Modelling the near-infrared spectra of Jupiter using line-by-line methods

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ABSTRACT

We have obtained long-slit, infrared spectra of Jupiter with the Anglo-Australian Telescope in the $K$ and $H$ bands at a resolving power of 2260. Using a line-by-line, radiative transfer model with the latest, improved spectral-line data for methane and ammonia, we derive a model of the zonal characteristics in the atmosphere of this giant planet. We fit our model to the spectra of the zones and belts visible at 2.1 μm using different distributions of cloud opacities. The modelled spectra for each region match observations remarkably well at the $K$ band and in low-pressure regions at the $H$ band. Our results for the upper deck cloud distribution are consistent with ∼ 2011 RAS KSTAR band and in low-pressure $H_k$ - (Conrath (Tomasko, West & Castillo 1978), (Carlson et al. 1996) and the Voyager 2011 The Authors K CASSINI C4 bands at a resolving power of 2260. Using a line-by-line, radiative transfer model on 27 July 2018 by guest

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methane absorption at a resolution of 10 cm

ammonia (NH₃), and by collision-induced absorption as a result of H₂ and He. Methane, however, has a very complex rovibrational spectrum and the available spectrum-line data are limited. Many models for Jupiter’s spectrum have therefore been based on low-resolution absorption coefficients or $k$-distribution data, rather than on line-by-line techniques. For example, Strong et al. (1993) and Irwin et al. (2005) have presented $k$-distribution models for methane absorption at a resolution of 10 cm⁻¹, and Irwin et al. (1999) have presented similar data for ammonia. Using data such as these, it is possible to model spectra at relatively low resolution, such as those from the Galileo Near-Infrared Mapping Spectrometer (NIMS). However, many infrared spectrographs on ground-based telescopes can provide much higher spectral resolution. Recently, there have been significant improvements in the available spectral-line data for methane and ammonia (Albert et al. 2009; Rothman et al. 2009; Yurchenko et al. 2009; Nikitin et al. 2010; Wang, Kassi & Campargue 2010).

In this paper, we present a set of observations of the spectrum of Jupiter at a spectral resolution of ∼2260 and we investigate our ability to model these data using line-by-line methods. We use the radiative transfer model VSTAR (Versatile Software for Transfer of Atmospheric Radiation), which is specifically designed for this purpose (Bailey 2006). It derives radiative transfer solutions for specified wavelength ranges in the transmission, emission or reflection spectrum of a planet. This software is designed to be extremely versatile in the range of atmospheres it can be applied to. In the past, we have used it for the atmospheres of Earth and Venus (Bailey, Simpson & Crisp 2007; Bailey et al. 2008; Bailey 2009). Recent additions to the system allow it to be used for the atmospheres of Solar system planets, exoplanets, brown dwarfs and cool stars.

Methane is an important absorber, not just in Jupiter and the other Solar system giant planets but also in brown dwarfs (the presence of methane absorption is the defining characteristic of a T-dwarf), and it is likely to be important in many exoplanets. It has been reported in the spectra of the transiting exoplanets (Swain, Vasisht & Tinetti 2008; Swain et al. 2009). While hot methane presents additional issues compared with the cool methane spectra required for Jupiter (e.g. Borysov et al. 2002), the problem of accurately modelling the methane absorption spectrum is common to a full understanding of all these objects. Thus, as well as being an interesting object in its own right, Jupiter can be considered as a test object for our future ability to model the spectra of extrasolar planets.

Despite decades of research dedicated to understanding the structure and composition of Jupiter’s atmosphere, unanswered questions remain about the detailed distribution and transport of gases over the surface of the most massive planet of the Solar system. The wealth of data across its optical and infrared spectrum from ground-based telescopes (e.g. Clark & McCord 1979; Karkoschka 1994), Pioneer 10 (Tomasko, West & Castillo 1978), Voyager (Conrath & Gierasch 1986), Galileo (Carlson et al. 1996) and the Cassini spacecraft (Bellucci et al. 2004; Kunde et al. 2004) have provided direct measurements of physical properties at different heights of the atmosphere, which can be used to constrain input parameters in models. Spectral information is used not only to derive the atomic and molecular abundances of the atmosphere, given the physical
properties, such as temperature and pressure, at different heights, but also to study the distribution of aerosols and clouds, and dynamic characteristics, which include wind and temperature patterns resulting from global weather effects.

Jupiter is covered with permanent layers of clouds, which are arranged into longitudinal, relatively stable regions determined by atmospheric circulation. The bright and dark bands are called zones and belts, respectively. These are understood to correspond to upward and down-welling of gas in the convective flow of the atmosphere. The most abundant constituents of Jupiter’s atmosphere are hydrogen, helium, methane and ammonia. Direct measurements of the scattering properties in Jupiter’s atmosphere taken with the Galileo probe Nephelometer (Ragent et al. 1998) suggest that the dense clouds of condensates, mostly ammonia, form in the almost adiabatic troposphere above 1600–700 mb. In addition, the thinner, stratospheric hazes, which contribute to the overall atmospheric opacity, have been detected at heights that vary depending on the longitude of the planet. For example, they appear elevated in the polar regions, where hydrocarbons, such as C_2H_6 and C_2H_2, are suggested to exist as a product of photochemical and auroral discharge processes (Pryor & Hord 1991). Another molecule considered in a composition of the stratosphere is photochemically produced N_2H_4 (Strobel 1983). The detailed composition of stratospheric haze remains uncertain because of the limitations of the currently available data. A comprehensive review of Jupiter’s cloud structure has been presented by Irwin (1999).

The observations described in this paper are long-slit spectra at relatively high resolving power ($R = \lambda/\Delta\lambda \sim 2260$) in the $H$ and $K$ bands (Table 1). The data were obtained with the Infrared Imager and Spectrograph 2 (IRIS2; Tinney et al. 2004) at the 3.9-m Anglo-Australian Telescope. The spectra were subdivided into latitudinal regions, which closely resemble the pattern of zones and belts visible in the acquisition image observed with the CH_4 filter at 1.673 $\mu$m (Fig. 1). Details of the calibration technique are discussed in Section 2. We used the vstar package to develop models of the cloud structure for each region to best fit the observed spectra. In Section 3, we describe the vstar modelling strategy to achieve this goal, which includes the model parameters and the lists of spectral lines used for each constituent of the atmosphere. The derived cloud opacities at different latitudinal locations are presented in Section 4, followed by a discussion in Section 5.

### 2 OBSERVATIONS AND DATA REDUCTION

The images and the IRIS2 spectra of Jupiter were acquired on 2007 May 25 (Table 1). The long slit (7.7 arcmin) was positioned across the meridian of the planet. The width of the slit is 1 arcsec, which is equivalent to 2.2 pixels on the detector. The spectra cover the $H$ (1.62–1.8 $\mu$m) and $K$ (2.0–2.4 $\mu$m) bands. The narrow-band image of the whole planet in CH_4 (Fig. 1) shows the characteristic band structure. The calibrated spectra were extracted and averaged over 11 regions denoted by the names given in Table 2. The region selection was based on the reflectivity profile averaged across the slit over the section of the $K$-band spectrum in the region of the collision-induced H_2–H_2 absorption between 2.08 and 2.13 $\mu$m. The black horizontal lines overplot on the image in Fig. 1 show the extent of each region.

Data reduction was carried out using the standard procedures of the FIGARO package (Shortridge et al. 1995). The wavelength calibration was achieved by using a xenon lamp. The spectra were divided by spectroscopic flat fields in order to remove the

| Region | 1 North Pole (NP) | 2 Northern Upper Belt (NUB) | 3 Northern Zone (NZ) | 4 Northern Equatorial Belt (NEB) | 5 Equatorial Zone (EZ) | 6 Equatorial Belt (EB) | 7 Southern Equatorial Zone (SEZ) | 8 Southern Belt (SB) | 9 Southern Zone (SZ) | 10 Southern Upper Belt (SUB) | 11 South Pole (SP) |
|--------|------------------|-----------------------------|----------------------|-------------------------------|-----------------------|-----------------------|-------------------------------|------------------|-------------------|-------------------------|------------------|

These spectra are affected by a contribution of light reflected by Europa.

A spectrum of the atmospheric region with a bright ‘white’ spot.

Figure 1. Narrow-band, acquisition image of Jupiter, taken in the CH_4 absorption region at 1.673 $\mu$m, shows a characteristic band structure of clouds in the atmosphere of the planet. The black lines mark the borders between regions, which correspond to zones and belts defined by the level of absorption visible at 2.1 $\mu$m through a 1-arcsec slit positioned vertically at the centre of the planetary disc. All observed spectra are derived as the averages over the number of pixels comprising each zone or belt.

Table 1. Observations of Jupiter on 2007 May 25.

| Band | Centre ($\mu$m) | Resolving power | Mean dispersion (nm pixel$^{-1}$) | Start (UT) | Integration time (s) | Total (s) |
|------|-----------------|-----------------|-------------------------------|-------------|---------------------|-----------|
| $H$  | 1.637           | 2270            | 0.341                         | 14:40       | 12                  | 48        |
| $K$  | 2.249           | 2250            | 0.442                         | 14:58       | 45                  | 180       |

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non-uniform response of the detector. The normalized flat-field images were formed by subtracting the image fully illuminated by a quartz calibration lamp and the dark image taken with the lamp switched off. Sky subtraction was achieved by taking four exposures with two spectra spatially offset in the same frame and subtracting two corresponding frames with offset spectra from each other.

Spectral curvature was removed by resampling the frames using correction derived from the spectra of standard stars taken for each band. Bad pixels resulting from cosmic rays and known imperfections of the detector were corrected by interpolation between their neighbours.

We used standard stars, which were close in angular separation to the planet. They were chosen to match the solar spectral type as closely as possible. The Jupiter spectrum was divided by the standard star spectrum to remove both telluric absorptions and solar features. The resulting spectrum corresponds to the reflectance from the planet. Bailey et al. (2007) have pointed out potential problems with using standard stars for the removal of telluric absorption for planetary spectra. However, in the case of Jupiter, the absorption features in the planet are a result of different molecules from those in the terrestrial atmosphere spectrum, and these problems are largely avoided.

A true level of intensity can be derived by converting a number of counts, $N_i$, in the spectra into the flux density derived from the calibrated flux density, $F_{\text{std}}$, of the standard star. We derive the radiance factor, $I/F_{\text{Sun}}$, where $I$ is the reflected intensity of the planet and $\pi F_{\text{Sun}}$ is the solar flux incident on the planet from:

$$\frac{I}{F_{\text{Sun}}} = \frac{I}{\pi F_{\text{Sun}} C} \left( \frac{N_i}{N_{\text{sun}}} \right) F_{\text{std}}. \tag{1}$$

The size of the slit, $A_{\text{slit}}$, is given in radians, and the distance of Jupiter, $D$, from the Sun is measured in astronomical units. The flux in each region is then scaled by the number of pixels, it encompasses.

The typical spectrum and our vstar model in the equatorial region of Jupiter are presented in Fig. 2 in the wavelength range between 1.62 and 2.4 µm. As expected, the methane absorption clearly dominates in this spectral range. The H$_2$–H$_2$ collision-induced smooth absorption peaks at 2.12 µm, which appears to be very shallow in the polar region spectra. This reflects the contributions of increasingly slant paths through the atmosphere, which probe vertically higher regions with a lower density of H$_2$.

The moon, Europa, was transiting in front of the planet during the observations and its reflected light was present in the slit while the spectra were taken. Its effect on the spectra of the Southern Equatorial Zone (SEZ) and Southern Belt (SB) is clearly visible showing the increased reflectivity in the regions of the largest methane absorption. Europa is thought to have a large amount of pure water ice on its surface (see the spectra in Calvin et al. 1995). The highly reflective shoulders of water bands observed in the spectra around 1.8 and 2.2 µm contribute to the combined high albedo of the planet and the moon in the regions where otherwise the planetary methane absorption is the highest.

3 VSTAR MODELLING PROCEDURE

VSTAR is a modular code written in FORTRAN, which solves the line-by-line, radiative transfer problem for light in a stratified atmosphere with a defined chemical composition and a specified size distribution of cloud particles. The code is composed of several packages (MOD, LIN, RAY, PART and RT), which contain routines called by a user-written program to build a specific atmospheric model.

The MOD package defines a two-dimensional grid, which stores the values of parameters for the atmospheric layers in one dimension and the array of spectral points at which the model is calculated in the second dimension. The LIN package reads spectral lines from the line databases, calculates line profiles and sets the optical depth for each layer of the atmosphere. The RAY package calculates Rayleigh scattering optical depth for the atmospheric layers. The particle scattering from aerosols and clouds is calculated with a Mie scattering code (Mishchenko, Travis & Lacis 2002). The PART package allows up to 20 different scattering particle modes with different size distributions, refractive indices and vertical distributions to be included in the model. The workhorse of the VSTAR code is the RT package, which performs the radiative transfer solution for each layer of the atmosphere using the data set up by the previously described packages. Different radiative transfer solvers can be selected, but for the purpose of this work we use DISORT, the discrete ordinate solver described in Stamnes et al. (1988).

We model Jupiter’s atmosphere using 36 vertical layers with specific physical properties given by pressure and temperature, as well as the chemical composition expressed in terms of gas mixing ratios. The $P$–$T$ profile of the planet’s atmosphere in the pressure range between 0.001 and 1 bar has been studied with infrared radiometry, radio occultations and direct sensing with the Atmospheric Structure Instrument (ASI) on the Galileo probe (Seiff et al. 1998). Most recent retrievals of atmospheric temperatures from the Cassini Composite Infrared Spectrometer (CIRS) data published by Simon-Miller et al. (2006) show time-variable, zonal differences in $P$–$T$ profiles, which are also present in the Voyager IRIS data. In the range of pressures probed with our model, the strongest zonal variations are of the order of a few Kelvin in the upper troposphere.

Figure 2. Observed spectrum (grey or red in the on-line version) of Jupiter’s equatorial region (EZ) at the $K$ and $H$ bands overlapped with the model (black). This also cover the region between 1.85 and 2 µm, characterized by strong H$_2$O absorption in the Earth’s atmosphere, and thus it is difficult to observe from the Earth. The main discrepancy between the model and observations appears at the low-absorption region below 1.65 µm, which probes atmosphere levels below 1 bar. In addition, we find a typically larger mismatch in the intensity of the methane absorption bands at the $H$ band than in the $K$ band; this is discussed in Section 4.
In Fig. 3, we plot the averaged profile from Voyager radio occultation experiments (Lindal 1992), and the profile obtained from the Galileo probe descending into the 5-μm hotspot region in the North Equatorial Belt (Seiff et al. 1998). The notable differences in the Voyager and Galileo profiles appear above about 300 mb in the upper troposphere, which is expected as both profiles were probing different locations on Jupiter’s surface at different times. The 5-μm hotspots are relatively dry, localized regions with a low level of cloud cover (Showman & Dowling 2000). We believe the Voyager occultation data are likely to be more robust in describing the average properties of zones and belts considered in our models. We tested the effects of changed temperature corresponding to the profile differences observed in Voyager ingress, egress occultation data and Galileo probe measurements for the equatorial belt, equatorial zone and the north polar region. Fig. 4 shows a typical example of the difference between the models with Voyager- and Galileo-derived P–T profiles. The differences are highest in the spectral ranges corresponding to the tropospheric pressures. However, these are an order of magnitude lower than the typical residuals of our fits to data, which are dominated by the opacities of different vertical regions in the atmosphere.

Therefore, for simplicity we used a single P–T profile to model the zonal composition of the atmosphere based on the Voyager radio occultation observations (Lindal et al. 1981; Lindal 1992).

The chemistry of Jupiter’s atmosphere is complex and involves a large number of atomic and molecular species produced in photochemical processes (Atreya et al. 1997). Our model considers only the major components of the atmosphere, which influence the shape of the observed spectra in the near-infrared region. The most abundant atmospheric gases are H₂ and He, which produce smooth, collision-induced absorption features around 2.12 μm. The other molecules that absorb in the infrared spectral region are methane (CH₄) and ammonia (NH₃). Methane is the most important absorber in the H- and K-band spectra. The mixing ratio of CH₄ adopted in our model is 2.3 x 10⁻³, which is consistent with the latest in situ measurements with the Galileo Probe Mass Spectrometer (GPMS; Wong et al. 2004). The mixing ratio of methane is relatively constant at pressures higher than 1 mbar (Moses et al. 2005).

### 3.1 Methane spectrum

A tetrahedral molecule, such as methane, has four vibrational modes: two bending modes described by quantum numbers v₁ and v₃ and two stretching modes v₂ and v₄. Thus, each vibrational level can be described by its four vibrational quantum numbers (v₁, v₂, v₃, v₄). The frequencies of the two stretching modes are both about 1500 cm⁻¹ and those of the two bending modes are both about 3000 cm⁻¹. These coincidences result in a complex series of interacting vibrational states, repeating at intervals of ~1500 cm⁻¹, known as polyads. Polyads are generally designated by Pₙ where n is the polyad number defined in terms of the vibrational quantum numbers by

\[ n = 2(v_1 + v_3) + v_2 + v_4. \]  

\( P_0 \) denotes the ground state. The first polyad \( P_1 \) is also known as the dyad, as it contains the two vibrational levels (0, 1, 0, 0) and (0, 0, 0, 1). The \( P_2 \) polyad (or pentad) contains five vibrational levels (1, 0, 0, 0), (0, 2, 0, 0), (0, 0, 1, 0), (0, 0, 0, 2) and (0, 1, 0, 1). Similarly, \( P_3 \) is the octad (eight levels) and \( P_4 \) is the tetradecad (14 levels). The number of levels grows rapidly for higher polyad numbers and this results in complex systems of interacting bands, which are increasingly difficult to model as the polyad number grows.

A significant recent development is a new global analysis of the methane spectrum over the wavenumber range 0–4800 cm⁻¹ (levels up to the octad) reported by Albert et al. (2009). The new model fits line positions and intensities much better than previous analyses of individual polyads (e.g. Hilico et al. 2001). The new model forms the basis of an improved set of methane line parameters included in the 2008 edition of the HITRAN database (Rothman et al. 2009). It provides a good model of the low-temperature methane spectrum for wavelengths greater than about 2.1 μm.

However, at shorter wavelengths (higher polyads) HITRAN 2008 lists mostly empirical line parameters from Brown (2005). These...
are measured line intensities and positions at room temperature, and mostly lack quantum identifications and lower-state energies. The lack of a lower-state energy means that line intensities cannot be reliably determined for temperatures other than those of the original measurement. These lines are therefore not useful for modelling the spectra of the giant planets. However, some lines in the strongest part of the $P_2$ band system have empirically determined lower state energies derived from measuring the lines at two or more different temperatures. These lines, with data from Margolis (1990) and Gao, Kassi & Campargue (2009), cover the wavenumber range from 5500 to 6180 cm$^{-1}$.

For this work, we therefore constructed a methane line list as follows. We used line data from HITRAN 2008 for all wavenumbers up to 4800 cm$^{-1}$. We also used HITRAN 2008 for the region from 5500 to 5550 cm$^{-1}$, where empirical lower state energies are available. For the wavenumber range from 4700 to 5500 cm$^{-1}$, we used line parameters calculated using the Spherical Top Data System (STDS; Wenger & Champion 1998). This range overlaps slightly with the range from HITRAN, but the lines from HITRAN are all in the $P_2$ polyyad system in this region, whereas the STDS lines are all from the $P_1$ polyyad, so there is no duplication. While the STDS effective Hamiltonian model for the tetradecad region is a preliminary one and does not give line positions that accurately match data, it does provide an adequate description of the overall band shape. Also, it provides the lower state energies that are missing from HITRAN in these regions. For the range 5550–6236 cm$^{-1}$, we used line data from Nikitin et al. (2010) supplemented with low-temperature empirical data from Wang et al. (2010). We have not attempted to model wavelengths shorter than 1.6 μm. However, new empirical methane line data for these wavelength regions are starting to become available (Sciama-O’Brien et al. 2009; Campargue et al. 2010a,b), which may enable our modelling to be extended to shorter wavelengths.

The linewidth data provided in HITRAN are for broadening in air. Data on broadening of methane lines in the $v_3$ band in a variety of broadening gases by Pine (1992) and Pine & Gabard (2003) show that linewidths broadened by H$_2$ are about 2 per cent higher than those broadened by N$_2$; those in O$_2$ are about 6 per cent less, and those in He are about 35 per cent lower. This suggests that linewidths in an H$_2$/He atmosphere should be very similar to those in an N$_2$/O$_2$ atmosphere. We have therefore used the air broadening data from HITRAN to determine the linewidths in this work. Where the line data are taken from sources without broadening parameters, we have used the default line half-width value of $\gamma = 0.06$ cm$^{-1}$ atm$^{-1}$ and a temperature exponent $N = 0.85$ as recommended by Nikitin et al. (2010).

### 3.3 Scattering

In our model, we have considered Rayleigh scattering from molecules and particle scattering from aerosols suspended in the atmosphere. The Rayleigh scattering at wavelengths above 1 μm is much reduced in comparison with scattering from clouds. The Rayleigh cross-sections (Liou 2002) were calculated for scattering in a mixture of H$_2$ and He, the dominant components of the atmosphere.

The vertical structure of aerosols in Jupiter’s atmosphere, derived directly from Galileo observations, was surprisingly different from theoretical predictions (Atreya et al. 1997), which can be attributed to the unique region of the probe entry. The Galileo Solid State Imager (SSI) observations covered more extended regions over belts and zones, as described in Banfield et al. (1998). The SSI images taken close to the limb of Jupiter gave good information about the cloud opacity in the stratosphere.

Banfield et al. (1998) used a retrieval technique (Banfield et al. 1996) to obtain the scatterer density with altitude in the same spectral region as our observations. The upper troposphere, between 700 and 100 mbar, and the stratosphere, at pressures lower than 100 mbar, defined by Banfield et al., are within the spectral sensitivity of the $H$ and $K$ bands. The results of the Banfield et al. retrieval of particle distribution from the Galileo imaging suggest two enhancements in cloud opacity corresponding to the upper...
haze between 200 and 20 mbar, and at the base of the tropospheric condensation cloud at about 850 mbar. In equatorial regions, the upper haze is elevated to even lower pressures.

The layer of smaller particles is believed to form a relatively uniform top of the tropospheric cloud, which contains larger particles of presumably NH₄ ice and other condensates. Observations of limb darkening in the ultraviolet (Tomasko, Karkoschka & Martinek 1986) constrain the size of the stratospheric haze to between 0.2 and 0.5 μm. To model the clouds, we chose a simple two-component distribution of mean particle sizes, 0.3 μm for the stratosphere and the conservative value of 1.3 μm size species for the upper tropospheric cloud. The combined observations from NIMS and NIR identify the lower tropospheric cloud as a mixture of two types of particles with sizes of 50 and 0.45 μm, consistent with the NH₄SH molecule (Irwin 1999). The upper troposphere, which our data is sensitive to, is believed to consist of 0.75 μm sized ammonia particles.

The scattering properties of these clouds are calculated using Lorentz–Mie theory for a power-law particle size distribution. The code calculates the asymmetry factor, extinction and scattering coefficient, which are required in the radiative transfer calculations. The refractive index of the cloud particles is approximated by the refractive index of ammonia ice given by Martonchik, Orton & Appleby (1984) for a wide range of wavelengths.

In our model, the vertical structure of the particle clouds is varied through the input list of optical depths for each layer of the atmosphere at the reference wavelength of 1.5 μm. Finally, the boundary conditions for the model are given. Solar illumination at a given beam angle is provided using data from Kurucz (2009) and a non-reflecting surface is specified at the base of the atmosphere. The set of line data, particle properties and their distribution form inputs for the DISORT radiation transfer equation solver, which returns the fluxes and radiances at the top of the atmosphere for each wavelength specified in the grid. The models were calculated at a spectral resolution of 0.01 cm⁻¹, sufficient to resolve the spectral structure, and then convolved with an instrumental point spread function for comparison with the observed spectra.

4 MODEL OF THE BANDS IN THE ATMOSPHERE OF JUPITER

To show the functionality of the vstar code, we used the most recent observational data described in the previous section, which provided the input parameters for characterization of Jupiter’s atmosphere. We tested the sensitivity of our models to changes in these parameters and we confirmed that spectral features are dominated by methane absorption with the addition of clouds above the 800-mbar level.

A simple model of the longitudinal belts and zones in the atmosphere of Jupiter was derived by manually varying the amount and vertical distribution of cloud opacity at different heights, while the chemical composition of the atmosphere was left constant across the surface of the planet. As this is clearly not practical to explore the full range of opacities at all levels of the atmosphere, we resorted to testing different combinations of opacities in an iterative way. We fine-tuned these until a reasonable fit, with the smallest scatter in residual differences, between spectra and models was achieved for both spectral bands H and K.

Fig. 5 shows the line-by-line models for the selected bands and zones with a resolution that matches the observed spectra. Our models mirror most spectral features remarkably accurately, considering that the average spectrum is a composite of subregions with possibly non-uniform cloud composition, as evident in high-resolution images from the Galileo SSI probes (Simon-Miller et al. 2001). We found that the most significant differences between the models and the data occurred in the equatorial zones, in spectral regions that correspond to the upper layers of the troposphere.

The most recognizable features of the K-band spectrum are the H₂–H₄ collision-induced broad absorption centred at 2.11 μm and stronger absorption in the 2.2–2.4 μm region, as a result of methane bands. The narrower CH₄ absorption features are a result of the Q branches (ΔJ = 0) of ν₂ + ν₃ at 2.2 μm, ν₁ + ν₄ at 2.32 μm and ν₁ + ν₄ at 2.37 μm. The latter two bands are not always clearly visible in the observed spectra because of low signal-to-noise in the high methane absorption region and a decreased sensitivity at the edge of the K-band filter.

Spectra of the polar regions show the broad methane, and H₂–H₄ collision-induced absorption much reduced, compared with the
equatorial zones and belts. This can be understood by noting that the spectra of the polar regions sample relatively longer path-lengths through the higher layers of the atmosphere. Unlike the deep layers, the higher layers contribute little to the \( H_\text{2} - H_\text{2} \) absorption.

The models are constrained by a simultaneous fit of absorption levels for the broad- and narrow-band features of the spectra in both bands \( H \) and \( K \). The lower panel of Fig. 5 shows the spectra and models of the \( H \) band. The narrow spectral lines in the models tend to agree better with the observed spectrum than the broad shape and the intensity of absorption. We attribute this to the less accurate models of methane line parameters in this spectral region, as discussed in Section 3.1. The accuracy of the wavelength fit is limited mostly by the spectral calibration of the data, dominated by the correction of spectral curvature in the IRIS2 grism system. The wavelength of the clearly identified lines in the data and models agrees within \( 5 \times 10^{-4} \mu \text{m} \). Most discrepancies in models and observed spectra are a result of the differences in intensity of a particular line or line series in methane absorption.

The Jupiter \( K \)-band spectrum is defined by the opacities distributed between about 700 and 2 mbar. The shape of collision-induced \( H_\text{2} - H_\text{2} \) absorption, which samples the deep layers of the atmosphere, is highly sensitive to the cloud optical depth in Jupiter’s troposphere, while the level of broad methane absorption beyond 2.2 \( \mu \text{m} \) varies dramatically in response to changes in the stratospheric cloud optical depth. The \( H \)-band spectral region samples the higher levels of the troposphere.

Table 3 shows the total optical depths of the tropospheric (1.3-\( \mu \text{m} \) particles) and stratospheric aerosols (0.3-\( \mu \text{m} \) particles), which give the best fit for each spectrum. All zones and belts show differences in the vertical distribution and the strength of opacity. Most notably, the atmosphere appears to be relatively clear between 200 and 40 mbar in the northern and equatorial regions. This is consistent with conclusions in Banfield et al. (1998), who find a similar clearing around 100 mbar in their models in the same spectral region. We find that no trial models with added cloud opacity in this pressure range were able to reproduce the observed spectra.

We find that the clouds tend to lie deeper in belts than in zones. The tropospheric cloud seems to extend up to 250 mbar in the equatorial region, with the highest total opacity of the order of \( \tau = 5 \), while the stratospheric haze is very thin with opacities below \( \tau \sim 0.005 \). Our models suggest that this haze may be slightly thicker in the Southern hemisphere of the planet. However, the SEZ and SB regions are affected by the spectrum of Europa, while the spectrum of the Southern Zone (SZ) may reflect a local cloud pattern.

The image of Jupiter (Fig. 1) shows a large white spot in this region, which is subtended by a slit. The high-resolution images taken by the New Horizons LEISA imager at 1.53 and 1.88 \( \mu \text{m} \) in 2007 February\(^1\) show similar weather features in the region of the SZ and the Southern Upper Belt (SUB). This spot is most likely a storm system, such as the anticyclonic white oval modelled in Simon-Miller et al. (2001). They note that fresh material is upwelled in such high-pressure systems, which forms slightly higher clouds. Our model of the SZ white spot requires a relatively thick cloud at 100–251 mbar pressures with small-sized particles, such as used for the stratospheric layers, which provided a better fit to the observed spectra than any larger particles.

The zones clear of Europa light show higher stratospheric cloud opacities, which are distributed more thinly than clouds in nearby belts. The stratosphere in the high-latitude Northern Zone (NZ), the Northern Upper Belt (NUB), is more spread out, but is relatively thin compared with the equatorial regions. The stratosphere above the SUB is also vertically extended but, in contrast to the NUB, has higher opacity. Previous models (West, Strobel & Tomasko 1986; Simon-Miller, Banfield & Gierasch 2001) have suggested that downwelling of the haze in the belt regions could produce thinner cloud at high pressures. Our models show unambiguously increased opacity of high stratospheric layers in the polar regions, which is consistent with the previous studies of Jupiter’s atmosphere (Pryor & Hord 1991).

Fig. 6 presents the models of the remaining regions. The NZ and the SZ display a slightly different shape of collisional absorption. This suggests the existence of more compressed, optically thicker tropospheric cloud in the SZ than the cloud in the NZ. The SEZ and SB spectra (Fig. 7) show the additional opacity as a result of Europa’s spectrum dominated by fine-grained water ice (Carlson et al. 1996). The effects of this opacity are clearly visible in the spectral region beyond 2.15 \( \mu \text{m} \), which is sensitive to the highest atmospheric levels in our model.

### Table 3. Total cloud optical depths in zones and belts.

| Zones | 1.3 \( \mu \text{m} \) particles Extent (mb) | 0.3 \( \mu \text{m} \) particles Extent (mb) | \( \tau \) | \( \tau \) |
|-------|----------------------------------|----------------------------------|------|------|
| NP | 563–631 | 1.50 | 56–200 | 0.0100 |
| | | | 3–7 | 0.0030 |
| NUB | 316–562 | 0.52 | 125–200 | 0.0003 |
| | | | 25–40 | 0.0015 |
| | | | 7–9 | 0.0001 |
| NZ | 316–631 | 1.72 | 22–25 | 0.0010 |
| NEB | 355–751 | 5.70 | 25–35 | 0.0018 |
| EZ | 251–631 | 5.72 | 18–22 | 0.0023 |
| EB | 316–708 | 5.09 | 25–35 | 0.0070 |
| SEZ\(^a\) | 447–708 | 3.10 | 39–50 | 0.0720 |
| SB\(^a\) | 355–708 | 6.06 | 141–251 | 0.0188 |
| | | | 40–50 | 0.0090 |
| SZ\(^b\) | 446–631 | 2.25 | 100–355 | 0.2995 |
| | | | 25–35 | 0.0060 |
| | | | 3–5 | 0.0010 |
| SUB | 316–751 | 1.29 | 141–316 | 0.0024 |
| | | | 25–40 | 0.0080 |
| SB | 251–708 | 2.20 | 22–251 | 0.0038 |
| | | | 2–4 | 0.0012 |

\(^a\) The spectra affected by a contribution of light reflected by Europa, which boosts reflection in the otherwise most highly absorbing methane bands regions in the \( K \) and \( H \) bands. This additional reflection was not included in the modelling.

\(^b\) A spectrum of the atmospheric region with a bright, ‘white’ spot, which can be modelled as the relatively thick stratospheric cloud extending upwards to 100 mbar.

5 DISCUSSION

The line-by-line radiative transfer models for high-resolution spectra from currently available ground-based instruments serve as an important test of the consistency in our understanding of the composition and processes that govern planetary atmospheres.

We achieved a good fit to the data, assuming a relatively simple physical structure and chemical composition of Jupiter’s atmosphere, which was kept uniform across the whole surface of the

\(^1\) On-line images available from the NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute (http://photojournal.jpl.nasa.gov/catalog/PIA09251).
Figure 6. Observed spectra, models and the difference between them (on the linear intensity scale) are shown for the northern and southern, high-latitude zones (NZ and SZ) and belts (NUB and SUB). Although the spectra of the northern regions show typically stronger absorption visible in both the $\text{H}_2$–$\text{H}_2$ feature and the wavelength region above 2.2 $\mu$m, this differences can be explained in terms of ‘local’ weather effects, as discussed in Section 4.

The planet. The real atmosphere is certainly more complex. Lacking a detailed $P$–$T$ profile for each zone and belt, we used a single profile of the atmosphere for all regions based on radio occultation observations (Lindal 1992). This seems justified, despite small differences in the atmospheric profiles observed by the Voyager 1 IRIS (Conrath et al. 1981) and Cassini CIRS experiments (Simon-Miller et al. 2006) for different locations on the planet. It is argued that because horizontal differences in observed brightness temperature are small, the larger deviations in observed brightness temperature are probably a result of varied opacity in the clouds (West et al. 1986).

We have also used a relatively simple representation of the chemical composition of the atmosphere, despite the fact that the abundances of gases in different regions of the atmosphere may vary with height because of the evidently complex, planetary weather system. The upwelling in zones may cause the depletion of volatiles because of condensation and precipitation. In the downwell regions, the mixing ratios of such volatiles may be increased in deeper layers of the atmosphere. While methane is well mixed within the vertical region of our sensitivity, there have been zonal differences in the mixing ratio profiles of ammonia below 600 mbar, suggested by Sault et al. (2004). It turned out that our models were not sensitive to these differences because of the combined effect of the low NH$_3$ absorption in our spectral range and the decreased sensitivity of our models to layers below $\sim$700 mbar. We find that it is sufficient to consider only the major contributors to the spectral absorption at the $H$ and $K$ bands ($\text{H}_2$, He, CH$_4$, and NH$_3$) and to modify the opacities of aerosols at different heights. However, our systematically worse fits in the equatorial zones may reflect the unrecognized complexity in these regions, which is not described in sufficient detail by the initial parameters of our model, such as the $P$–$T$ profile and the mixing ratios of the chemical components.

The suggested constituents of clouds in the troposphere below 500 mbar are H$_2$O, NH$_4$SH and NH$_3$. Ammonia condensation occurs at the highest level at about 700 mbar at its saturation point. The actual condensation level can be lowered or lifted because of differences in the molar abundances of NH$_3$. West et al. (1986) suggested that the cloud needs to have a mixed composition of particles with sizes between 3 and 100 $\mu$m to explain the high opacity observed at 45 $\mu$m. The larger particles are concentrated at the base of the cloud at pressures below our sensitivity limit. Consistently, our models are most sensitive to changes in the particle sizes below 3 $\mu$m. We find that the tropospheric cloud in the belt regions occurs at typically higher pressures compared to zones, which could be interpreted as the result of a vigorous convective downwelling and upwelling process.

In contrast, the stable haze of $\sim$1-$\mu$m-sized particles, the mixture of ammonia ices and residual chromophores responsible for the colouration of the clouds, exists above the lower, convective troposphere. In warmer temperatures, there is no condensation expected, and consequently no cloud formation. The origin of the stratospheric haze is thought to be a result of photochemical processes.
This original picture of the layers above 700 mbar shown in West et al. (1986) was developed further by Banfield et al. (1998), whose model includes a clearing of the haze at about 100-mbar pressures. They explain it by the aerosol coagulation at this level of the stratosphere, which is the cause of the increased, gravitational fallout of heavy particles. We observe such a clearing in models of most of the northern zones and belts of the planet. Above the clearing, we find an optically thin haze of reflective particles with predominantly lower sizes than particles in the troposphere. This haze extends to low pressures of 2 mbar in the polar regions. The chemical composition of the stratospheric haze is still debated. It is also not clear if the polar haze observed at lower pressures has the same composition as the equatorial stratosphere.

6 SUMMARY

We have used the new, line-by-line, radiative transfer package, VS-TAR, to model the near-infrared spectra of Jupiter. The models were produced for regions with different absorption properties implied by varied cloud patterns in the atmosphere of the planet. With our improved database of methane absorption lines at low temperatures, we achieved a good fit to the spectra obtained with the Anglo-Australian Telescope IRIS2. We were able to reproduce conclusions suggested in previous studies about the atmospheric conditions at pressures below 1 bar, which probe the upper troposphere and stratosphere of the planet. We have shown that ground-based spectroscopy with large telescopes can significantly enhance the results achieved from space. With continued improvements in methane line parameters, we will be able to extend our model of the near-infrared spectrum of Jupiter and other giant planets, and to cover the full range of wavelengths between 1 and 2.5 μm with almost arbitrary resolution. This will make it possible to search for and measure weak spectral features resulting from trace constituents, which at present cannot be picked out of the forest of methane lines. These include, for example, absorption as a result of monodeuterated methane (CH₂D) with lines at ~1.55 μm, which can be used to measure the D/H ratio of the giant planets with much higher accuracy than has been possible so far.

The most appealing feature of the VS-TAR package is its versatility. Although slower than correlated-k techniques, it allows the spectral modelling of a wide range of objects, from cool brown dwarfs to cold planets and their moons. These models can be calculated at any required spectral resolution and can therefore be used in conjunction with data from instruments now available on large ground-based telescopes, which can provide near-infrared spectra at resolving powers as high as 100,000. With the ever increasing speed of computing devices, it may soon be practical to use line-by-line techniques, such as VS-TAR, to achieve best fits to the high-resolution spectra via automated retrieval schemes.

The methane line list used in this work (in HITRAN 2004 format) is available for download from http://www.phys.unsw.edu.au/~jbailey/ch4.html.

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