New limits on $\text{H}_3^+$ abundance on Neptune using Keck NIRSPEC

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ABSTRACT
Neptune and Uranus are observed with Keck II NIRSPEC in an attempt to detect $\text{H}_3^+$ emission from Neptune. In this set of observations, $\text{H}_3^+$ emission remains undetected at Neptune, whereas line-resolved emission from Uranus was observed with a signal-to-noise ratio of $\sim$100. Using this, we have derived an upper limit of the column-integrated $\text{H}_3^+$ density on Neptune of $1.5 \times 10^{13}$ m$^{-2}$, assuming a temperature of 550±100 K. This value improves the previous established limit by a factor of 20 and shows that the $\text{H}_3^+$ density predicted by the best available model overestimate the density by at least a factor of 3.

In addition, the solar reflection continuum of Neptune in the $K$ and $L'$ bands is seen to be brighter on the Northern hemisphere by a factor of $\sim$2, whereas previous observations had noted the solar reflection as being brighter on the Southern hemisphere.


1 INTRODUCTION
The two most distant planets in our Solar system, Uranus and Neptune, have only been visited once, by one single spacecraft – Voyager 2 in 1986 and 1989, respectively. Similar in size and atmospheric composition, they are the sole representatives of ice giants in our Solar system, and yet despite this they are remarkably different. Uranus has a very extended upper atmosphere (Broadfoot et al. 1986), having twice the vertical extent of that of Neptune (Broadfoot et al. 1989). In addition, Uranus does not have a strong internal heat source (Pearl et al. 1990), whilst Neptune has an eddy diffusion coefficient at the homopause that is more like that of Saturn than Uranus (Atreya 1992).

Ground-based infrared observations of $\text{H}_3^+$ have proven to be a very powerful tool in studying the atmosphere and magnetosphere interaction for both Jupiter (e.g. Drossart et al. 1989; Stallard et al. 2003), Saturn (e.g. Geballe, Jagod & Oka 1993; Melin et al. 2007; Stallard et al. 2008) and Uranus (e.g. Trafton et al. 1993; Melin et al. 2010). This very simplest of polyatomic ions is formed where energy high enough to ionize $\text{H}_2$ is being injected into the upper atmosphere of the giant planets, either in the form of solar extreme ultraviolet (EUV) radiation or auroral particle precipitation. Consequently, formation of $\text{H}_3^+$ is a tracer of energy inputs and observations of its emission can be used to gain valuable insights into both atmospheric processes and plasma flows inside the magnetosphere.

All reported attempts at detecting $\text{H}_3^+$ emission from Neptune have been unsuccessful (Trafton et al. 1993; Encenra et al. 2000; Feuchtgruber & Encenra 2003). The United Kingdom Infrared Telescope (UKIRT) observations of Trafton et al. (1993) derived an upper limit to the $\text{H}_3^+$ Q branch discrete single line emission flux of $5 \times 10^{-13}$ W m$^{-2}$, equating to an upper limit of the $\text{H}_3^+$ column density of a few $10^{14}$ m$^{-2}$, assuming a temperature of 550 K. Feuchtgruber & Encenra (2003) derived an upper limit on the density of $2.9 \times 10^{14}$ m$^{-2}$ using observations with the Very Large Telescope (VLT), assuming a temperature of 550 K. Both of these density limits are about an order of magnitude smaller than the column densities observed at Uranus and about 2 orders smaller than those observed at Jupiter.

$\text{H}_3^+$ observations of Uranus indicate that there is a strong particle precipitation component to the emission – up to 20 per cent of the total (Lam et al. 1997). With increasing distances from the Sun, solar EUV becomes a less important production path for $\text{H}_3^+$, and particle precipitation may become a dominant mechanism. However, Sandel et al. (1990) observed only very weak aurora on Neptune during the Voyager 2 fly-by, emitting 60 MW globally in the ultraviolet. In contrast, the total auroral power of Uranus is 2.5 GW (Herbert 2009). So whilst Neptune receives only 40 per cent of the solar...
flux density at Uranus, auroral processes are still likely only to be responsible for a small fraction of the total H$_2^+$ density.

The model of Lyons (1995) predicts a H$_2^+$ peak density of 250 cm$^{-3}$ at an altitude of about 1350 km above the 1 bar level, giving a column-integrated density of $4\times10^{13}$ m$^{-2}$ (Feuchtgruber & Encrenaz 2003).

Here, we present the analysis of Keck II NISPEC observations of Uranus and Neptune in an effort to improve the upper limit for the column-integrated H$_2^+$ density of Neptune.

\section*{2 DATA & ANALYSIS}

Spectra were obtained using NIRSPEC on Keck II on 2006 September 5, at wavelengths sensitive to emission from the H$_2^+$ molecular ion. NIRSPEC (McLean et al. 1998) is a medium to high resolution spectrograph ($R = 25\,000$) mounted on the Keck II 10-m telescope on the summit of Mauna Kea, Hawaii. We used the KL grating (2.134–4.228 µm) with the 0.288 × 24 high-resolution slit giving a pixel scale of 0.144 arcsec pixel$^{-1}$. This produces a cross-dispersed spectrum with five spectral orders within the L’ atmospheric window – a region that contains both the brightest rovibrational H$_2^+$ emission lines and a region of methane absorption in the underlying atmosphere. Each of these orders contains some degree of curvature, in both the spectral and spatial dimension; so prior to any reduction, each individual spectral image was straightened using the REDSPEC IDL package. This paper only considers the orders that contain strong H$_2^+$ emission: order 22 (3.40–3.46 µm), order 21 (3.56–3.62 µm) and order 19 (3.94–4.01 µm).

Table 1 lists the observations of both Uranus and Neptune analysed here. The spectrograph slit was aligned along each planet’s rotational axis. There were a total of 64 exposures of Neptune, each 60 s long, contained within 16 ABBA sequences, where B is a beam offset from A such that the target remains on the slit for both exposures. The total set of observations includes a larger set of Uranus spectra, but in order to compare equivalent levels of signal-to-noise ratio only 64 of these were used, giving a total integration time for Uranus and Neptune of 64 min each.

The spectral image for each target was dark current subtracted, flat-fielded, co-added and flux calibrated using a 240-s exposure of HD 218639, an A0V star with $T_{\text{eff}} = 10\,000$ K and a $K$ magnitude of 6.369 (Cutri et al. 2003). The seeing during these and subsequent observations was 0.7 arcsec.

The angular diameter of Uranus on the sky at the time of observation was 3.6 arcsec, covering 26 pixels, whereas the angular diameter of Neptune was 2.3 arcsec, covering 16 pixels. The spatial position of Uranus was easily located in the spectral image by its prominent Q and R branch H$_2^+$ emission lines – these were also used to establish the wavelength scale for each order.

Since H$_2^+$ emission lines were absent in the co-added spectral image of Neptune, the position subtended by the planet on the spectrometer slit was deduced from the continuum of sunlight reflected from the reflected sunlight continuum from the disc of the planet. Fig. 1 shows a K-band image of Neptune (right-hand side) taken with the Keck II Near InfraRed Camera (NIRC2) at 05:35 UT on 2006 September 4 (24 h prior to the L’ observations), utilizing adaptive optics (AO). The pixel scale is 0.01 arcsec and the total integration time is 6 min. The image shows two distinct bands of reflected sunlight, with the northern being brighter than the southern band by a factor of $\sim 2$. This bimodal cloud structure was also observed by Feuchtgruber & Encrenaz (2003; in K and L’ bands) and by Max et al. (2003; in H and J bands), but they both noted a brighter reflection from the Southern hemisphere.

The intensity profile of the reflected sunlight across the planet, along the direction of the slit, can be seen on the left-hand side of Fig. 1. The profile derived from the K-band image has been smoothed by 0.7 arcsec (70 NIRC2 pixels) to match the seeing of the L’ NISPEC spectrum, which does not utilize AO. The Neptunian longitude difference between the two profiles is $\sim 180^\circ$ ($\sim 24$ h) suggesting that the Northern hemisphere is consistently brighter over a wide range of longitudes during this epoch – there is good correspondence between the distribution of reflected sunlight in the K-band image and L’ spectrum.

The co-added spectrum of Uranus and Neptune can be seen in Fig. 2 – Uranus shows distinct H$_2^+$ emission lines across all three orders, whereas Neptune has no discernible emission at the same level, giving a column-integrated density of $4\times10^{13}$ m$^{-2}$.
wavelengths. Note that in order 22, and to a lesser extent in order 21, there is significant absorption of the emission by water in the Earth’s atmosphere. This absorption is difficult to correct for, and it produces narrow regions with large noise, seen in both the Uranus and Neptune spectra.

Order 19 is not affected by terrestrial water vapour. The Uranus spectrum (top right-hand side of Fig. 2) was fitted with a model \( H_3^+ \) spectrum assuming condition of local thermodynamic equilibrium (LTE). We derive a column-averaged rotational \( H_3^+ \) temperature of 604 \( \pm \) 8 K and a column-integrated density of \( 1.13 \pm 0.07 \times 10^{15} \text{ m}^{-2} \). This is well within the range of the previously reported values, e.g. Trafton et al. (1999) and Encrenaz et al. (2003), confirming that the flux calibration is sensible. The small errors of this fit highlight the excellent signal-to-noise ratio achievable with NIRSPEC when observing \( H_3^+ \) emission from the gas giants.

For Jupiter, the Q branch emission at 3.9 \( \mu \text{m} \) is the least affected by departures from LTE (Melin et al. 2005). However, the modelled reduction in line emission intensity ranges between 70 per cent for the Q(1, 0) line and 4 per cent for the R(6, 6) of the LTE intensity.

On Neptune, assuming the \( H_3^+ \) density and temperature values of Broadfoot et al. (1989) at the \( H_3^+ \) peak at 1350 km (Lyns 1995), the \( H_3^+ \) collisional population lifetime for the \( H_3^+ \) v3 level is \( \sim 0.5 \text{ ms} \) (using the proton-hopping rates of Theard & Huntress 1974), compared to the radiation lifetime of 8 ms (Neale, Miller & Tennyson 1996). This suggests that the fundamental rovibrational energy levels of \( H_3^+ \) have enough time to kinetically equilibrate with the ambient temperature and that the assumption of \( H_3^+ \) is valid, and therefore the \( H_3^+ \) flux from Neptune will not be significantly reduced by non-LTE effects.

Fig. 3 shows each of the 13 identified \( H_3^+ \) emission lines in the Uranus spectral image – these lines are contained within 12 wavelength regions.

The line-of-sight orbital velocity difference between Uranus and Neptune, as viewed from Earth at the time of observation, is 2 km s\(^{-1}\), which is well below the velocity resolution of NIRSPEC of 12 km s\(^{-1}\). Consequently, we expect any \( H_3^+ \) emission lines at Neptune to be found at the same spectral position in the spectral array as for Uranus. Fig. 3 shows the equivalent regions for Neptune, with no obvious line emission present. In order to achieve the maximum possible signal-to-noise ratio, these regions were summed for each planet, shown on the right-hand side of Fig. 3. These sums were integrated in the spatial direction, the result of which is seen in Fig. 4. \( H_3^+ \) emission remains undetected from Neptune.

Using the \( H_3^+ \) line list of Neale et al. (1996), one can calculate the total emission per molecule for the sum of the 13 emission lines that are added here. The intensity per molecule, \( I_m^{13} \), as a function of temperature, \( T \), takes the approximate form

\[
I_m^{13}(T) = (30.4 - 0.17T + 0.23 \times 10^{-3}T^2) \times 10^{-18}
\]

in units of W sr\(^{-1}\).

3 RESULTS & DISCUSSION

3.1 Variability of hydrocarbon absorption

In these observations, taken in 2006 September, the solar reflection component from the Northern hemisphere of Neptune is observed to be brighter than the Southern by a factor of \( \sim 2 \). Observations obtained in 1999 in H and J bands (Max et al. 2003) and observations taken in 2002 in K and L' bands (Feuchtgruber & Encrenaz 2003) both see a more intense solar reflection in the Southern hemisphere. The time-scale is too short to suggest seasonal variability (\( P = 165 \text{ yr} \)), but it does tell us that the hydrocarbon layer is very dynamic, which was also noted by Feuchtgruber & Encrenaz (2003).
3.2 Upper limit on H$_3^+$ abundance on Neptune

We derived an upper limit for the H$_3^+$ column density of Neptune to be 1.5 (±0.9) × 10$^{13}$ m$^{-2}$, assuming a temperature of 550 K. This is a factor of 20 times smaller than the 2.9 (±1.1) × 10$^{14}$ m$^{-2}$ derived by Feuchtgruber & Encrenaz (2003). The result obtained here represents a significant downward revision for the upper limit of the H$_3^+$ column density and thus the magnitude of the Neptunian ionosphere. The results presented here can be compared to the model of Lyons (1995), which predicts a column-integrated H$_3^+$ density of 4–5 × 10$^{13}$ m$^{-2}$ (Feuchtgruber & Encrenaz 2003). The fact that the upper limit for the density derived here is a factor of 3 lower than this predicted value allows direct constraints to be placed on models of the upper atmosphere of Neptune.

The fact that Neptune have very low densities of H$_3^+$ is curious. Sandel et al. (1990) reported very low levels of auroral emissions – they are minuscule when compared to those observed at Uranus (Herbert 2009). But even if there were no aurora on Uranus, H$_3^+$ will be produced via the path of ionization of H$_2$ by the solar EUV ionization. Broadfoot et al. (1989) observed hydrocarbons up to an altitude of 500 km above the 1 bar level, with a mole fraction of CH$_4$ of 4–5% (Herbert 2009). But even if there were no aurora on Uranus, H$_3^+$ will be produced via the path of ionization of H$_2$ by the solar EUV ionization. Broadfoot et al. (1989) observed hydrocarbons up to an altitude of 500 km above the 1 bar level, with a mole fraction of CH$_4$ of 4–5%.

This result may be important for the stability of exoplanet atmospheres, for which H$_3^+$ cooling has been invoked to show that gas and ice giants may be stable as close as (the equivalent of) 0.16 au from a Sun-like star (Koskinen, Aylward & Miller 2007). Mixing of methane into the lower thermosphere, as may be the case for Neptune, will reduce the formation of this ion, and consequently any cooling it may produce.

Figure 5. The column-integrated density of H$_3^+$ on Neptune as a function of temperature, given the upper limit of H$_3^+$ flux derived here. A is the modelled temperature used by Feuchtgruber & Encrenaz (2003), and B is the exobase temperature derived by Voyager 2 occultations (Broadfoot et al. 1989).

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