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Production of N_2 Vegard–Kaplan and Lyman–Birge–Hopfield emissions on Pluto

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ABSTRACT

We have developed a model to calculate the emission intensities of various vibrational transitions of N_2 triplet band and Lyman–Birge–Hopfield (LBH) band emissions in the dayglow of Pluto for solar minimum, moderate, and maximum conditions. The calculated overhead intensities of Vegard–Kaplan ($A^3\Sigma_u^+$–$X^1\Sigma_g^+$), First Positive ($B^3\Pi_g$–$A^3\Sigma_u^+$), Second Positive ($C^3\Pi_u$–$B^3\Pi_g$), Wu–Benesch ($W^3\Delta_u$–$B^3\Pi_g$), Reverse First Positive, and LBH ($a^1\Pi_g$–$X^1\Sigma_g^+$) bands of N_2 are 17 (74), 14.8 (64), 2.4 (10.8), 2.9 (12.7), 2.9 (12.5), and 2.3 (10) R, respectively, for solar minimum (maximum) condition. We have predicted the overhead and limb intensities of VK (150–190 nm) and LBH (120–190 nm) bands of N_2 on Pluto for the New Horizons (NH) flyby condition that can be observed by ALICE: the ultraviolet imaging spectrograph also know as P-ALICE. The predicted limb intensities of VK and LBH bands peak at radial distance of ~2000 km with the value of about 5 (13) and 9.5 (22) R for solar zenith angle 60° (0°), respectively. We have also calculated overhead and limb intensities of few prominent transition of CO Fourth Positive bands for NH flyby condition.

1. Introduction

The atmosphere of Pluto is believed to be hydrodynamically escaping and extending to heights comparable to its radius (Krasnopolsky and Cruikshank, 1999; Strobel, 2008). Most of the information about the atmosphere of Pluto have come from the ground based occultation observations (Elliot et al., 2007; Young et al., 2008). Schindhelm et al. (2015) have provided a brief review of ultraviolet spectra observed from Pluto–Charon system by IUE. The data from these occultation observations are used to understand Pluto's atmosphere and are instrumental in the recent developments of general circulation models (Zalucha and Gulbis, 2012). Occultation studies have also shown that Pluto's atmosphere has undergone a surface pressure expansion by a factor of 2 from 1988 to 2002, followed by a stabilization from 2002 to 2007 (Elliot et al., 2007; Young et al., 2008). The atmosphere of Pluto is similar to the Saturn's largest moon Titan: dominated by the N_2 (97–99%), followed by CH_4 (3–1%), and a trace amount of CO. Titan's extreme ultraviolet (EUV) dayglow spectra is dominated by N_2 Carroll–Yoshino (CY) Rydberg bands, while far ultraviolet (FUV) spectra is dominated by N_2 Lyman–Birge–Hopfield (LBH) and Vegard–Kaplan (VK) bands, and N and N^+ lines (Ajello et al., 2008; Stevens et al., 2011). Pluto's dayglow spectrum is expected to be similar to that of Titan. Summers et al. (1997) have estimated the overhead emission intensities of possible airglow features in the atmosphere of Pluto, and calculated vertical column rates of various emission of N_2 and N, and N^+ in airglow of Pluto.

New Horizons (NH) flyby of Pluto in July 2015 will be the first visit of a man made object to Pluto. NH is carrying a host of instruments to understand the atmosphere and surface properties of Pluto. One of the instruments, ALICE: an ultraviolet imaging spectrograph (Pluto-ALICE or P-ALICE), is aimed at observing Pluto at EUV and FUV wavelength regions, and might observe various emissions from N_2 and its dissociated products mentioned above. We have developed the N_2 triplet band emission model for atmospheres of Mars, Venus, and Titan (Jain and Bhardwaj, 2011; Bhardwaj and Jain, 2012a,b). In the present study, we have extended the N_2 triplet band emission model to Pluto, and have added the calculation of LBH (singlet) band emissions. We have made calculations for solar minimum, moderate, and maximum conditions as well as for the New Horizons flyby conditions. These model calculations will help in making observations of Pluto's airglow by P-ALICE. In this study, we give volume emission rate and limb intensity of N_2 VK and LBH in the wavelength region 120–190 nm region, which lies in spectral range of P-ALICE

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(Stern et al., 2008). For the N_2 VK band major focus is given to transitions that lie between 150 and 190 nm region because emissions in wavelength region 120–150 nm constitute less than 1% of N_2 VK emission in wavelength region 120–190 nm (Jain and Bhardwaj, 2011; Bhardwaj and Jain, 2012a,b). We have also reported limb and overhead intensities for CO Fourth Positive bands.

2. Model

Model atmosphere of Pluto for solar minimum, moderate, and maximum conditions, and for NH arrival condition is taken from Strobel (2008). The mixing ratios of N_2, CH_4, and CO is taken as 0.97, 0.03, and 0.00046, respectively (Strobel, 2008). The mean Sun–Pluto distance is taken as 30 AU for solar minimum, moderate, and maximum conditions, and 33.4 AU for the NH arrival time prediction.

We have used the solar irradiance measured at Earth (between 2.5 and 120.5 nm) by Solar EUV Experiment (SEE, Version 10.2) (Woods et al., 2005; Lean et al., 2011) for solar minimum (F10.7 = 68), moderate (F10.7 = 150), and maximum (F10.7 = 250) conditions at 1 nm spectral resolution. For the NH flyby prediction (July 2015), the SEE solar flux is taken as on 1 May 2011, for which F10.7 = 106; the F10.7 solar flux index value is based on the solar cycle prediction made by Hathaway et al. (1994) (http://solarscience.msfc.nasa.gov/predict.shtml). The solar flux is scaled to the Sun–Pluto distance of 30 AU for solar minimum, moderate, and maximum conditions, and 33.4 AU for NH flyby predicted intensity calculations. The solar zenith angle (SZA) is taken as 60° unless otherwise mentioned in the text. All distances mentioned are radial distances measured from the center of the planet.

The limb intensity of various airglow emissions is calculated as

$$I = \int \left[n_l(Z) \int_{E_{th}}^{E} \left(\int_{W_{kl}}^{100} \frac{Q(Z,E)U(E,E_0)}{\sum_l n_l(Z)\sigma_{lT}(E)} dE_0 \right) \sigma_{il}(E) dE \right] dr, \quad (1)$$

where $n_l(Z)$ is the density of the lth gas at altitude Z, $\sigma_{lT}(E)$ is the total inelastic cross section for the lth gas, $\sigma_{il}(E)$ is the electron impact cross section for the ith state of the lth gas, for which the threshold is E_{th}, $Q(Z, E)$ is the photoelectron production rate at altitude Z, W_{kl} is minimum excitation energy for k excited state of lth gas, r is abscissa along the horizontal line of sight, and $U(E, E_0)$ is the two-dimensional Analytical Yield Spectra (AYS), which embodies the non-spatial information of degradation process. It represents the equilibrium number of photoelectrons per unit energy at an energy E resulting from the local energy degradation of an incident electron of energy E_0 (Bhardwaj et al., 1990, 1996; Bhardwaj, 2003; Bhardwaj and Michael, 1999; Bhardwaj and Jain, 2009). While calculating the line of sight intensities of various LBH transition, we have taken absorption by N_2 and CH_4 into consideration, because below 140 nm, absorption by atmospheric gases can significantly affect the calculated limb intensities.

Electron impact excitation following XUV photoionization is the major source of N_2 triplet band emissions. The details of the model calculation of N_2 triplet band emissions is provided in our earlier studies on Mars (Jain and Bhardwaj, 2011), Venus (Bhardwaj and Jain, 2012a), and Titan (Bhardwaj and Jain, 2012b). In the present paper we have extended the model to include the N_2 LBH band emission calculation. Johnson et al. (2005) have reported the excitation cross section of $a^1\Pi_g$ state. Young et al. (2010) have measured emission cross section for the $a^1\Pi_g$ ($v' = 3$)–$X^1\Sigma_g^+$ ($v'' = 0$) and $a^1\Pi_g$ ($v' = 2$)–$X^1\Sigma_g^+$ ($v'' = 0$) transitions. The shape and magnitude of their relative emission cross section of $a(3,0)$ and $a(2,0)$ emission is consistent with the results of Johnson et al. (2005). Young et al. (2010) have not given emission cross section for entire LBH band system, though they suggested the emission cross section value of $6.3 \pm 1.1 \times 10^{-16}$ cm^2 at 100 eV. The electron impact excitation cross section of singlet (a^1, a'^1, w^1) states are taken from Johnson et al. (2005) and fitted analytically for ease of usage in the model (see Jain and Bhardwaj, 2011 and references therein). We have included radiative cascading between three lowest singlet states of N_2 ($a^1\Pi_g, a'\Sigma_u^-$, and $w^1\Delta_u$). For a state, vibrational levels which lie above $v = 6$ are not considered since these vibrational levels predissociated, and we have excluded the cascade contributions from a' and w states vibrational levels which lie above $v = 6$ of the a state (Eastes, 2000; Eastes et al., 2011). The radiative transition data for the $a' \leftrightarrow a, w \leftrightarrow a$, and $a \rightarrow X$ are taken from Gilmore et al. (1992). For the $a' \rightarrow X$ transition, lifetime of 17 ms is taken for all vibrational level (Eastes, 2000). The collisional quenching rates of a, a', w states are taken as described by Eastes (2000).

3. Results

The volume emission rates of vibrational transitions of various triplet and LBH bands of N_2 on Pluto are calculated for the three solar conditions. Fig. 1 shows the volume emission rates of N_2 VK (150–190 nm) and LBH (120–190 nm) bands for solar moderate condition at SZA = 60°. Total emission rates of N_2 VK and LBH bands are also shown in the figure. Emission rates of both VK (150–190 nm) and LBH (120–190 nm) bands peak at radial distance of about 2200 km, with a value of 0.02 and 0.06 cm^{-3} s^{-1}, respectively. Table 1 shows the total height-integrated overhead intensity for Vegard–Kaplan (VK) ($A \rightarrow X$), First Positive ($B \rightarrow A$), Second Positive ($C \rightarrow B$), Herman–Kaplan (HK) ($E \rightarrow A$), $E \rightarrow B$, Reverse First Positive ($A \rightarrow B$), $E \rightarrow C$, and Lyman–Birge–Hopfield ($a \rightarrow X$) bands of N_2 at SZA = 60°, for minimum, moderate, and maximum solar conditions. Since many bands of N_2 span a large wavelength region, the overhead intensities of VK and LBH bands in different wavelength regions are also given in Table 1. Summers et al. (1997) have calculated volume emission rates of various emissions of N_2 and N on Pluto for moderate solar activity condition at Sun–Pluto distance of 30 AU. Their calculated volume emission rates peaks at ~2000 km radial distance. For N_2 LBH bands, Summers et al. (1997) have calculated an overhead intensity of about 5.7 R for CH_4 mixing ratio of 5×10^{-4}. Our calculated overhead intensity of N_2 LBH is 4.9 R for solar moderate condition. The minor difference in the two studies may largely be due to the cross section for N_2 LBH band used in the two studies and the input solar flux model.

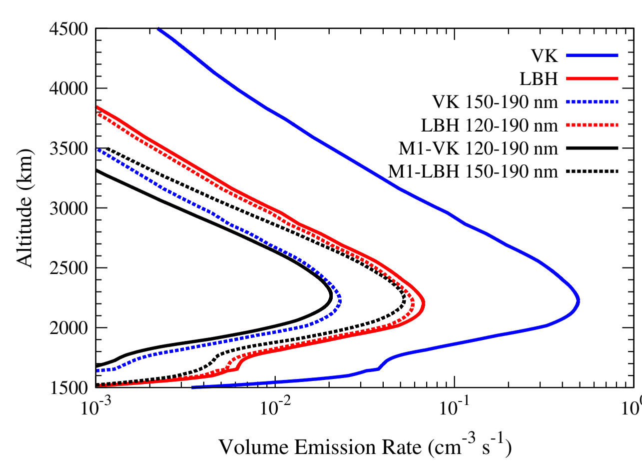

Fig. 1. Calculated volume emissions rates of N_2 VK (total), LBH (total), N_2 VK (150–190 nm) and LBH (120–190 nm) bands for solar moderate condition at SZA = 60° and Pluto–Sun distance of 30 AU. Black curves show the emission rate calculated using the M1 model atmosphere of Krasnopolsky and Cruikshank (1999) for VK (150–190 nm) and LBH (120–190 nm) bands.