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H_2 vibrational temperatures in the upper atmosphere of Jupiter

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Abstract. The Jovian upper atmosphere has been extensively studied over the past few decades with many observations having been made. Typically, the H_2 vibrational temperatures have always been considered as kinetic temperatures in modelling efforts to date. However, recent studies have shown that this assumption is not robust and that we can expect enhanced vibrational temperatures due to overlapping lines to play an important role in the thermosphere of Jupiter. In this paper, we use a radiative transfer code to compute the total integrated H Lyman α dayglow intensity taking into account the overlapping with H_2 hot bands. We show that an atmosphere with H_2 vibrational temperatures equal to about 1.4 to 1.5 times kinetic reproduce the Voyager observations.

Key words. ultraviolet: solar system – radiative transfer – planets and satellites: individual: Jupiter

1. Introduction

The upper atmosphere of Jupiter has been studied in detail since the first spectroscopic observations by Voyager (Broadfoot et al. 1979; Sandel et al. 1979) and IUE (Clarke et al. 1980). The main ultraviolet thermospheric emissions are an intense anti-bulge H Lyman α dayglow of 12–13 kR, (under a solar Lyman α flux of 5.0×10^{11} ph cm^{-2} s^{-1} at 1 AU (Emerich et al. 1993)) and an H_2 dayglow due to the Lyman and Werner systems (Feldman et al. 1993). The coincidence between the H-Lyman series and H_2 Lyman and Werner systems makes the interpretation of the observed dayglow more complicated.

For example, the H Lyman beta line overlaps with the 6–0 P(1) line of the H_2 Lyman system with a wavelength difference of only 0.22 Å (Barthélemy et al. 2004). Also, spectroscopic studies (Abgrall et al. 1993) show that the H_2 Lyman system has several lines of hot bands that are overlapping with H Lyman α, most notably, the 1–2 R(6) and 1–2 P(5) transition. These coincidences have been observed in Herbig – Haro objects such as HH47 (Curiel et al. 1995). The energy of the vibrational level $v = 2$ is very high: $E = 8086$ cm^{-1} which corresponds to a temperature of about 12 000 K. If vibrational temperatures are equal to kinetic ones, the population of this level remains quite negligible. However, the densities and temperatures that exist in the upper atmosphere of Jupiter make Local Thermodynamic Equilibrium (LTE) impossible to maintain. Parkinson (2002) suggest that vibrational temperatures are larger than kinetic temperatures by a factor 1 to 4. The effect would be then to populate the $v = 1$ or $v = 2$ vibrational levels of the $X^1\Sigma_g^+$ electronic state. Wolven et al. (1997) have measured a fluorescence induced by the solar Lyman alpha line of about 100 R before the Shoemaker-Levy 9 impact. This is the only observation available and one of our aims in this work is to check whether this is consistent with the assumption of an enhanced vibrational temperature.

We have applied a resonance scattering model to the coupled line problem that uses the Feautrier technique to solve the coupled equations of radiative transfer assuming partial frequency redistribution which takes into account the overlapping lines. This model allows us to discriminate between the column density of the atomic and molecular hydrogen and giving information on their kinetic temperatures. We only consider equatorial regions.

2. Method

The Feautrier method is based on the work by Gladstone (1983). It has been upgraded by Gladstone (1988) to study other lines including Lyman beta. This method was used by Vervack et al. (1995) to study the He 584 Å line and model Voyager observations. Griffoen (2000) and Parkinson (2002) utilised the technique to include the case of several overlapping lines. Their code has recently been employed to describe the jovian Lyman beta emission line (Barthélemy et al. 2004). The formalism is based on the 1-D radiative transfer equation

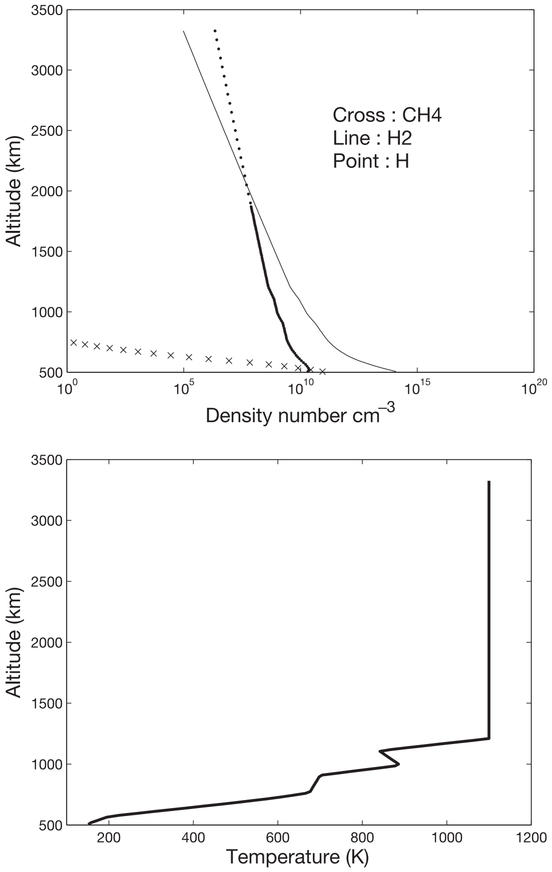

Fig. 1. Jovian atmospheric model. *Upper panel*: composition. *Lower panel*: temperature.

considering the frequency redistribution and is described in detail by Mihalas (1978), Gladstone (1983), Cannon (1985) and Griffioen (2000).

We assume a neutral atmosphere (Parkinson 2002) with three main species, viz., H, H_2, and CH_4. At low altitudes (between 500 km and 2000 km above the 1-bar level) molecular hydrogen dominates, whereas at higher altitudes, the atomic hydrogen becomes more abundant due to H_2 photodissociation. The scattering region (i.e. the region where the absorption optical depth in CH_4 for some of the hydrogen emissions we are considering is less than unity) generally lies above 500 km and so the absorbing layer of CH_4 is included. The exospheric temperature from Galileo probe measurements is equal to 1100 K. The profile is based on the deceleration measurements of the same probe (Seiff et al. 1997) (Fig. 1).

We also assume a quiet solar activity where the solar input flux is modelled with a double Gaussian having an intensity 5.0×10^{11} ph cm^{-2} s^{-1} at 1 AU. The line width and the offset from the line centre of each peak are respectively $x_w = 12.5$ sdu and $x_{\rm off} = 14.5$ sdu (standard doppler unit, $x = (\nu - \nu_0)/\Delta\nu_d$). Our spectroscopic parameters for the atomic hydrogen Lyman beta line and the molecular hydrogen line are summarised in Table 1 and are taken from Gladstone (1988) and Abgrall et al. (1993), respectively.

In the case of Lyman α, we only have information on the polulation of the $v = 2$ level. To calculate the vibrationnal temperatures, we have made the assumption that the population of each level follows a maxwellian law with a vibrational temperature different from the other temperatures.

Table 1. Spectroscopic parameters.

Line	λ (Å)	E (g level)	f	A (s^{-1})	ϖ
H Ly α	1215.69	0 cm^{-1}	0.416	6.26×10^8	1
H_2R(6)1–2	1215.73	6516 cm^{-1}	0.035	0.14×10^9	0.089
H_2P(5) 1–2	1216.07	5848 cm^{-1}	0.029	0.16×10^9	0.083

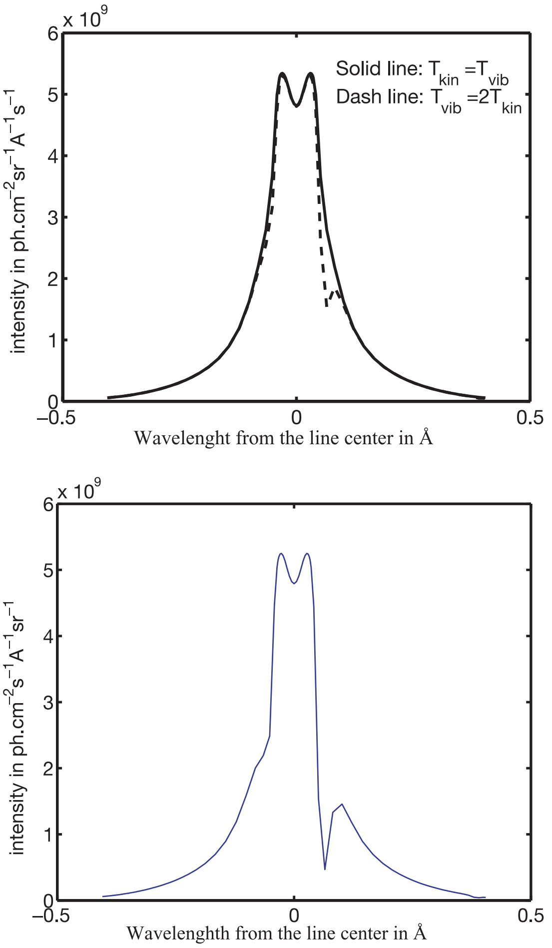

Fig. 2. Lyman alpha line profile with vibrational temperatures 1, 2 (*upper panel*) or 4 (*lower panel*) times higher than kinetic temperatures.

$$N(v, z) = N_0(z) \frac{\exp(-E_v/kT_{\rm vib})}{\sum_v \exp(-E_v/kT_{\rm vib})}. \qquad (1)$$

This assumption means we consider in a first approximation that there is no mechanism that overpopulate one level.

Owing to a lack of altitudinally dependent temperature profile information, we consider a mean vibrational temperature over all the entire altitude range.

3. Results

We first consider the case with equal kinetic and vibrational temperatures.

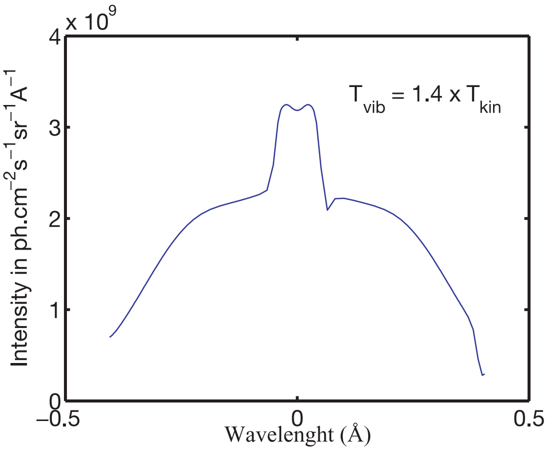

Fig. 3. Lyman alpha line profile with vibrational temperature 1.4 higher than kinetic temperature. We note the little absorption dip on the red side of the line.

In graphs shown in Fig. 2, the 1215.69 Å wavelength has been normalised to be centred on 0. The H Lyman α integrated intensity is 12.80 kR at the centre of the disc, which is consistent with Voyager observations (Emerich et al. 1993). As expected, the profile we obtain is consistent with previous calculations by Gladstone (1983) and Griffioen (2000).

We now introduce vibrational temperatures that vary from 1 to 4 times the assumed kinetic value. The effect on the profile is also shown in Fig. 2: on the red side, an absorption occurs which decreases the profile to about 10^9 photons cm^{-2} sr^{-1} s^{-1} Å^{-1} when the vibrational temperatures equals to 4 times the kinetic temperature. The total intensity at the centre of the disk is respectively 12.80 kR, 12.08 kR, 11.14 kR and 10.85 kR for multiplication factors of 1, 2, 3 and 4. We consider that the difference between results gives us the intensity lost by fluorescence. In performing this calculation, we consider there is no radiative transfer effect on the fluorescence lines. Wolven et al. (1997) have measured a fluorescence induced by the solar Lyman alpha line of about 100 R before the Shoemaker–Levy 9 impact. The multiplication factor that reproduces this difference in the Lyman α dayglow is between 1.4 and 1.5. The corresponding intensities are respectively 12.72 kR and 12.66 kR. It is not necessary to obtain a better precision in the calculation since we apply a constant factor at all altitudes. The important point to note from using this approach is there is already a difference between the vibrational temperature and the kinetic temperature although the atmospheric temperatures are not as high as in extreme case seen in the HH 47 object. The line profile does not show any significant change at the centre of the disk. However, at the limb, the 1.4 factor introduces a slight decrease of the red side of the line profile (cf. Fig. 3).

4. Conclusion

In most previous studies, the vibrational temperature profile of hydrogen has always been considered equal to kinetic values because the overall temperature is relatively small (the exospheric temperature is about 1100 K). However, the Wolven et al. (1997) observations at the time of the SL 9 impact challenge the veracity of this assumption. Through a radiative transfer approach, we have shown that these observations are consistent with vibrational temperatures equal to about 1.4 to 1.5 times the kinetic temperatures. The excitation mechanisms remain to be explained. In the near future, coupling the radiative transfer approach with a particle collision methodology will help to ameliorate this problem. More precise correction factors for the vibrational temperature will also be obtained by comparing the computed line profiles with STIS and FUSE observations.

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