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On the feasibility of characterizing jovian auroral electrons via H_3^+ infrared line-emission analysis

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ABSTRACT

Here we investigate the feasibility of characterizing the jovian auroral electron energy and flux via H_3^+ infrared (IR) emission line analysis. Ground based telescopes can monitor jovian infrared auroral activities continuously for an extended time interval compared to the more restricted temporal coverage of ultraviolet (UV) observations. Since the departure from local thermodynamic equilibrium (LTE) varies with vibrational levels and altitude, measurements of the relative emission line intensities reveal the altitude of emission and hence the electron energy. The combination of three H_3^+ line-intensity ratios is required to determine the electron energy and the background temperature. The feasibility issue is evaluated by studying how the observational error propagates into the error of the estimated electron energy. We have found several best sets of H_3^+ lines from which the intensity-ratios can be utilized for the present purpose. Using these lines in the observed 2- and 4- micron wavelength ranges, we can estimate the electron energy and the background temperature within errors of a factor of ~3.5% and 3%, respectively, if the observation error is 1%. Since saturnian H_3^+ emissions vary far more substantially according to temperature variations, the method described here is not applicable to observations of Saturn.

1. Introduction

Planetary aurorae are observed at various wavelengths according to the energy relaxation of atmospheric particles following impact by energetic auroral electrons. Infrared (IR) emission from H_3^+, H_2, CH_4, C_2H_4, C_2H_6, and C_2H_2 has been identified in the jovian aurora so far (e.g., A'Hearn and Livengood, 1998; Bhardwaj and Gladstone, 2000). IR light is emitted from thermally excited ions and molecules when they transition between vibrational and rotational states, thus the emitted IR intensity reflects the atmospheric temperature. The enhancement of H_3^+ in the high-latitude atmosphere (e.g., Miller et al., 1997; Satoh and Connerney, 1999) is mainly produced by incident auroral electrons through ion chemistry (e.g., Tao et al., 2009). Because of this close relationship of H_3^+ production with the auroral electrons of our interest, we focus on H_3^+ IR lines in this study. This H_3^+ IR emission is considered to come from above the methane homopause because dissociative recombination by hydrocarbons is a dominant H_3^+ loss process, and the low temperature at low altitudes decreases the infrared emission intensity. Spatially resolved H_3^+ IR spectra are observable from ground telescopes which enable long-term monitoring.

Previous studies have related the observed H_3^+ IR emission to H_3^+ column density and atmospheric temperature. For Jupiter, Lam et al. (1997) utilized 4 μm spectra observed by the United Kingdom Infrared Telescope (UKIRT, spectral resolving power $\lambda/\Delta\lambda \sim 1200$) to estimate the global temperature to vary over the range 700–1000 K and the auroral H_3^+ column density to be of order 10^{12} cm^{-2}. Stallard et al. (2001) obtained temporal and spatial variations of temperature across the range 900–1250 K from the intensity ratio of 4 μm $Q(1,0)$ and $R(3,4)$ emission lines observed by the Infrared Telescope Facility (IRTF, $\lambda/\Delta\lambda \sim 40{,}000$). Raynaud et al. (2004) estimated an H_3^+ rotational temperature of 1170 ± 75 K and a column density of $(4–8)\times10^{10}$ cm^{-2} using 2 μm spectra observed by the Canada–France–Hawaii telescope ($\lambda/\Delta\lambda \sim 25{,}000$). Lystrup et al. (2008) found that the exospheric temperature reached 1450 K based on 4 μm limb observations by the Keck II telescope ($\lambda/\Delta\lambda \sim 37{,}500$). The differences in the temperatures and column densities obtained are likely to be caused by temporal and spatial variations. The errors in estimating the temperature and column density for the above observations are 10–18% and −50% to +150%, respectively. For Saturn, Melin et al. (2007) estimated the temperature and column density to be (380–420) ± 70 K and $(1.9 \pm 0.2–7.3 \pm 0.7) \times 10^{12}$ cm^{-2}, respectively, from 4 μm UKIRT spectra ($\lambda/\Delta\lambda \sim 5570–18{,}500$).

The incident auroral electron energy has been mainly estimated from UV auroral emission by the following three methods: (1) the UV color ratio, defined as the ratio of the intensity of a waveband

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unabsorbed by hydrocarbons to that of an absorbed waveband. Since the hydrocarbons exist at low altitudes, which can be reached by higher energy electrons, the color ratio increases with increasing electron energy (e.g., Livengood et al., 1990; Harris et al., 1996; Gérard et al., 2002, 2003; Gustin et al., 2004). (2) Fitting of UV spectra to determine the absorption by H_2, where the H_2 column density is related to the auroral electron energy (e.g., Wolven and Feldman, 1998; Gustin et al., 2009). (3) Comparing UV altitude profiles from limb observations with model profiles for various electron energy cases (e.g., Gérard et al., 2009).

Using the color ratio method (1), the electron energy is estimated to be 30–200 keV in the jovian main aurora, e.g., from observations by the Hubble Space Telescope (HST) (Gérard et al., 2003; Gustin et al., 2004). For Saturn, implementation of methods (1) and (2) using spectra obtained by Far Ultraviolet Spectroscopic Explorer indicate the electron energy to be 10–15 keV (Gustin et al., 2009). Using the limb observation method (3) with HST observations, Gérard et al. (2009) suggested an electron energy of 5–30 keV.

The departure of H_3^+ vibrational populations from local thermal equilibrium (LTE) is important for H_3^+ IR emission, especially in the case of Jupiter at high altitude where reduced H_2 density leads to a reduction in collisionally excited H_3^+. Melin et al. (2005) showed that the non-LTE effects become significant in Jupiter at altitudes >1500 km, and vary with vibrational levels, i.e., emission lines. Because the H_2 density, and thus the departure from LTE, varies with altitude, measurement of the non-LTE effects on emission line intensities can be used to determine the emission altitude and hence the incident electron energy.

This study newly attempts to test the feasibility of monitoring not only the atmospheric conditions (temperature, H_3^+ column density, and ion velocity) as in previous studies but also the auroral electron energy and flux using H_3^+ IR emission lines. The auroral electron energy flux determines the energy deposition and ion–neutral interactions in the upper atmosphere by modifying the ionospheric conductance profile. Since IR wavelengths are observable from the ground with some spatial information, they can be used to monitor the plasma environment variability. The structure of the paper is as follows. Section 2 introduces the H_3^+ IR emission model and estimation method used in this study. We show examples of H_3^+ emission line ratios providing the auroral electron energy and atmospheric temperature for Jupiter (Section 3) and Saturn (Section 4). We investigate the best combination of H_3^+ lines for estimating the electron energy among those detected from ground-based observations by Raynaud et al. (2004) and Lystrup et al. (2008) in Section 5. The applicability to observations is discussed in Section 6. Section 7 concludes this study.

2. Model and approach

We use the auroral emission model for the hydrogen-dominant outer planets described by Tao et al. (2011). We estimate the H_3^+ IR emission intensity accounting for atmospheric ionization by solar extreme ultraviolet radiation and auroral electrons, ion chemistry, and the non-LTE vibrational distribution of H_3^+. We focus on the steady state output, i.e., when equilibrium is achieved between H_3^+ creation and dissociation, and between excitation and de-excitation (Tao et al., 2011). The outline of the model is introduced here.

We assume a temperature profile based on observations by Grodent et al. (2001) for Jupiter and Gérard et al. (2009) for Saturn. Chemical mixing ratios follow detailed chemical models by Gladstone et al. (1996) and Perry et al. (1999) for Jupiter, and Moses et al. (2000), Moses and Bass (2000), and Moore et al. (2009) for Saturn. Ionization profiles caused by auroral electrons are obtained from Monte Carlo simulation results by Hiraki and Tao (2008). We solve neutral–ion chemical reactions for 13 ions (H^+, H_2^+, H_3^+, H_2O^+, H_3O^+, CH_3^+, CH_4^+, CH_5^+, $C_2H_2^+$, $C_2H_3^+$, $C_2H_5^+$, $C_3H_n^+$, $C_4H_n^+$, where the latter two symbols represent classes of ions) and six fixed neutral species (H_2, H, CH_4, C_2H_2, C_2H_4, H_2O). We estimate the non-LTE populations of the H_3^+ vibrational states resulting from excitation and de-excitation by collisions with H_2 and de-excitation by IR emission. The LTE fraction at an altitude, z, is the ratio of the number density of a particular ro-vibrational state determined by including non-LTE effects to the density determined in LTE, i.e., $\eta(z) = n_{H_3^+,\mathrm{nonLTE}}/n_{H_3^+,\mathrm{LTE}}$. Then H_3^+ IR intensity is estimated as follows:

$$I_{IR}(\omega_{if}, z) = N_{H_3^+}\eta(z)g(2J+1)hc\omega_{if}A_{if}\exp(-E_i/k_BT)/Q(T), \quad (1)$$

where I_{IR} is the emission intensity; ω_{if} is the wavenumber; g is the nuclear spin weight; J is the rotational quantum number of the upper level of transition; h is the Planck constant; c is the light velocity; A_{if} is the Einstein coefficient; E_i is the energy of the upper level of the transition; k_B is the Boltzmann constant; $Q = \sum_i (2J+1)g_i \exp(-E_i/k_BT)$ is the partition function (Neale and Tennyson, 1995).

Tao et al. (2011) described results using only the fundamental $Q(1,0)$ emission line, whereas this study considers the main H_3^+ lines in the 4 μm (Lystrup et al., 2008) and 2 μm bands (Raynaud et al., 2004) detected by the ground-based observations, as listed in Table 1. The auroral electrons are assumed to form a Maxwellian distribution with variable mean energy. The electron energy ε quoted hereafter is the characteristic energy of the Maxwellian distribution, which is equal to half the mean energy of the distribution, and the electron temperature is ε/k_B. The choice of a particular mathematical form is a convenience to assess the physical processes. This is a first step toward the main focus: distinguishing the effects of auroral electron energy from the atmospheric temperature. For simplicity, the atmosphere temperature is kept constant through the modeled processes. We assume auroral electrons precipitate into the atmosphere vertically for simplicity, which means that the electron energies derived in this study represent a lower limit. We set various exospheric temperatures T_{ex} with the same altitude profile.

We deduce the auroral electron energy, flux, and exospheric temperature from the modeled H_3^+ emission lines as follows: (1) Electron energy and exospheric temperature are obtained from three emission line intensity ratios. Then (2) the absolute intensity values of the lines are used to estimate the electron flux. Since process (2) is directly determined once the electron energy and temperature are fixed, here we focus on process (1), i.e., how we distinguish the electron energy and temperature. Next we show an example of this estimation.

3. Jupiter 4 μm emission lines

3.1. Results

Fig. 1 presents one example of the H_3^+ spectral lines we estimated in our model in the 4 μm (Fig. 1a) and 2 μm (Fig. 1b) wavelength ranges for T_{ex} = 1200 K, ε = 10 keV, and an electron number flux of 0.15 μA m^{-2}, equivalent to 9.4×10^{11} m^{-2} s^{-1}. Fig. 2 shows the intensities of the fundamental (Fig. 2a) and hotband (Fig. 2b) lines taken from Fig. 1a as functions of auroral electron energy and exospheric temperature. The electron number flux is set to be 0.15 μA m^{-2}, within the range of observed flux 0.04–0.4 μA m^{-2} at the main auroral oval (Gustin et al., 2004). The peak altitudes of the ionization by ε = 0.1, 1, 10, and 100 keV electrons are 1740, 1146, 635, and 277 km, respectively (Tao et al., 2011). The intensities have a local maximum at $\varepsilon \sim 10$ keV. The electron energy