the VIMS spectral resolution being less than our model resolution. We approximate the line-spread function of the VIMS instrument
as a Gaussian of FWHM that is wavelength dependent (Kevin Baines, private communication 2010), and is typically about 0.015 \( \mu m \). We then collect all the opacity values within \( \pm \)FWHM of a VIMS sample wavelength, weight those according to the relative amplitude of the line-spread function, then sort and refit to ten terms in the exponential sums representing transmission.

3.5. Fitting cloud models to observations

Our cloud models were constructed as an assemblage of discrete compact layers. Model parameters were adjusted to minimize \( \chi^2 \) using a form of the Levenberg-Marquardt algorithm, as described by Press et al. (1992). The parameter uncertainties obtained from this method are based on the assumption of normally distributed errors, and thus cannot be absolutely relied on. For the reflecting layer models, we have supplemented these estimates by varying each fitted parameter about its best fit value, refitting all the other parameters to minimize \( \chi^2 \), then setting the parameter uncertainty equal to the deviation needed to increase \( \chi^2 \) by one unit. This alternate method generally agreed with that obtained from the Levenberg-Marquardt algorithm to within a factor of two. It was not practical to use this alternate method for multiple scattering fits because of the enormously increased computation time that would be required.

In computing \( \chi^2 \) we tried to account for measurement errors as well as errors in the modeling of atmospheric opacity. For the measurements we assigned a random error for all sources a value of 2.5\% of the VIMS I/F value, with an additional I/F offset error of 5 \( \times \) 10\(^{-4} \), as discussed in Sec. 2. A more important error source, which is not strictly random, but can vary from wavelength to wavelength, is the uncertainty in radiation transfer modeling due to the uncertainty in opacity calculations. The transmission curves on which the methane opacity models are based have an assumed fractional error of 0.05 (Irwin et al. 2006). To convert this uncertainty to an I/F uncertainty, we assume that the derived optical depths themselves have a fractional error of similar size. We assigned a value of 6\% to the error in computed optical depth, but converted this to I/F under the crude assumption that I/F would be proportional to the negative exponential of optical depth. This leads to a fractional I/F error estimate of 1-(I/F)\(^a\), where \( a \) is the fractional error in optical depth. Thus a 6\% error in optical depth would lead to errors that range from nearly zero at low absorption optical depths to 6\% near \( \tau = 1 \) and to 100\% for \( \tau \gg 1 \).

To judge whether one fit is significantly better than another on the basis of a difference in \( \chi^2 \), we need to know how that difference compares to the uncertainty in \( \chi^2 \) itself. The latter uncertainty arises from measurement and gas opacity modeling errors, and is easily determined from a simple Monte-Carlo calculation. For our reflecting layer models, we fit 94 measurements using 10 fitted parameters (typical), which implies an expected \( \chi^2 \) of 84 and an expected standard deviation of \( \sigma_{\chi^2} = 13 \). The expected values for the multiple scattering fits are increased to \( \chi^2 = 110 \) and \( \sigma_{\chi^2} = 15 \) (more spectral samples are fit). Deviations from the expected value of \( \chi^2 \) are a result of a combination of factors: statistical variability in \( \chi^2 \) itself, errors in estimating uncertainties, and errors in the physical features of the model.

4. Evidence for Jupiter’s 3-\( \mu \)m Absorption

To clearly display the need for a 3-\( \mu \)m absorber, we first fit VIMS spectra with aerosol models that did not contain such an absorber. We chose the low-latitude VIMS spectra from pixel locations given in Fig. 2 (low phase angles) and in Fig. 3 (intermediate phase angles). The model spectra are compared with observation in Figs. 9 and 10 respectively. In these figures the observed spectra are shown in black, with models shown in gray. The three spectral regions used to constrain the fits are indicated by gray bars plotted in the bottom panels. The region from 2.85 to 3.3 \( \mu \)m is omitted from the fits because it contains local absorption and including it greatly worsens the fit in other regions. The region near 2 \( \mu \)m is avoided because of a potential connection between absorption at 2 \( \mu \)m and absorption near 3 \( \mu \)m if the cloud absorber is ammonia ice. The 1.60-1.68 \( \mu \)m region is also excluded because of the previously noted VIMS responsivity correction error in this region. The fits outside these excluded regions are generally excellent, with \( \chi^2 \) values close to expected values.

Each layer in our 3-layer model has three parameters: a pressure \( p \), a fractional reflectivity \( f \) at 2 \( \mu \)m and a wavelength dependence exponent \( n \). The fit parameters are listed in Table 1 for each of the spectra, and the listed uncertainties show that the parameters are well constrained by the observations. The need for significant absorption in the 2.85-3.2 \( \mu \)m region is apparent from the large ratios between model and observed spectra in this region (the ratios between the gray and black curves in Figs. 9 and 11). The quantitative ratios at 2.04 \( \mu \)m, 2.96 \( \mu \)m, and 3.0-3.1 \( \mu \)m are listed in Table 2. We see that as clouds brighten (I/F at 1.96 \( \mu \)m increases), the absorption needs to increase in the 3-\( \mu \)m region, while the fractional absorption near 2 \( \mu \)m decreases slightly, suggesting that the two absorptions are not both due to the same cloud component (or same material). What appears to be happening here is that as the absorbing cloud layer thickens, it gets brighter in spectral regions where it doesn’t absorb much, but it can’t brighten in regions where it absorbs strongly (there its reflectivity saturates at a very low optical depth). Also, we find that the peak in the 2-\( \mu \)m absorption is nearer to 2.04 \( \mu \)m than it is to the NH\(_3\) peak at 2.0 \( \mu \)m, and the local dip in reflectivity near 2.97 \( \mu \)m is shifted from the minimum single-scattering albedo of pure NH\(_3\), which is located at 2.95 \( \mu \)m (the peak in the imaginary index is actually located at 2.965 \( \mu \)m).

The overall character of the 3-layer model fit parameters is illustrated in Fig. 11. A high altitude aerosol is needed to account for the I/F in the 2.3-\( \mu \)m region, but there are two problems with the result. The effective pressure of this layer is only well constrained for the 11x14y, 12x16y, and 28x31y spectra, for which \( P \approx 50 \) mb. At that level the reflectivity is \( \sim 0.008 \) (\( \tau \sim 0.03 \) for conservative symmetric scatterers), which is nearly 20 times the integrated value obtained by Banfield et al. (1995a). Banfield et al. measured low-latitude I/F values of 2-3 \( \times \) 10\(^{-4} \) at 2.3 \( \mu \)m, while the VIMS values in Fig. 9 are \( \sim 10 \) times larger and are likely due in part to a VIMS measurement artifact, possibly due to scat-
Fig. 9.—Selected low phase angle VIMS spectra (black) compared to reflecting layer model spectra (gray). Pairs of lines surrounding the model spectra indicate uncertainties in opacity calculations; measurement uncertainties (not shown for clarity) are similar but slightly smaller. The gray horizontal bars in the bottom panel indicate the ranges over which observations were used to constrain the models. Each panel legend provides pixel coordinates in the VIMS cubes (as in Fig. 2) and $\chi^2$ values ($\text{80} \pm 13$ is expected). Vertical dotted lines indicate pure NH$_3$ ice absorption features at 2.0 and 2.95 $\mu$m.

The reflecting layer fits put the second layer in the 340-600 mb region, with a reflectivity of 15-21%. The third layer, located in the 770-1600 mb region has a relatively high reflectivity of 40-60%. The best-fit wavelength dependence exponents are roughly in accord with expectations. The high altitude contributions have an exponent of -2 to -2.9, indicating relatively small particles. This scattering of light from the VIMS grating, as described in Sec. 2.4. Our previous comparison with NICMOS observations (Fig. 7) also indicates that a simple offset error is not consistent with the observations. The substantial difference between the Banfield et al. (1998a) reflectivity and our value in the 400-mb layer might also be a result of excessive VIMS I/F values at low levels of I/F.
Fig. 10.—As in Fig. 9 except that the spectra are for medium phase angles (as in Fig. 3).

might have been closer to -4 if the excess I/F near 2.3 μm could have been removed. The next layer has best-fit exponents in the -0.75 to -1 range, which indicates larger particles, and the deepest layer has even smaller exponents (-0.5 to +0.15), indicating even larger particles.

We also tried fitting the observations with gas opacity profiles other than the nominal EZ profile, but even for the least opaque region sampled in the NEB, the best fit was obtained with the EZ profile.

The latitude dependence of the fit parameters (Fig.
Table 1

| Spectrum Parameter | Layer 1 | Layer 2 | Layer 3 |
|--------------------|---------|---------|---------|
| 11x14y p (bars)    | 0.0450+0.014−0.015 | 0.392+0.02−0.01 | 0.919+0.004−0.004 |
| 11x15y p (bars)    | 0.0020+0.015−0.001 | 0.380+0.02−0.02 | 0.935+0.005−0.005 |
| 12x16y p (bars)    | 0.0335+0.013−0.015 | 0.411+0.03−0.03 | 0.978+0.013−0.011 |
| 13x14y p (bars)    | 0.0005 | 0.602+0.01−0.01 | 1.624+0.16−0.16 |
| 25x35y p (bars)    | 0.0005 | 0.462+0.02−0.02 | 1.024+0.16−0.14 |
| 26x31y p (bars)    | 0.0179+0.019−0.017 | 0.397+0.02−0.02 | 0.754+0.003−0.003 |
| 27x34y p (bars)    | 0.0019+0.026−0.001 | 0.343+0.01−0.01 | 0.819+0.010−0.009 |
| 28x31y p (bars)    | 0.0558+0.016−0.014 | 0.377+0.03−0.03 | 0.774+0.009−0.008 |
| 11x14y f           | 0.0070+0.0022−0.0018 | 0.183+0.01−0.01 | 0.624+0.06−0.05 |
| 11x15y f           | 0.0058+0.0006−0.0005 | 0.177+0.02−0.02 | 0.594+0.002−0.002 |
| 12x16y f           | 0.0082+0.0003−0.0003 | 0.146+0.01−0.01 | 0.363+0.02−0.02 |
| 13x14y f           | 0.0030+0.0003−0.0002 | 0.209+0.02−0.02 | 0.601+0.02−0.02 |
| 25x35y f           | 0.0024+0.0002−0.0002 | 0.138+0.01−0.01 | 0.372+0.04−0.04 |
| 26x31y f           | 0.0026+0.0000−0.0000 | 0.184+0.02−0.02 | 0.248+0.04−0.04 |
| 27x34y f           | 0.0037+0.0019−0.0011 | 0.192+0.00−0.00 | 0.424+0.04−0.04 |
| 28x31y f           | 0.0090+0.0010−0.0010 | 0.214+0.01−0.01 | 0.468+0.04−0.04 |
| 11x14y n (in λ°)   | -2.86+0.24−0.25 | -0.92+0.19−0.19 | -0.15+0.23−0.23 |
| 11x15y n (in λ°)   | -2.06+0.35−0.34 | -1.00+0.19−0.21 | -0.19+0.11−0.10 |
| 12x16y n (in λ°)   | -1.94+0.46−0.10 | -1.91+0.10−0.10 | -0.24+0.33−0.30 |
| 13x14y n (in λ°)   | -2.54+0.12−0.12 | -0.65+0.11−0.13 | -0.51+0.07−0.07 |
| 25x35y n (in λ°)   | -1.99+0.26−0.26 | -0.91+0.16−0.15 | -0.29+0.38−0.38 |
| 26x31y n (in λ°)   | -2.86+0.49−0.41 | -0.85+0.17−0.11 | -0.18+0.08−0.08 |
| 27x34y n (in λ°)   | -2.17+0.29−0.30 | -0.85+0.10−0.10 | -0.15+0.39−0.47 |
| 28x31y n (in λ°)   | -2.34+0.25−0.24 | -0.75+0.07−0.07 | -0.05+0.09−0.05 |

NOTE: Layer-1 pressures without uncertainties had best fit values at the lower limit of the fit range.

Fig. 11.—Pressure and reflectivity parameters for 3-layer modeling that provide best fits to VIMS spectra, as given in Table 1. The dashed curve displays the vertically integrated reflectivity derived by Banfield et al. (1998a) for the GRS but is broadly representative of other regions as well.

Fig. 12.—Pressure and reflectivity parameters versus latitude for best-fit 3-layer reflecting layer models given in Table 1. Parameters are plotted for layer 1 (diamonds), layer 2 (open squares), and layer 3 (filled circles).

Jupiter’s 3-µm absorber displays an increase in pressure towards the north equatorial belt for both layers 2 and 3. (The Cassini VIMS 0.45-µm image in Fig. 2D indicates that the NEB extended from about 8°N to 18°N in 2000.) The trends in Layer 1 pressures is not shown because it is likely not meaningful (several fits yielded best-fit pressures at the lower limit of the allowed range). The pressure changes seem to have more impact on the observed I/F than the changes in optical depths.

The pressure level at which the 3-µm absorber resides is roughly that of layer 2 in the 3-layer model, which is in the 300-600 mb range where NH3 ice is a plausible condensate. The location is inferred from the cloud reflectivity and the penetration depth profile given in Fig. 1. Vertical penetration depths at 2 µm and 3 µm are comparable and limited to pressures less than 1 bar or so. The relatively high reflectivity seen at 2 µm (compared to that at 3 µm) is produced by contributions mainly from layer 2, which would be seen even better at 3 µm. It thus follows that layer 2 must be strongly absorbing at 3 µm to account for its much lower I/F at that wavelength.
However, the layer-2 and layer-3 fractions in this model are too large for the reflecting layer equations to provide physically meaningful parameter values if the clouds are actually uniform and translucent rather than broken and opaque. For the case of uniform translucent clouds, we need multiple scattering fits, which are presented after first identifying a plausible composition for the particles in such clouds.

5. MODELING THE 3-µm ABSORPTION.

5.1. Candidate 3-µm absorbers.

Candidate cloud materials expected in Jupiter’s atmosphere that also absorb light in the 3-µm region include NH$_3$, NH$_3$SH (ammonium hydrosulfide), N$_2$H$_4$ (hydrazine), and water ice. Their real and imaginary refractive indexes are shown vs. wavelength in Fig. 7. Because of its very high imaginary index, water ice cannot produce the absolute reflectivity level needed at 3 µm and the transparency needed at 2.7 µm. Trial fits with water ice resulted in very large $\chi^2$ values. Water is also a poor candidate because of its extremely low mixing ratio in the pressure range where the 3-µm absorber seems to be located. Hydrazine has a pair of strong absorption peaks between 3 and 3.2 µm, which were very apparent in in preliminary model spectra, and thus seemed inconsistent with observations. Among the more plausible compounds, only NH$_3$ has a known absorption at 2 µm (the 2.25 µm absorption feature of NH$_3$ would not be visible due to overlying gas absorption). NH$_3$SH has an absorption that is roughly comparable to that of NH$_3$ at 3 µm (except for the sharp NH$_3$ feature at 2.95 µm), but continues to increase beyond 3.1 µm where NH$_3$ absorption drops significantly. In the following detailed discussion we only include ammonia and ammonium hydrosulfide as viable candidates (see Sromovsky and Fry (2010) for an evaluation of a broader range of materials).

The cloud layers at which the 3-µm and 2-µm absorptions contribute do so primarily through their reflected intensities. Thus, it is useful to consider the spectral reflectivity of unit optical depth layers of NH$_3$ and NH$_3$SH for a variety of particle sizes and for low and medium phase angle observations. As shown in Fig. 13 the reflectivity plots provide clues as to what sorts of layers can provide the appropriate shortwave reflectivity and the needed 3-µm absorption. Fig. 13 also displays the effect of NQUAD (quadrature angles per hemisphere) on the accuracy of the computed reflectivity. The difference between calculations for NQUAD values of 10 and 60 show that as particle size increases much beyond a few microns model computations for low phase angles are much more demanding than for medium phase angles. This occurs because the scattering phase function is very smooth at middle phase angles (and scattering angles) but becomes quite sharp and more strongly wavelength dependent for large size parameters in near backscatter configurations (low phase angles).

A prominent feature in the reflectivity of ammonia layers is the deep and sharp minimum at 2.95 µm. The lack of such a feature in the VIMS spectra, or in the higher resolution ISO spectrum (Sromovsky and Fry 2010) implies that the top cloud layer on Jupiter cannot be made of pure NH$_3$ ice. If only ammonia is considered for the middle layer (500-700 mb), then only relatively large particles provide roughly the correct spectral variation in reflectivity. But even then, to fill in the deep minimum at 2.95 µm some additional reflectivity must be provided by a gray particle layer extending above the ammonia layer. Small particle layers of ammonia (0.25-1 µm in radius) are relatively too bright just beyond 3 µm, and they also contribute too much reflection at short wavelengths. Large ammonia particles produce a relatively strong 2-µm feature that is too strong to be compatible with observations, as pointed out by Irwin et al. (2001). The NH$_3$SH layers provide a flatter absorption between 3 and 3.4 µm, with a slope between 3 and 3.1 µm that depends on particle size. Note that NH$_3$SH particle layers are brighter than NH$_3$ layers of the same optical depth and particle size, a result of the higher real index of NH$_3$SH.

The VIMS spectra display a significant variation in brightness at 1.95 µm, without a significant variation in brightness at 3 µm, and the fractional absorption at 2 µm remains relatively constant, while the fractional absorption at 3 µm changes by a factor of two. Another feature of the spectra is the small dip at 2.97 µm, which is close to the 2.95-µm dip that is characteristic of an ammonia ice layer. These facts suggest that both absorbers are present at pressure levels that are visible at 2 µm and 2.9-3.3 µm, with NH$_3$SH providing most of the

| Spectrum | Measured I/F at 1.95 µm | Ratio of model I/F to measured I/F at 2.04 µm | at 2.96 µm | at 3.0-3.1 µm |
|----------|-------------------------|---------------------------------------------|------------|----------------|
| 13x14y   | 0.048                   | 1.300                                       | 3.44       | 2.76           |
| 25x35y   | 0.058                   | 1.261                                       | 4.32       | 3.35           |
| 12x16y   | 0.095                   | 1.191                                       | 4.03       | 3.40           |
| 11x15y   | 0.124                   | 1.233                                       | 5.45       | 4.24           |
| 11x14y   | 0.125                   | 1.211                                       | 6.65       | 4.68           |
| 26x31y   | 0.133                   | 1.200                                       | 5.43       | 4.06           |
| 27x34y   | 0.137                   | 1.180                                       | 4.55       | 4.36           |
| 28x31y   | 0.163                   | 1.143                                       | 6.54       | 5.02           |

Note: above rows are in order of increasing I/F at 1.95 µm.
cloud mass and most of the 3-µm absorption, and ammonia ice contributing a small amount of 2 µm absorption and helping to produce the small dip at 2.97 µm. These suggestions are quantitatively evaluated in the following section of multiple scattering model fits.

5.2. Models with an ammonia cloud layer.

We first considered the possibility that NH₃ could provide all the needed 3-µm absorption. Our initial multiple scattering models consisted of four scattering layers. The top layer was a small particle haze characterized by symmetric Henyey-Greenstein (H-G) phase function, a λ⁻³ wavelength dependence, an adjustable optical depth, and a fixed pressure of either 15 mb or 50 mb, with the choice guided by the reflecting layer fits. This top layer is needed to provide reflectivity in the 2.3-µm region. The second layer is a Mie-scattering layer of conservative particles with adjustable particle size, pressure and optical depth. The third layer consists of spherical NH₃ ice particles, with adjustable particle size, pressure and optical depth. The fourth layer was modeled as a nearly conservative layer (β = 0.997) using the H-G phase function of Stromovsky and Fry (2002) and a λⁿ wavelength dependence, with fit-adjustable pressure, optical depth, and λ exponent n. We also found comparable fits treating this as a Mie-scattering layer of NH₃SH particles, although in that case a stronger backscatter peak is needed to provide enough reflectivity. Without this deeper layer it appears impossible to match the spectral shape of the reflectivity peak near 1.23 µm. This structure, with NH₃ as the only aerosol absorber, provides an excellent fit to the lower opacity regions, such as the 13x14y spectrum, as shown in Fig. 15A,B. In this example the ammonia layer pressure (673 mb) is high enough that its spectral features at 9.6 µm and 26 µm would likely be hidden from view in observed thermal emission spectra, where such features are not easily observed.

In regions of higher opacity, such as location 11x14y in the low phase angle cube, the spectra cannot be as accurately fit with this structure. As shown in Fig. 15C and D, there is an absorption at 2 µm in the model spectra that does not appear in the observed spectra. The best-fit parameter values for both fits are listed in Table 3.

5.3. Models with NH₄SH as the only 3-µm absorber.

We next considered the possibility that NH₄SH could provide all the absorption at 3 µm. This would certainly eliminate the problem of excessive absorption at 2 µm, although it would not be able to fit the feature at 2.97 µm. For this study we used a model similar to that used for the NH₃ analysis, with the third layer consisting of NH₄SH instead of NH₃. We used a composite refractive index function for NH₄SH: at wavelengths where Howett et al. (2007) observations exist we used the average of their 80 K and 160 K measurements; elsewhere
Fig. 14.—$I/F$ vs. wavelength for unit optical depth layers of spherical NH$_3$ (left) and NH$_4$SH (right) particles of radii from 0.3 µm to 10 µm. Results for two phase angles are shown: 2.5° (top panels) and 67.8° (bottom panels) and for NQUAD values of 10 (solid) and 60 (dot-dash). Note that the NH$_4$SH calculations between 1 and 2.5 µm are based on interpolation of refractive index measurements at 1 and 2.5 µm. Frost reflection spectra (Fanale et al. 1977) show broad absorption features that may be significant between 1 and 2 µm, but no refractive index values are available.

we used Barbara Carlson’s compilation (personal communication 1994). Again we tried the two extreme cases (13x14y for low cloud opacity, and 11x14y for high cloud opacity). The best-fit spectra are displayed in Fig. 15, and the corresponding parameters given in Table 3. The low-opacity fit is slightly worse than the NH$_3$-only fit (by only 0.26×$\sigma_\chi^2$), but the high opacity fit is better (by 1×$\sigma_\chi^2$) than we obtained using NH$_3$ as the sole 3-µm absorber. However, the NH$_4$SH fits have specific local deficiencies: as expected, they don’t fit the feature at 2.97 µm, they still don’t provide close fits in the 1.9-2.0 µm region, and they have problems fitting the 2.7-µm peak and its long-wavelength shoulder.

There is also some question concerning the appropriate NH$_4$SH absorption model to use. The standard equilibrium chemistry model places NH$_4$SH condensation near 160 K, and particles formed at that level and lofted to higher altitudes will retain the same crystal structure, as evident from laboratory measurements of Ferraro et al. (1980). On the other hand if particles formed at somewhat lower temperatures, a different crystal structure would apply and the absorption would be close to that measured at 80 K. By picking an average of measurements at 80 K and 160 K, we are allowing for a 50:50 mix of formation temperatures above and below 160 K. A trial spectral fit to the 11x14y spectrum, assuming that all the NH$_4$SH was formed at high temperatures and that NH$_4$SH was the sole absorber, was somewhat degraded: $\chi^2$ increased by 1.5×$\sigma_\chi^2$. A trial spectral fit using the 80 K absorption model for NH$_4$SH, was also worse, but less significantly so (by 0.8×$\sigma_\chi^2$). Thus the observations slightly favor a mix of formation temperatures.

We see that neither NH$_3$ alone nor NH$_4$SH alone provides accurate fits to spectra over the full range of cloud structures. NH$_4$SH seems useful for fitting the high opacity cases and either NH$_3$ or NH$_4$SH are equally useful for fitting the low-opacity cases (the improvement of NH$_3$ over NH$_4$SH in those cases is really insignificant). It is worth noting however, that NH$_4$SH and NH$_3$ have somewhat complementary fitting defects: (1) NH$_3$ tends to be low near 2.85 µm where NH$_4$SH tends to be slightly higher (see location Y in Figs. 15 and 16); (2) NH$_3$ tends to be increasingly high beyond 3.05 µm where NH$_4$SH tends to be increasingly low. A combination of the two absorbers thus offers the possibility of reducing the net fitting defects in these areas. The most compelling reason to keep both NH$_3$ and NH$_4$SH particles in the model is that when NH$_3$ is combined with a non-absorbing material it becomes possible to fit the 2.97-µm feature (location Z in Figs. 15 and 16). While the NH$_3$ reflectivity minimum for pure NH$_3$ particles is displaced from this feature, a shift towards the peak in the NH$_3$ imaginary index (at 2.965 µm) can be accomplished if NH$_3$ is diluted by coating or mixing it with a conservative material, or by condensing it as a coating on a conservative core, as will be shown in the following section.
5.4. Models with both NH$_3$ and NH$_4$SH layers.

We first considered a structure similar to the previous models except that we inserted a layer of NH$_3$ particles between a conservative Mie layer and a Mie layer of NH$_4$SH particles, which is essentially the same structure used by Sromovsky and Fry (2010) to successfully fit the ISO spectrum. This approach produced relatively good fits for the low-opacity spectra, such as 13x14y and 25x35y, with best fits obtained with all three particle layers at nearly the same pressure. However, this structure did poorly at fitting the high-opacity spectra, such as 11x14y, for which the result was a poor match to the 2.97-µm feature and too low an I/F in the 1.95-2.1 µm region. This suggests that the structure inferred from the ISO spectrum does indeed not apply at all locations, which is not surprising, given the large FOV of the ISO spectrum and the wide variety of clouds averaged together.

We then considered the possibility raised by Sromovsky and Fry (2010) that an NH$_3$-coated particle might provide a better fit, either as a coating on the larger NH$_4$SH particles, or as a coating on the smaller conservative particles usually found near 350 mb. We computed scattering properties of coated spheres using the Fortran subroutine DMiLay, based on original work by Toon and Ackerman (1981), and further refined by W. Wiscombe (program code and documentation available at [ftp://climate1.gsfc.nasa.gov/wiscombe/]). Although the 2.95-µm absorption feature of pure NH$_3$ is not seen in the VIMS spectra, the feature near 2.97 µm could still be due to NH$_3$ when it is applied as a coating. An example is provided in Fig. 17. The upper right panel of that figure displays the reflectivity of a thin layer of spherical particles of 0.8 µm in radius, viewed in a backscatter configuration. When the particles are com-
Table 3
Best-fit cloud structures with single and multiple 3-μm absorbers.

| Parameter                | Low Opacity Spectrum (13x14y) | High Opacity Spectrum (11x14y) |
|--------------------------|-------------------------------|--------------------------------|
|                         | NH₃   | NH₄SH | NH₄SH | NH₃   | NH₄SH | NH₄SH |
| Layer-2 Composition      |       |       |       |       |       |       |
| p₁ (bars)                | 0.015 | 0.015 | 0.015 | 0.050 | 0.050 | 0.050 |
| p₂ (bars)                | 0.517 | 0.553 | 0.546 | 0.303 | 0.307 | 0.336 |
| p₃ (bars)                | 0.628 | 0.608 | 0.566 | 0.625 | 0.646 | 0.635 |
| p₄ (bars)                | 1.261 | 1.158 | 1.128 | 1.616 | 1.285 | 1.252 |
| T₁                       | 0.014 | 0.014 | 0.014 | 0.023 | 0.023 | 0.025 |
| T₂                       | 0.270 | 0.369 | 0.414 | 0.306 | 0.291 | 0.420 |
| T₃                       | 1.569 | 0.386 | 0.231 | 6.63  | 2.83  | 2.10  |
| T₄                       | 4.66  | 5.51  | 5.19  | 14.50 | 20.0  | 10.64 |
| Layer-3 Composition      |       |       |       |       |       |       |
|                         | NH₃   | NH₄SH | NH₄SH | NH₃   | NH₄SH | NH₄SH |
| r₂ (μm)                  | 0.289 | 0.293 | 0.303 | 0.265 | 0.237 | 0.259 |
| r₃ (μm)                  | 6.98  | 13.35 | 6.86  | 6.51  | 12.54 | 10.80 |
| Layer-2 λ exponent       | -3    | -3    | -3    | -3    | -3    | -3    |
| Layer-1 λ exponent       |       |       |       |       |       |       |
|                         | 2.7   | 2.12  | 2.12  | 1.28  | -0.62  | -1.12 |
| Layer-4 λ exponent       |       |       |       |       |       |       |
|                         |       |       |       |       |       |       |
| Layer-1 optical depth    | 125    | 129    | 118    | 175    | 160    | 124    |

Notes: For layer 1 we used a symmetric phase function and fixed pressures and λ exponents. For layer 4 we used the double Henyey-Greenstein phase function of Sromovsky and Fry (2002). Parameter uncertainties are given for the composite fit in Table 4. Optical depths are evaluated at 2 μm. The NH₃ shell* is a simulation of an NH₄-coated particle as described in the text. χ² values less than 15 are of marginal significance.

Posed of pure NH₃, a deep minimum is seen in the layer I/F, exactly at 2.95 μm (shown as the solid curve). But when the particles are composed of N=1.75 material out to 80% of the radius, and the remainder consists of NH₃, the I/F minimum is shallow and shifted close to the 2.97-μm peak in the imaginary index of NH₃. A similar effect is seen when an ammonia core is covered by a heavy coat of benzene (thickness equal to core radius), as shown in Fig. 5 of Kalogerakis et al. (2008). It is also noteworthy that the coated particle has a greatly reduced extinction efficiency relative to pure NH₃ particles at thermal wavelengths, making them less likely to be detected in thermal spectra.

Also shown in Fig. 17 is the I/F for uniform particles with a synthetic refractive index that roughly simulates the reflectivity of the composite particle. This allows us to incorporate the essence of a coated particle into the Mie calculations contained in our multiple scattering model without the time penalty of carrying out the more complex and time-consuming coated sphere calculations. We created the synthetic imaginary index by inserting a Gaussian absorption feature of amplitude 0.08 and FWHM of 0.06 μm at 2.98 μm, and using 1/2 of the NH₃ imaginary index, wherever that exceeded the wings of the absorption feature. We then used the Kramers-Kronig relation, following Howett et al. (2007), to compute a spectrally varying real index that was consistent with the imaginary index. The synthetic index provides an absorption feature that crudely matches the coated-sphere feature. However, the detailed character of this absorption depends on particle size, core material, shell thickness, and probably particle shape. Thus, the example shown in Fig. 17 should be considered suggestive, rather than typical, of the absorption feature that can be created by coatings of NH₃ on other materials. We tried to create absorption features of this type on larger (10-15 μm) particles with NH₄SH as the core material, but were unsuccessful, largely because of the rapid increase in absorption by NH₄SH on the long-wavelength side of the feature. We thus find that the most plausible means of creating an absorption feature at 2.97 μm is by coating small conservative particles with NH₃ (or by coating NH₃ cores with a conservative shell). We thus proceeded to carry out fits using small particles made of the synthetic index material that roughly simulated these composite particles.

Our revised structure placed the synthetic index particles in layer 2, to simulate the absorption by an ammonia coating on a conservative core. Fit-adjusted parameters included the pressures of the bottom three layers, the optical depths of all four layers, and the particle sizes of layers 2 and 3. From the comparisons of model and measured spectra, shown in Figs. 18 and 19, we see that these model fits are much better than were obtained when only a single 3-μm absorber was used. The shape of the 2.7-μm peak and its shoulder down to the 2.97-μm NH₃ feature is especially well matched, and overall χ² values are much improved as well, as can be seen in Table 3 which compares parameter values and fit quality for all three absorber models (the improvement in χ² is 2.4-3.4 ×σ² for the high opacity case and 0.5-0.8 ×σ² for the low opacity case). For the 13x14y spectrum, we see that layer 2 and layer 3 are closer together than for the single absorber models, the layer 3 optical depth is less, and the bottom cloud pressures are very similar. For the 11x14y spectrum, which is from a much cloudier region, the pressures of layers 2 and 3 are similar to those for the NH₃ case, but the optical depth for layer 2 is about 40% more than for either of the single-absorber cases, and the pressure of the bottom layer has been reduced from ∼1.6
bars to 1.25 bars.

The best-fit parameter values for the two-absorber model are listed for all eight fitted spectra in Table 4. We find that the preferred sizes of the NH$_4$SH particles are relatively large ($r \sim 7-16 \mu$m), which is comparable to the sizes we inferred for models in which only one absorber is present. On the other hand, the preferred size of the NH$_3$-coated particles is quite small, $\sim 0.3 \mu$m. In these models the NH$_4$SH layer provides most of the 3-μm absorption, but NH$_3$ provides additional spectral shaping that helps to achieve a better match to the observed spectra. Because we did not include sufficient quadrature points to characterize the complex backward scattering phase functions of the larger particles (if treated as spheres), the larger particle sizes are mainly constrained by the spectral shape of the 3-μm absorption feature, rather than the large scale wavelength dependence. For models in which there was a close proximity of layers containing NH$_3$ and NH$_4$SH particles, cross-correlations resulted in very poorly constrained uncertainty estimates. This was handled by forcing the layer 2 pressure to follow the layer 3 pressure by a fixed offset (usually 20-30 mb).

The vertical structure of the two-absorber models is visualized in Fig. 20 by plotting layer optical depth as a function of pressure. Comparing this to Fig. 11, we see that the derived pressures are similar, with layer 3 of the reflecting-layer model being split into two layers of different composition in the current model. For comparison we also show two independent results, converted to cumulative vertical optical depth. Because most of our layers have much higher optical depths than overlying layers, our cumulative optical depths would be stair-steps that would be just slightly to the right of our plotted layer values. The pair of triple-dot-dash curves are from belt and zone profiles of [Irwin et al. 2001]. These are well below most of our values, typically by factors of 2 or more. Both our results and those of [Irwin et al. 2001] probably contain far too much aerosol optical depth in the stratosphere because both NIMS and VIMS observations near 2.3 μm seem excessively high compared to measurements of [Banfield et al. 1998a] and to NICMOS observations (Fig. 7). The high stratospheric opacity from our VIMS
analysis is a result of the VIMS artifact previously discussed in Sect. 2.4, which is probably caused by light scattered off the VIMS grating. At least part of the high stratospheric opacity obtained by Irwin et al. (2001) is due to their assumption of a Henyey-Greenstein phase function with an asymmetry parameter of 0.5, which provides far less backscatter than the sub-micron particles which are the likely source of stratospheric scattering. To make up for this lack of backscatter, the inferred optical depth for their model had to increase to match I/F measurements. A more detailed comparison with NIMS results can be found in Sec. 6.2.

The variations of model parameters with respect to latitude are shown in Fig. 21. These results show some of the tendencies observed in the reflecting layer parameters. The cloud layers seem to descend to higher pressures moving from zone to belt, but there is not a clear tendency in optical depth. The remarkable feature is the close proximity of the layer of small NH$_3$ particles to the layer of much larger NH$_4$SH particles, suggesting that both particle populations might actually overlap in the same layer, perhaps with different scale heights. The descent to higher pressures in the NEB also helps to hide the NH$_3$ particles from observations at thermal wave-lengths, helping to explain the latitudinal dependence of NH$_3$ features detected by Wong et al. (2004), as we discuss later in Sec. 6.7.

There are two counter examples to the general rule of near overlap of NH$_3$ and NH$_4$SH layers. These are for two near equatorial spectra (11x14y and 11x15y), for which these two layers are separated by nearly 300 mb. For these spectra the NH$_3$ layer stayed at low pressures characteristic of the equatorial zone, but the NH$_4$SH layer moved to higher pressures, as did the bottom cloud layer. Optical depths for these cases did not deviate much from those inferred for the other spectra.

5.5. Sensitivity of spectra to model parameters.

The contributions of each model layer to the spectral features in the 11x14y spectrum are illustrated in Fig. 22, where the best-fit spectrum is compared to four spectra that each have one layer removed. This shows that the NH$_3$-coated particle layer (336 mb) provides important contributions in several regions, including near 1.5 $\mu$m, near 2 $\mu$m, and from 2.95 $\mu$m to 3.2 $\mu$m. The NH$_4$SH layer (635 mb) provides important contributions near 2 $\mu$m, 2.5 $\mu$m, and from 2.65 $\mu$m to 2.95 $\mu$m, but has so much absorption beyond 2.97 $\mu$m that it contributes es-

![Fig. 17.—Comparison of scattering properties of 0.8-µm radius spherical particles of pure NH$_3$ (solid curves), N=1.75 cores coated with NH$_3$ shells of 20% of total radius (dot-dash), and particles with a synthetic refractive index described in the text (dashed). Shown are extinction optical depth normalized to 0.34 at 2 $\mu$m (upper left), extinction efficiency near 9.4 $\mu$m (lower left) and 26 $\mu$m (lower right), and reflectivity of a thin layer in the backscatter direction near 2.95 $\mu$m (upper right).]
Jupiter’s 3-µm absorber

Fig. 18.—Selected low phase angle VIMS spectra (lines) compared to translucent layer multiple scattering model spectra (filled circles) using both simulated NH$_3$-coated and NH$_4$SH cloud layers. Light gray lines indicate combined uncertainty bands. The VIMS spectra from 1.58 to 1.68 µm are not used for constraining fits because of a responsivity error. Each panel legend provides pixel coordinates in the VIMS cubes (as in Fig. 2) and $\chi^2$ values (a value of 110±15 is expected). Here a vertical dotted line marks a wavelength of 2.97 µm.

sentially nothing to the I/F from 2.97 to 3.2 µm. Thus, these two different absorbers are seen to make distinctly different contributions. The deepest cloud layer (1252 mb) is seen to make significant contributions only to the window regions.

The sensitivity of model spectra to specific model pa-
parameters can be discerned from the fractional derivatives of a model spectrum with respect to each of the model parameters. This is shown in Fig. 23 for a model that is the best fit to the 25x35y spectrum. This example illustrates the relative independence of the spectral derivatives from each other, confirming the possibility of using observations to independently constrain the parameters. For example, although the upper layer of particles is only important in the more opaque regions of the spectrum, the fractional derivatives with respect to pressure (right,
Jupiter’s 3-µm absorber

Table 4
Best fit parameter values for 4-layer multiple-scattering 2-absorber fits to VIMS spectra.

| Spectrum | Parameter | Layer 1 (λ^4) | Layer 2 (NH₃ shell) | Layer 3 (NH₄SH) | Layer 4 (λ^4) |
|----------|-----------|---------------|---------------------|-----------------|---------------|
| 11x14y   | p (bars)  | 0.0500        | 0.336±0.014         | 0.635±0.042     | 1.252±0.04   |
| 11x15y   | p (bars)  | 0.0150        | 0.350±0.003         | 0.619±0.013     | 1.268±0.19   |
| 12x16y   | p (bars)  | 0.0150        | 0.381 (p₃-0.030)    | 0.411±0.006     | 0.885±0.04   |
| 13x14y   | p (bars)  | 0.0150        | 0.546 (p₃-0.020)    | 0.566±0.001     | 1.128±0.01   |
| 25x35y   | p (bars)  | 0.0150        | 0.460 (p₃-0.060)    | 0.520±0.011     | 1.007±0.01   |
| 26x31y   | p (bars)  | 0.0500        | 0.409 (p₃-0.030)    | 0.439±0.010     | 0.954±0.04   |
| 27x34y   | p (bars)  | 0.0150        | 0.345 (p₃-0.013)    | 0.358±0.028     | 0.885±0.04   |
| 28x31y   | p (bars)  | 0.0150        | 0.341 (p₃-0.030)    | 0.371±0.001     | 0.789±0.02   |
| 11x14y   | T         | 0.0250±0.005  | 0.420±0.04          | 2.10±0.54       | 10.64±1.37   |
| 11x15y   | T         | 0.0204±0.002  | 0.450±0.01          | 2.10±0.25       | 19.99±1.33   |
| 12x16y   | T         | 0.0143±0.003  | 0.414±0.05          | 2.3±0.01        | 5.19±0.73    |
| 13x14y   | T         | 0.0101±0.002  | 0.284±0.01          | 1.26±0.06       | 8.03±0.70    |
| 25x35y   | T         | 0.0168±0.003  | 0.373±0.04          | 1.75±0.24       | 6.80±0.57    |
| 26x31y   | T         | 0.0160±0.019  | 0.387±0.14          | 1.39±0.35       | 10.90±4.46   |
| 28x31y   | T         | 0.0129±0.001  | 0.374±0.06          | 1.48±0.22       | 12.10±3.38   |
| 11x14y   | r (µm) or n | n = -3 | 0.259±0.11          | r = 10.80+0.29−0.29 | n = -1.12±0.09−0.07 |
| 11x15y   | r (µm) or n | n = -3 | 0.280±0.05          | r = 16.39±1.18−1.20 | n = 0.00 |
| 12x16y   | r (µm) or n | n = -3 | 0.270±0.01          | r = 16.48±0.13−0.13 | n = -0.82±0.18−0.03 |
| 13x14y   | r (µm) or n | n = -3 | 0.303±0.42          | r = 6.86±1.13−1.23 | n = -2.15±0.03−0.03 |
| 25x35y   | r (µm) or n | n = -3 | 0.364±0.01          | r = 11.83±0.39−0.40 | n = 0.43±0.01−0.03 |
| 26x31y   | r (µm) or n | n = -3 | 0.355±0.06          | r = 13.84±0.23−0.23 | n = 1.73 |
| 27x34y   | r (µm) or n | n = -3 | 0.333±0.03          | r = 11.30±0.38−0.37 | n = 1.56 |
| 28x31y   | r (µm) or n | n = -3 | 0.304±0.14          | r = 10.93±0.02−0.11 | n = 1.64±0.34−0.25 |

Note: Only formal uncertainties from the fits are given; see text for other sources of uncertainty. Layer 2 pressures without uncertainties follow layer 3 pressures with fixed offsets. Some Layer 4 wavelength exponents were also fixed to stabilize uncertainty estimates.

Top row and optical depth (right, third row) are distinctly different. A similar difference can be found for other layers, and especially large differences exist between different layers. Note that particle size changes in layer 2 (the NH₃-coated layer) have the greatest effect at 2.97 µm and from there to 3.2 µm, while the size changes in layer 3 (the NH₄SH layer) have the largest impact between 2.5 and 2.9 µm. If we had used as the example a fit at low phase angles, and included an appropriately large number of quadrature points to capture the backward phase function peak, then the large particle layer (layer 3) would also have an important effect at short wavelengths. But models with such phase functions don’t fit as well as models without strong backward peaks.

In spite of the distinctive derivative spectra shown in Fig. 23, there are many spectra where the best fit NH₃ and NH₄SH layers are so close together that they become much more highly correlated with respect to pressure and optical depth variations. To fit these spectra and derive reasonable uncertainty estimates, we revised the model to use a fixed pressure offset between layers 2 and 3, so that the uncertainty for the layer 2 pressure then becomes the same as that for the layer 3 pressure, except that the two layers have correlated uncertainties. This tendency for both small NH₃-coated particles and much larger NH₄SH particles to reside at nearly the same pressure level suggests that they might actually be members of two different populations in the same layer. It is also possible that NH₃ forms as a coating on the larger...
Fig. 20.— Pressure vs. optical depth parameters for 4-layer multiple-scattering models that provide best fits to VIMS spectra, as given in Table 4. The pair of triple-dot-dash curves are cumulative optical depth profiles derived from belt and zone opacity profiles of Irwin et al. (2001).

Fig. 21.— Optical depth vs. latitude (top) and pressure vs latitude (bottom) for the 4-layer model with NH$_3$ in layer 2 (plotted as asterisks) and NH$_4$SH in layer 3 (plotted as open circles). Layer 1 pressure are excluded from the bottom plot because they are not very meaningful.

NH$_4$SH particles, although that would not work well for the entire NH$_3$ contribution, because the small particle component is needed to raise the reflectivity at short wavelengths, and the coated large particles don’t seem capable of producing the 2.97-µm feature.

5.6. Sensitivity of spectra to absorber gas profiles.

The effects of different ammonia and para hydrogen profiles are illustrated in Fig. 24. The difference between NEB and EZ profiles is relatively small, and our best fits were obtained with the the EZ profile for all spectra for which we did fits with both profiles, suggesting that the NEB profile we chose did not contain quite enough NH$_3$ at high altitudes. The probe profile makes a huge difference and is not a best fit with even the darkest spectrum we observed (13x14y). While we cannot rule it out in a local region, due to lack of spatial resolution, it is certainly not acceptable over an extended region comparable to the area sampled by a VIMS pixel. The difference between normal and equilibrium hydrogen profiles is also relatively small and restricted to a region that does not provide a significant constraint on the cloud models. Given that atmosphere appears to be intermediate between these states at low latitudes (Conrath and Gierasch 1984), the actual difference is about half that between the extreme cases shown in the figure. Thus, we did not try to account for potential variations in the ortho-para ratio. Instead we assumed equilibrium hydrogen in all the fits, confident that this convenience would have no significant effect on our conclusions.

5.7. Effects of calibration scale-factor errors

We fit several spectra with the nominal calibration and also with the VIMS I/F spectra multiplied by a scaling factor to simulate the effect of a change in absolute calibration. For a uniform fractional decrease in the measured I/F, we found that derived pressures and optical depths also decreased, the former by relatively little, just a fraction of the fractional calibration change, and the latter by much more, changing by one (at low optical depths) to several times (at higher optical depths) the fractional change in calibration (large optical depths require a larger fractional change to produce the same fractional change in reflectivity). This is not too surprising, since the overall brightness (which is changed by the scaling) is a strong function of the aerosol loading, while the shape of the spectrum (which is not changed) is strongly controlled by the vertical distribution of the aerosols. These results suggest that opacities we derive have additional uncertainties contributed by calibration uncertainties of about 5% to 20%, while the pressures have additional uncertainties 0-4%. We also found about a 10% affect on the wavelength dependence exponent for the bottom layer. The particle radius error contribution was not significant for layer 2 but 5-10% for layer 3. All these contributions should be combined with prior estimates using the root-sum-square method.

6. DISCUSSION

6.1. Comparison with Galileo Probe results

The Galileo Probe entered the atmosphere of Jupiter on 7 December 1995 at a latitude of 6.6°N, near the boundary between the Equatorial Zone and NEB, and at the edge of a 5-µm hot spot, which is a region of unusually low aerosol opacity (in the deeper layers). The
Nephelometer (Ragent et al. 1998) and the Net Flux Radiometer (Sromovsky et al. 1998) both detected a cloud near the 1.2-bar level (base near 1.35 bars) at the edge of a hot spot, with roughly unit opacity at a wavelength of 5 \( \mu \text{m} \). This pressure and optical depth are roughly comparable to that of the bottom cloud derived from several of the VIMS spectra, but there is not a good match to any obtained close to the probe entry latitude. This mismatch is not too surprising; given the large size of the VIMS pixels and the small scale of a typical hot spot, a close agreement cannot be expected.

An additional cloud layer was detected indirectly. A cloud above the level at which probe measurements began (440 mb) was inferred from Net Flux Radiometer observations of spin-induced modulations of the direct solar beam signal at multiple wavelengths (Sromovsky et al. 1998). The optical depth was estimated to be \( \sim 1.5-2 \) at a wavelength of 0.5 \( \mu \text{m} \), and the particle size between 0.5 and 0.75 \( \mu \text{m} \). This upper cloud seems reasonably consistent with our VIMS results for nearby latitudes (12x16y and 26x31y). As clouds close to this level are found throughout the equatorial zone, it is plausible that these might also be present at the edge or even over a hot spot. Although we find a combination of small and large particles, their spectral effects on the solar beam intensity in the NFR passbands might be similar to those of a single population of particles of intermediate size. Our lowest opacity model (for the 12x16y spectrum) has two contributions that would come from above the probe deployment level. At 2 \( \mu \text{m} \) the NH\(_3\)SH layer has a small optical depth of 0.23, which would not increase much at 0.5 \( \mu \text{m} \) because of the large particle size in this layer. The layer of NH\(_3\)-coated particles, with an optical depth of 0.37 at 2 \( \mu \text{m} \), would provide most of the opacity at 0.5 \( \mu \text{m} \), which could plausibly 4-5 times greater than its 2-\( \mu \text{m} \) value. This would yield a total 0.5-\( \mu \text{m} \) opacity comparable to the probe estimate, which is for a layer that does not vary much in optical depth for any of our spectral models, making it more likely that the probe comparison is a meaningful one.

Our VIMS model results also agree with a lack of cloud particles in the 700 mb region, and we do find lower cloud layers close to the probe cloud density maximum near 1.2 bars, although the optical depth we find there is generally much higher than obtained by the probe, which was in an unusually transparent region of the atmosphere. We don’t agree with the probe-derived ammonia profile however; when we try to fit the least cloudy region (13x14y) with that ammonia profile, the best fit \( \chi^2 \) value is nearly double what we obtained using either equatorial zone or NEB ammonia profiles. The part of the profile that presents problems is the low level of NH\(_3\) in the 400 mb to 1.5 bar pressure range, which is the part derived from NFR net flux measurements.

### 6.2. Comparison with Galileo NIMS results

In Fig. 25 we compare our opacity results at a reference wavelength of 2 \( \mu \text{m} \) to those of Irwin et al. (2001) and Irwin and Dyudina (2002). These comparisons are made in terms of the extinction optical depth per unit ln \( P \) interval. This is roughly equivalent to optical depth per unit altitude. We estimated that function for our results by convolving our opacities at discrete layers with a Gaussian smoothing function of the form \( \exp(-x^2/w^2) \), where the width \( w \) was set to roughly simulate the vertical correlation used in the NIMS retrievals. We didn’t scale the Irwin et al. (2001) results because they assumed wavelength-independent parameters over the entire 1-2.5 \( \mu \text{m} \) interval. We did scale the Irwin and Dyudina (2002) results from their 1-\( \mu \text{m} \) reference wavelength to our 2-\( \mu \text{m} \)
Fig. 23.— Best-fit model spectrum for location 25x35y (upper left), and fractional derivatives of that spectrum with respect to model parameters for pressure (P1, P2, P3, P4), optical depth (TAU1, TAU2, TAU3, TAU4), particle radius (R2, R3), and λ exponent for layer 4 (WLEXP4), in order from left to right and top to bottom. Here model layer 2 is made of synthetic NH$_3$-coated particles and layer 3 of NH$_4$SH.

We find a rough agreement on the fractional increase of opacity with depth and agreement on the pressure level of the local peak in opacity, but don’t agree well on the absolute values of opacity. Our results contain several times as much optical depth as the obtained by Irwin et al. (2001), and disagree even more with the profile of Irwin and Dyudina (2002), which has nearly an order of magnitude less opacity when scaled to a wavelength of 2 µm. At that wavelength it also disagrees with Irwin et al. (2001).

A factor that might introduce disagreements with the NIMS analysis of Irwin et al. (2001) and Irwin and Dyudina (2002) is the difference in treatments...
Jupiter’s 3-μm absorber

Fig. 24.— Spectra (top) for different gas opacity profiles using the same aerosol structure (the best fit structure for 25x35y and the EZ profile), and ratio (bottom) of each spectrum to the EZ spectrum. Note that no values were computed between 1.58 μm and 1.68 μm.

Fig. 25.— Extinction optical depth per unit per unit lnP interval for a belt sample (left) and for a zone sample (right) derived by Irwin et al. (2001) (solid lines). The over-plotted circles are optical depths from VIMS fits for the 13x14y spectrum (left) and the 11x14y spectrum (right), which represent belt and zone cloud structures respectively. The dashed lines are the dτ/dlnP values derived from the smoothing of VIMS scaled layer optical depths, computed as described in the text. The dotted curves (left panel) is the opacity profile from Irwin and Dyudina (2002) scaled to a wavelength of 2 μm, as described in the text.

of NH₃ absorption. Sromovsky and Fry (2010) show that prior ammonia absorption models provided too little absorption at 1.59, 1.9, and 2.3 μm. As can be seen from Fig. 24, variations in the amount of ammonia absorption have a significant impact on the I/F observed in the deeply penetrating windows at 1.28 and 1.59 μm, which provide important constraints on the vertical location of aerosols. Likewise, variations in NH₃ absorption models might affect the pressure derived from fitting the spectra.
Another difference that might affect the comparisons is that our fits result in different particle sizes, with the \( \text{NH}_3 \text{SH} \) layer having much larger particles than those derived by Irwin and Dyudina (2002). Our \( \text{NH}_3 \) and \( \text{NH}_3 \text{SH} \) layers are made with refractive indexes of specific materials, while Irwin and Dyudina (2002) used conservative particles, which have a strong influence on scaling results to other wavelengths.

### 6.3. Comparison with Galileo SSI results

Our results are also in partial agreement with results based on Galileo Solid State Imager (SSI) observations. Banfield et al. (1998a), who analyzed SSI data in three channels at 756 nm, 727 nm, and 889 nm, conclude that below an ubiquitous upper tropospheric haze, which exhibits little small scale variation, there is a highly variable cloud component (0 to 20 in optical depth), usually at \( p = 750 \pm 200 \text{mb} \), less than a scale height in vertical extent, and the principal cause of features seen at red and longer wavelengths. At first, this appears to be in serious conflict with our VIMS results, but it is only the lower end of the pressure range that is most in conflict, as a comparison of cumulative opacities will soon demonstrate. The subsequent analysis by Simon-Miller et al. (2001) reached similar conclusions, though somewhat less discrepant with near-IR results, specifically that a white cloud exists at pressures of 880-970 mb in belts and 620-720 mb in zones. These models use a relatively simple cloud structure with a small number of parameters, befitting the small number of spectral constraints provided by the observations. The structure consists of a stratospheric haze extending to a pressure that marks the top of the main cloud layer with a bottom pressure at which (generally) is located a physically thin sheet cloud. The main cloud is assumed to have the same scale height as the gas, leaving two pressures and three optical depths to be constrained by the models.

In Fig. 26 we provide comparisons for a belt (panel A) and a zone (panel B) between our VIMS cumulative optical depths and those of Banfield et al. (1998a) and Simon-Miller et al. (2001). Here our VIMS-derived opacities are scaled to their wavelength of 0.75 \( \mu \text{m} \). We scaled up the stratospheric haze opacity by a factor of 19 (assuming a \( \lambda^{-3} \) dependence) and the layer near 300 mb by a factor of ten, which is appropriate for our composite particle with a radius of 0.3 \( \mu \text{m} \). The bottom layer was scaled up by a factor of 2.67, to account for the approximate \( \lambda^{-1} \) dependence we inferred for that layer. The main \( \text{NH}_3 \text{SH} \) 500-600 mb layer, was not scaled because its opacity is relatively flat for the best-fit particle sizes, although its reflectivity can increase significantly at shorter wavelengths due to its high real index and reduced absorption. At SSI wavelengths this layer appears to make a relatively small contribution compared to the layers surrounding it.

Turning to the SSI-VIMS comparison itself, it is not surprising that our stratospheric haze opacity is much too high because of the excessive I/F values in the VIMS spectra near 2.3 \( \mu \text{m} \). Otherwise, there is gross agreement on the opacity levels deeper in the atmosphere. For the belt comparison (panel A) the cumulative opacity maximum is in close agreement with the Simon-Miller et al. (2001) result, while for the zone comparison (panel B) the best agreement is with the Banfield et al. (1998a) result, although there is a significant disagreement in the vertical location of the high-opacity bottom cloud. Our VIMS analysis puts it close to 1.1 bars, while the SSI results place it closer to 700 mb. On the other hand, we do find a significant cloud layer close to 700 mb in this region, and perhaps with a different scaling from 2 \( \mu \text{m} \) to 0.75 \( \mu \text{m} \) the disagreement might be substantially reduced, suggesting that the particle size is smaller or the inferred wavelength dependence is greater than what we obtain from our best fit over the 1-3.2 \( \mu \text{m} \) region. Another point worth remembering is that we are not comparing a large statistical sample, and some of the differences observed might be attributable to spatial and temporal variations. In the belt region, for example we obtain somewhat better agreement with the 25x35y spectrum. Clearly, a larger sampling of variations would allow for a more meaningful comparison.

Features of the SSI analysis that might contribute the disagreement in bottom cloud locations include changes made in the methane absorption coefficients of Karkoschka (1998), failing to include hydrogen collision-induced opacity from the third overtone band, which provides significant opacity in the 756-nm window, and uncertainties in the actual transmissions of the Galileo SSI filters. According to Simon-Miller et al. (2001), the 756-nm absorption coefficient was increased by a factor of 10 and the 727-nm coefficient from 0.17 to 0.22. The latest constraints on these coefficients, given by Karkoschka and Tomasko (2004), have resulted in only a factor of two increase in the 756-nm coefficient and no change in the 727-nm coefficient. The two Galileo SSI analyses thus place more absorption at higher altitudes than current best estimates would imply, and thus the pressures of the deeper cloud layers might be underestimated somewhat. Particle size differences are also a potential source of disagreements on opacity. Banfield et al. (1998b) use a fixed particle size of 0.2 \( \mu \text{m} \), while Simon-Miller et al. (2001) made particle size a fitted parameter, but didn’t report specific values because they were poorly constrained.

### 6.4. Comparison with Matcheva et al. (2003) CIRS results

The Matcheva et al. (2003) analysis of 2000 Cassini CIRS observations of Jupiter is unusual in relying on emission rather than reflected sunlight and in not requiring the use of band models, but instead relying on line-by-line calculations. This work also provides an important constraint on cloud composition because they are sensitive primarily to absorption, which varies greatly from one material to another (Fig. 13). Matcheva et al. (2003) made a narrow spectral window centered at 7.18 \( \mu \text{m} \), which is free of \( \text{NH}_3 \) absorption and thus independent of the \( \text{NH}_3 \) mixing ratio profile. Their analysis ignores scattering, based on the assumption that all particle radii are less than 1 \( \mu \text{m} \), although this is contradicted by other modeling efforts, e.g. this work as well as that of Brooke et al. (1998) and Wong et al. (2004), which generally find a significant component of large particles (~10 \( \mu \text{m} \) in radius) within the region relevant to the Matcheva et al. analysis. At latitudes with relatively low cloud opacity, such as the NEB, they find a cloud absorption peak at 1100±50 mb, and a cumulative optical depth near 1 down to 1400 mb. At latitudes with thick
Jupiter’s 3-µm absorber

Fig. 26.—Cumulative optical depth for a belt sample (A) and for a zone sample (B) derived from Galileo SSI observations by Banfield et al. (1998b) (dashed curves) and by Simon-Miller et al. (2001) (dot-dash curves). The over-plotted circles are optical depths from VIMS fits for the 13x14y spectrum (A) and the 11x14y spectrum (B), which represent belt and zone cloud structures respectively. VIMS layer optical depths (circles) and cumulative optical depths (solid lines) have been scaled to a wavelength of 0.75 µm as described in the text. The triple-dot-dash curve is the cumulative opacity profile from Irwin and Dyudina (2002) scaled to a wavelength of 0.75 µm, using their particle radius profile.

overcast such as the EZ, they find peak absorptions at $p \geq 900$ mb and optical depths up to $\tau \geq 4$. Their technique is limited to total optical depth (cloud plus gas) of $\tau < 4$. In the EZ, this limits retrievals to $p < 980$ mb, and in the NEB to $p < 1.5$ bars.

In Fig. 27 we compare our absorption optical depth profiles inferred from the 13x14y and 11x14y VIMS spectra with the Matcheva et al. (2005) absorption optical depth profiles for a region near 12° N (left panel) and the equator (right panel), respectively. The comparison is made in terms of the parameter $d\tau_a/d\ln P$, which can be thought of as a crude measure of optical depth per unit height. Our model opacities from VIMS are scaled to a wavelength of 7.18 µm to make a more appropriate comparison to the Matcheva et al. results. The VIMS stratospheric opacities, scaled using a $\lambda^{-3}$ dependence, are too small to be relevant at 7.18 µm. For the 300 mb layer we scaled from 2-µm values to 7.18-µm values using the factor of 57 reduction that applies for our 0.3-µm composite particle, and a further reduction to account for the absorption optical depth being 80% of the extinction value. These scalings make this layer ignorable as well. The optical depth of the main 3-µm absorbing layer has a relatively flat wavelength dependence and was used without adjustment, except that we accounted for absorption optical depth being only 43% of the total. At 7.18 µm the particles in this layer have a single scattering albedo of $\sim 0.57$ if they are pure NH$_4$SH compared to $\sim 0.7-0.85$ if they are pure NH$_3$.

The appropriate scaling for the VIMS bottom cloud is unclear. The wavelength exponents for the bottom layer in the reflecting layer fits (Table I) are generally small and slightly negative for most models. However, the exponents obtained from the multiple scattering fits (Table

| $n$ | $d\tau_a/d\ln P$ |
|-----|-----------------|
| -1  | 0.5             |
| 0   | 0.6             |

As for the NIMS comparison, this time adjusting the vertical width to simulate the vertical resolution of the Matcheva et al. retrieval. This was done to facilitate comparison and not because we believe that the opacity is so distributed.

At 12° N, the VIMS and CIRS opacity profiles are in crude agreement on vertical gradient, total absorption, pressure location of the absorption peak (near 1.1 bars), but disagree on the magnitude of the peak. This is probably about as good an agreement as might be expected, given the very different models for vertical distribution. For the 12° N case, we also included a scaled version of the Irwin and Dyudina (2002) profile, but added an imaginary index of 0.02 to simulate NH$_3$ absorption and 0.2 to simulate NH$_4$SH absorption. Here we see that the NIMS result does not scale well to the 7-µm region, no matter which absorber we assume. The vertical gradient, peak location, and magnitude are in strong disagreement with the other results.

The equatorial comparison in Fig. 27 tells a somewhat different story. Our results provide a weaker vertical opacity (after smoothing), while the CIRS analysis yields a very strong gradient. It is worth noting that the layers in disagreement are those in which we find significant
scattering contributions, suggesting that the Matcheva et al. analysis might need to be revised to take account of scattering effects. The comparison might also be affected by local variations, and might be better if we had a larger statistical sample. It may also be a problem for one or the other analyses to obtain accurate results for regions with very high cloud opacity, since sensitivity beyond the first few optical depths is very diminished for both VIMS and CIRS analyses. Perhaps the greatest uncertainty in this comparison is associated with the uncertainty in how to scale the bottom cloud results to the same wavelength. Currently we can only say that the two results might be consistent.

6.5. Cloud composition

Models that fit the VIMS spectra have some ammonia ice in the 330-550 mb region, probably in the form of ammonia combined with conservative material (near 3 μm) of relatively high real refractive index. NH₃ could be present either as a coating or as the core material, in either case representing less than half the total particle volume. These particles have sub-micron particle radii, probably near 0.3 μm. The non-NH₃ component might be sedimented hydrocarbons generated by photolysis of stratospheric methane, although it does not appear likely that hydrazine is a major component. The main layer responsible for the 3-μm absorption feature is generally in the 500-600 mb region, and the best-fit composition of this layer is NH₃SH, although this layer could also contain a contribution from NH₃ ice, either in the form of a separate particle population or perhaps as a coating. In fact, the close proximity of the NH₃ and NH₃SH layers in many cases, suggest that they might be co-mingled.

It is possible within the constraints of the spectra that low-opacity regions have 3-μm absorption provided entirely by NH₃ and that NH₃SH is only needed in the higher-opacity regions. But it seems more sensible that the deeper clouds are all composed of similar materials, and that NH₃ contributions appear in a different layer at generally lower pressures, although the fact that the two layers are virtually on top of each other in the low opacity regions raises questions about that possibility as well. Perhaps the entire particle distribution is coated with NH₃, but that only the small-particle component actually allows the NH₃ absorption features to become visible. Perhaps the top layer of clouds is the small-particle component that displays these features, while the bulk of the cloud is larger particles that don’t show the features.

We tried a number of models for the bottom cloud. The one that seemed to work best is one in which the phase function is wavelength independent and matches that of Sromovsky and Fry (2002), while the optical depth varies as λⁿ, with n ranging from -1.3 to +1.6. This resulted in pressures from 800 mb to 1.3 bars and optical depths from 5 to 20 (Table 1). This cloud might be composed of NH₃SH, but using that material in spherical particles degraded the fit quality. If we used a large number of quadrature points to capture the wavelength dependence of the phase function with higher accuracy, we found the details of that variation did not match the observations. On the other hand, if we used a small number of quadrature points to suppress the backscatter peak and its variations, this also made the lower cloud insufficiently bright, resulting in poor fits to the window regions. It appears that if NH₃SH is the main component of this cloud, it must have a lower imaginary index in the near-IR window regions, or have increased backscatter with a wavelength dependence different from that of spherical particles. There may also be accompanying variations in deeper regions of the atmosphere that are not constrained by the observations we used.

6.6. Dynamical considerations

At first glance, a scenario in which NH₃SH provides the main component of cloud particles in vicinity of 500 mb seems implausible. Such a scenario is certainly not consistent with a uniform upwelling in zones and descending air in belts, as commonly suggested in early studies of Jovian dynamics (e.g. Hess and Panofsky (1969); Stone (1976)). However, there is an observational conflict with that simple belt-zone dynamical model, namely the Galileo discovery that most of the lightning occurs within belts, where air was thought to be descending, and is associated with rapidly growing cloud clusters reaching pressures of a few hundred millibars (Ingersoll et al. 2000). These events would certainly dredge up condensible material from deeper levels, including NH₃, H₂S, water, and likely particles of NH₃SH. If these events provided a major source of condensibles in the upper troposphere, then it is less difficult to understand how NH₃SH particles might contribute a major source of cloud material near 500 mb. The potentially important role of these thunderstorms in controlling the composition of the upper troposphere is also highlighted by Showman and de Pater (2005), who provide a dynamical explanation for another non-intuitive observation, namely the global depletion of NH₃ vapor between 500 mb and 5 bars in both belts and zones. Their explanation is based on the idea “(1) that the majority of air that ascends across the 5 bar interface resides in isolated thunderstorms, and (2) that 50% of the ammonia within these storms is lost through the 4-6 bar level either by direct ammonia rainout through the base of the storms or downward transport of ammonia vapor in convective downdrafts moistened by evaporation of rainfall.” They speculate that “air undergoing large scale ascent above the 0.5-bar cloud tops in zones is probably supplied horizontally from the belts (where thunderstorms predominantly occur) rather than from below.” The belt-to-zone mass flux could be provided by eddies (Ingersoll et al. 2000). It also seems plausible that during the strong convective events, composite particles could form, including ammonia-coated NH₃SH. When distributed horizontally, such particles would be mixed with less ammonia-rich air, promoting evaporation of the coating and leaving behind the NH₃SH core, which might also contain some component of H₂O, although the VIMS spectra would not be consistent with a large fraction of water ice in such composite particles. A quantitative microphysical investigation of this scenario is needed to provide a better understanding of its plausibility.

6.7. Relation to ammonia ice detected at thermal wavelengths

Detections of NH₃ spectral features near 10 μm were first obtained by Wong et al. (2003). They used the
Fig. 27.—Cloud absorption optical depth per unit ln $P$ interval for 12° N (left) and the equator (right) derived by Matcheva et al. (2005) from CIRS thermal emission observations at 7.18 $\mu$m. Above and below the plotted pressures, the retrieval is dominated by guess profiles and thus not shown. The over-plotted circles are optical depths from VIMS fits for the 13x14y spectrum (left) and the 11x14y spectrum (right), which represent belt and zone cloud structures respectively. The scaling of VIMS results to 7.18 $\mu$m is described in the text. The dashed lines are the VIMS results convolved with a smoothing function that crudely simulates the vertical resolution of the Matcheva et al. retrieval. The $d\tau_{a}/d\ln P$ values for Irwin and Dyudina (2002) (dotted lines at left) are scaled according to particle size using imaginary indexes of NH$_3$ ($N_{i}$=0.02) and NH$_4$SH ($N_{i}$=0.2) to simulate NH$_3$ and NH$_4$SH absorption respectively.

Although the vertical variation in opacity of the Wong et al. (2004) cloud models is not a good match to ours, the latitudinal variation in ammonia ice they infer is at least qualitatively consistent with our results in Fig. 21. In our models the NH$_3$-containing layer descends from 400 mb to 600 mb from the equator to 14°N. This change is especially relevant because of the Wong et al. (2004) conclusion that ammonia ice present deeper than 500 mb would not be detectable at 10 $\mu$m because it would be too far below the peak of the contribution function of the observations. This implies that their observations would detect much less NH$_3$ in the NEB. Their broad vertical distribution of the small particle component for the cloudiest region, which should be similar to the equatorial region, would place about half its optical depth at pressures less than 450 mb, which would be about 0.38 extinction optical depths, comparable to what we would estimate for the layer of small ammonia-coated particles. Their more compact cloud could easily be composed of NH$_4$SH.

6.8. Relation to SIACs

Baines et al. (2002) identified anomalous discrete cloud features in the wake of the GRS, which they termed spectrally identifiable ammonia cloud (SIACs) based on low reflectivity at 2.7 $\mu$m relative to high reflectivity at 1.6 $\mu$m, and a local dip in reflectivity at 2 $\mu$m relative to 1.94 $\mu$m, both depressions characteristic of ammonia ice absorption (the longer wavelength absorption is only apparent in optically thick clouds, and not noticeable in Fig. 14). These features were observed in Galileo NIMS spectra, taken at very high spatial resolution, and appear to occupy less than 1% of Jupiter’s cloud-top surface. The VIMS spectra we analyzed (or any other VIMS spectra) have far too low a spatial resolution to detect SIACs. Unlike SIACs, the 3-$\mu$m absorption feature we analyzed appears to be very widely distributed on Jupiter. Although we focused on low-latitude spectra for detailed analysis in this paper, we did look at VIMS spectra over a wide range of latitudes and longitudes, and found obvious strong absorption at 3 $\mu$m everywhere we looked. The SIACs appear to be the result of unusually strong localized vertical transport that causes significant condensation of ammonia vapor, such that the ammonia spectral features become significantly enhanced. It appears from our results, that most locations on Jupiter don’t have very much condensed NH$_3$, so that the the spectral character of SIACs is rarely observed. The alternative possibility that NH$_3$ is in fact the major cloud component, but
has its spectral signature significantly altered by some photochemical “tanning” process remains to be quantitatively investigated, and whether it could satisfy known spectral and photochemical constraints seems doubtful.

6.9. Comparison with Saturn

Saturn’s near-IR spectrum does not contain the broad and strong 3-µm absorption feature so apparent in Jupiter’s spectrum (Encrenaz et al. 1994; Baines et al. 2003). The stark difference between spectra of these two planets is illustrated in Fig. [28], where we compare a typical low-latitude Saturn spectrum from VIMS data cube CML1587635989 with a VIMS Jupiter spectrum (12x16y). The high reflectance of Saturn’s clouds at 3.0 µm (~0.2), just where Jupiter’s I/F is quite low (~0.02), implies that the main cloud layer contributing to Saturn’s reflection spectrum in the near IR is not composed of medium sized pure ammonia ice particles (nor NH₄SH particles). This is likely the layer of upper tropospheric haze that Pérez-Hoyos et al. (2005) found to extend from a base at 300 mb - 500 mb to a top near 40 mb - 80 mb, varying with latitude and season, but generally of substantial optical depth (∼6-20 at ∼1 µm), with a weak dependence on wavelength. This layer is probably thick enough at 3 µm to obscure the much deeper ammonia cloud thought to reside between 1.4 and 1.8 bars.

However, there is some evidence for at least a component of ammonia ice in Saturn’s tropospheric haze. From analysis of a high-resolution ground-based spectrum of Saturn, Kim et al. (2006) developed evidence for a weak cloud absorption feature at 2.96 µm, where their inferred model cloud layer at 460 mb had its albedo drop by ∼20%, which they suggested might be due to ammonia ice. A small absorption feature at the same wavelength is also seen in many spatially resolved VIMS spectra of Saturn (also evident in Fig. [28]), and is not a characteristic of the phosphine spectrum that provides the main absorption in this region. This very well may be due to a population of ammonia-coated particles within the main tropospheric haze layer of Saturn. A small composite absorption feature near 2.97 µm, which they suggested might be due to ammonia ice, and have a relatively narrow, but subdued, peak absorption displaced towards the ammonia imaginary index peak at 2.965 µm, as is shown in Fig. [17]. This shifted and attenuated feature could also be produced by particles with a small core of ammonia ice coated by a thick layer of hydrocarbons, as demonstrated by the benzene-coated example of Kalogerakis et al. (2008). It seems likely, but remains to be demonstrated, that a moderately thick tropospheric haze containing a component of such particles could provide accurate fits to Saturn’s near-IR spectra.

7. SUMMARY AND CONCLUSIONS

From an analysis of VIMS low and medium phase angle spatially resolved spectra obtained during the Cassini 2000 flyby of Jupiter, we obtained the following main conclusions regarding the VIMS instrument performance, the source of Jupiter’s 3-µm absorption, and Jupiter’s low-latitude cloud structure.

1. By comparing VIMS spectra with groundbased spectra, selected NICMOS observations, and an ISO spectrum, we were able to confirm that the VIMS absolute calibration is relatively consistent with other observations, but that VIMS measurements have two significant artifacts, one in the 1.60-1.68 µm region where a huge responsivity correction turns out to be insufficiently accurate, and the other is an excessively high I/F measurements at low signal levels, which caused model fits to yield stratospheric haze opacity ∼10 times that derived from groundbased spectra.

2. We found that VIMS spectra contain evidence for a prominent and widespread 3-µm absorber in Jupiter’s clouds and a much weaker absorber active near 2.0 µm. This was made obvious by reflecting layer fits constrained outside the absorbing region, which produce more than the observed reflectivity in the absorbing regions, by ∼20% at 2.04 µm and by 300-500% at 3-3.1 µm.

3. We were able to fit a low-opacity VIMS spectrum quite well using NH₃ ice as the only 3-µm absorber, but were not able to fit very well the spectra from much cloudier regions, the main defect being an absorption feature near 2.5 µm in the model spectra that was much larger than observed. Models with NH₄SH as the only absorber in a similar layer structure were more successful in fitting high opacity spectra and almost as good fitting low opacity spectra, the main defect being lack of a 2.97-µm spectral feature which appears to require a contribution from NH₃.

4. The best fits to VIMS spectra were obtained with both NH₃ and NH₄SH absorbers present in Jupiter’s clouds, but the NH₃ contribution appears to help most in the form of a coating or as a core material comprising less than half the total particle volume. We roughly simulated NH₃-coated particles using a synthetic refractive index with absorption similar to that of NH₃ but significantly weaker. A layer of these small (∼0.3 µm) particles above...
a layer of much larger (r~10 μm) NH₃SH particles provided the best fits to all the spectra. The NH₃-coated cloud layer (modeled as physically thin but ranging from 330 to 550 mb) was found to have the least variability in optical depth among the eight low latitude spectra, with an average of 0.38 and a standard deviation of only 0.05. The main 3-μm absorbing layer varies in optical depth from 0.23 to 2.1, a factor of nine, with pressures ranging from 358 to 635 mb. In most cases the NH₃-containing layer was found in such close proximity to the NH₄SH layer that they could be intermingled. A caveat in these results is that the simulation of the NH₃-coated particle does not closely follow the size and wavelength dependence of a true NH₃-coated particle, and thus some other structure may be required to provide physically consistent fits.

5. Comparison with Galileo Probe results provided crude agreement on the vertical location of clouds, the upper level cloud opacity, the pressure of the lower cloud, and the relative lack of cloud particles near 700 mb, but did not agree with the NFR-derived vertical profile of NH₃.

6. Comparison with the analysis of Galileo NIMS observations by Irwin et al. (2001) shows a rough agreement with the vertical trend of opacity and the location of the peaks in opacity, but we find greater absolute opacity values. We cannot confirm (or rule out) the large belt-zone differences they found in the 1.5-2 bar region. When the results of Irwin and Dyudina (2002), which apply to belt regions, are scaled to 2 μm, there is an even larger discrepancy than with Irwin et al. (2001).

7. Comparison of our results scaled to a wavelength of 0.75 μm with Galileo SSI results by Banfield et al. (1998b) and Simon-Miller et al. (2001) finds reasonable agreement with cumulative opacity profiles, with the exception of the location of the lower high-opacity cloud in zone models, which the SSI analysis places near 700 mb and our analysis places near 1100 mb.

8. Comparison of our absorption profiles with the analysis of Cassini CIRS observations by Matcheva et al. (2003), with plausible scalings with wavelength, reveals a rough agreement, but with CIRS opacities less than ours by a factor of two or more. However, the validity of the comparison is uncertain because of the large uncertainty in appropriate scaling factors to use for the lower cloud.

9. The presence of a layer of sub-micron NH₃ ice coated particles at pressures of 300-500 mb does not appear to conflict with thermal spectra in the 9-10 μm region, where only a weak ammonia signature is observed. This is possible because the coated particle can produce the reflective contribution needed to match the near-IR spectra, but ten times less extinction optical depth at 9.4 μm than would be obtained from pure NH₃ particles of the same size. Our estimated extinction optical depth for this layer is crudely compatible with the optical depth estimate of Wong et al. (2004) in the latitude band we analyzed. The increased pressure we find for the NH₃ layer in the NEB is qualitatively consistent with the low signature found by Wong et al. in a similar region.

10. Saturn’s spectra do not exhibit the broad 3-μm absorption feature characteristic of Jovian spectra, perhaps because the cloud layer containing that absorber is obscured by the moderately thick tropospheric haze that overlies it. However, Saturn spectra do exhibit a small absorption feature near 2.965 μm, which is qualitatively consistent with NH₃ absorption when diluted by combining NH₃ with a substantial conservative core or shell.

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