

## Observation of $O^+ 4P-4D^0$ lines in proton aurora over Svalbard

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[1] Spectra of a proton aurora event show lines of  $O^+ 4P-4D^0$  multiplet (4639–4696 Å) enhanced relative to the  $N_2^+ 1N(0,2)$  compared to normal electron aurora. Conjugate satellite particle measurements are used as input to electron and proton transport models, to show that  $p/H$  precipitation is the dominant source of both the  $O^+$  and  $N_2^+ 1N$  emissions. The emission cross-section of the multiplet in  $p$  collisions with O and  $O_2$  estimated from published work does not explain the observed  $O^+$  brightness, suggesting a higher emission cross-section for low energy  $p$  impact on O. **INDEX TERMS:** 0310 Atmospheric Composition and Structure: Airglow and aurora; 2407 Ionosphere: Auroral ionosphere (2704); 2419 Ionosphere: Ion chemistry and composition (0335); 2455 Ionosphere: Particle precipitation. **Citation:** Ivchenko, N., M. Galand, B. S. Lanchester, M. H. Rees, D. Lummerzheim, I. Furniss, and J. Fordham (2004), Observation of  $O^+ 4P-4D^0$  lines in proton aurora over Svalbard, *Geophys. Res. Lett.*, 31, L10807, doi:10.1029/2003GL019313.

### 1. Introduction

[2] The ultimate source of auroral emissions is precipitation of energetic particles into the atmosphere. The auroral spectrum depends on the composition of the upper atmosphere, and the type and energy distribution of the precipitating particles. Doppler-shifted atomic hydrogen lines [e.g., Lanchester *et al.*, 2003] are the unique signature of  $p$  precipitation, and are emitted by the energetic H atoms produced by charge exchange in the  $p$  beam. Various other spectral features seen in electron aurora are observed in proton aurora as well [Galand *et al.*, 2002], excited both by direct  $p/H$  impact and by secondary  $e^-$ .

[3] An important auroral diagnostic emission of  $N_2^+ 1N(1,3)$  is blended with the  $O^+ 4P-4D^0$  multiplet (4638–4696 Å). Recently the  $O^+$  lines were studied in electron aurora, and their emission cross-section was estimated [Ivchenko *et al.*, 2004, and references therein]. The multiplet is emitted in the transition between  $2s^2 2p^2 3p^4 D^0$  and  $2s^2 2p^2 3s^4 P$  levels (Figure 1). We present a case study of proton aurora, combining ground-based spectral measurements with conjugate satellite particle measurements.

We show that the observed  $O^+$  multiplet brightness cannot be due to  $e^-$  excitation. Excitation in collisions with  $p$  and H is discussed, leading to the conclusion that reported cross-sections of  $p$  processes are not sufficient alone to produce the observed  $O^+$  brightness.

### 2. Spectrographic Imaging Facility

[4] The Spectrographic Imaging Facility (SIF) is a suite of optical instruments, located at the auroral station (78.2°N, 15.8°E) near Longyearbyen, Svalbard. A description of the SIF is given by McWhirter *et al.* [2003], and data reduction techniques are described by Ivchenko *et al.* [2004]. Here we use data from the High Throughput Imaging Echelle Spectrograph (HiTIES) [Chakrabarti *et al.*, 2001]. The field of view is defined by a slit covering 8° centered on the magnetic zenith. By using high orders high spectral resolution is achieved. The overlapping orders are separated by a mosaic of interference filters placed at the image plane of the light diffracted from the grating. In the data used here, three spectral intervals were selected containing the  $H_\beta$ ,  $N_2^+ 1N(0,2)$  and  $N_2^+ 1N(1,3)$ . The data were acquired with the MIC detector [Fordham *et al.*, 1991]. We believe the absolute calibration uncertainties to be below 50%. The presented spectra are integrated over the central 2° of the slit. The spectral resolution is 1 Å and integration time 30 sec.

### 3. December 15, 2001 Event

[5] On December 15, 2001 solar wind number densities were above  $50 \text{ cm}^{-3}$  between 14:00 and 17:00 UT, while the IMF  $B_z$  stayed positive (ACE satellite data not shown). These conditions were favourable for intense  $p$  precipitation at high magnetic latitudes. Intense  $H_\beta$  emission (over 100 R) was measured by the SIF in the dusk auroral oval during the time of high solar wind density. The DMSP F-14 satellite overflew the auroral station (closest approach of the magnetic footprint to the station was at 17:02 UT; see Figure 2). LLBL-type precipitation was measured by the satellite between 17:01:20 UT and 17:03:40 UT. The energy spectra of electrons and protons for the time of the closest conjunction were used as input to the respective transport models. Most of the precipitating energy flux is carried by protons ( $0.4 \text{ mW m}^{-2}$ ), with two peaks at characteristic energies of just below 1 keV and about 8 keV. Electron energy flux of under  $0.1 \text{ mW m}^{-2}$  is carried by electrons with energies below 0.3 keV.

[6] The time history of SIF spectra is presented in Figure 3. The top panel is dominated by the  $O^+$  lines at 4649.1 Å and 4641.8 Å, with the weaker feature at 4652 Å being the head of the  $N_2^+ 1N(1,3)$  band, which is degraded towards the blue. The second panel shows the spectrum of the  $H_\beta$  emission from energetic H, Doppler broadened and

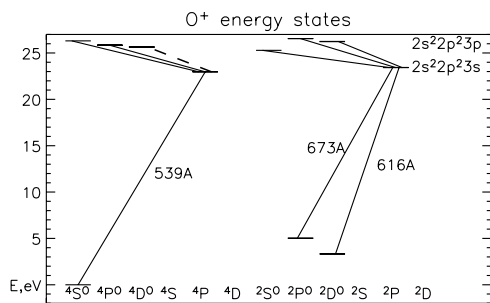
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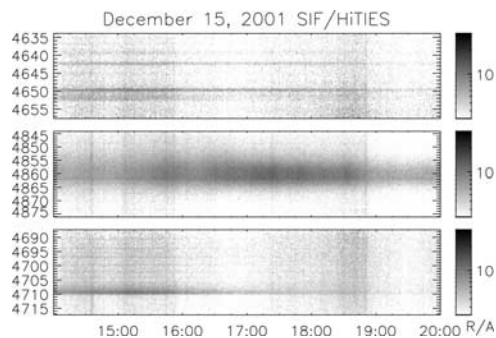
**Figure 1.** Energy diagram of O<sup>+</sup> with O<sup>++</sup>(<sup>3</sup>P) core. The <sup>4</sup>P-<sup>4</sup>D<sup>0</sup> multiplet is dashed.

shifted towards shorter wavelengths (coming downward). The bottom panel shows the N<sub>2</sub><sup>+</sup> 1N(0,2) band, with the head at 4709 Å and degraded to the blue.

[7] Figure 4 shows the spectrum at the time of conjunction. It differs noticeably from a typical electron aurora spectrum that is also shown. The grey curve is the fitted background spectrum. Besides the continuum, it contains weak contributions from N<sub>2</sub> first positive and Vegard-Kaplan bands [Sivjee, 1980]. After subtracting the background, the brightnesses can be estimated. For N<sub>2</sub><sup>+</sup> 1N(0,2) integration over the observed spectral range yields about 10 R, which is an underestimate, since part of the R branch extends further into the blue. Using the method described by Ivchenko *et al.* [2004] we obtain 13 R for the 1N(0,2). Table 1 lists this value together with the observed brightnesses of O<sup>+</sup> 4P-4D<sup>0</sup> multiplet and H<sub>β</sub>, 11.9 R and 102 R respectively.

[8] Ivchenko *et al.* [2004] found that the O<sup>+</sup> 4P-4D<sup>0</sup> brightness in electron aurora is on average 0.1 of N<sub>2</sub><sup>+</sup> 1N(0,2). Modelling showed that the maximum ratio of the emissions does not exceed 0.5, a value only reached for electrons with energies of several 100 eV. In our case the O<sup>+</sup> and N<sub>2</sub><sup>+</sup> 1N(0,2) brightnesses are nearly equal.

[9] The quality of the data is compromised by the hazy sky conditions. However, apart from enhancements of the

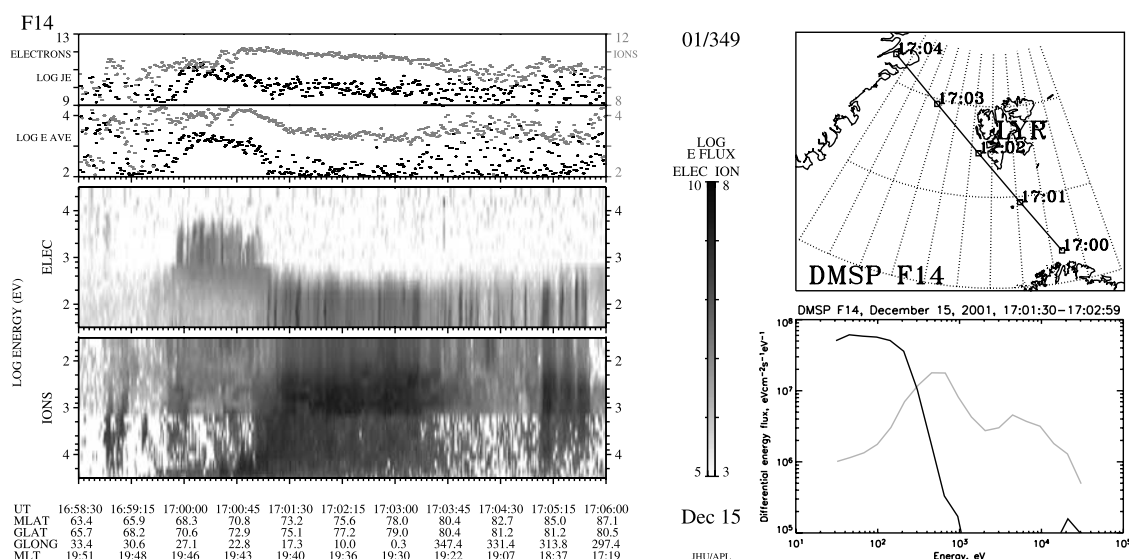


**Figure 3.** Spectra taken between 14:00 UT and 20:00 UT on December 15, 2001. Geocoronal emission is visible at the unshifted H<sub>β</sub> wavelength (4861.3 Å).

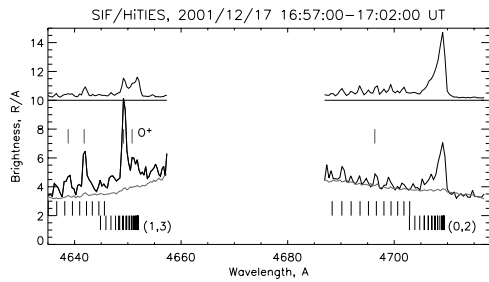
background due to variations in the haze, seen in all panels between 15 UT and 16 UT, and between 18:20 UT and 18:50 UT, the brightness variations are rather smooth in time. The DMSP F-14 data suggest a large spatial scale of *p* precipitation. The thin cloud cover has two effects - it reduces intensities in the field of view because of stronger extinction, but also it scatters emissions generated elsewhere into the instrument aperture [Gattinger *et al.*, 1991]. This makes the interpretation of the absolute intensities difficult if small transverse scales are present in the auroral display. However, we believe that in our case the aurora was uniform on scales larger than the field of view of the spectrograph, so that the scattering would mainly result in lower intensities. As the measured features are all within a small wavelength range, the same extinction factor applies and the relative brightnesses are unaffected.

#### 4. Modelling the Emissions

[10] Particle data from the DMSP F-14 satellite can be used to predict the individual contributions of various processes to the brightnesses of the emissions observed.



**Figure 2.** Electron and ion data from DMSP F-14 satellite. Top panels - energy flux (ev/cm<sup>2</sup>/s) and characteristic energy (eV) of precipitating electrons and ions. Bottom panel - differential energy flux (eV/(cm<sup>2</sup> s sr eV)) of electrons and ions. Top right: DMSP F14 magnetic footprint at 100 km (triangle and LYR mark the auroral station). Bottom right: proton (grey) and electron (black) energy spectra at the conjunction.



**Figure 4.** Spectrum of the N<sub>2</sub><sup>+</sup> 1N bands and O<sup>+</sup> lines at the time of conjunction. Thin grey line is the background spectrum (see text). Vertical lines mark position of the O<sup>+</sup> lines and the rotational lines of the P and R branches of the N<sub>2</sub><sup>+</sup> (0,2) and (1,3) bands. The upper curve is an electron aurora spectrum (17:02 UT on Dec 17, 2001), reduced by a factor of 25, and shifted upward for clarity.

The N<sub>2</sub><sup>+</sup> and O<sup>+</sup> emissions can be excited in electron, proton and energetic hydrogen collisions.

[11] We model the contribution from the electron precipitation using a transport model by *Lummerzheim and Liliensten* [1994], and the O<sup>+</sup> emission cross sections from *Ivchenko et al.* [2004]. The modelled brightnesses are summarized in Table 1. Electron precipitation produces no H<sub>3</sub>. The brightness of N<sub>2</sub><sup>+</sup> 1N(0,2) excited in e<sup>-</sup> collisions is 1.75 R, and that of the O<sup>+</sup> multiplet is 0.5 R.

[12] The transport of the precipitating *p* and H is a complicated process, because protons capture electrons in charge exchange processes, becoming hydrogen atoms; and energetic hydrogen atoms lose electrons in stripping processes. Thus, a pure *p* or H precipitation on its way down through the atmosphere becomes a mixed *p*/H beam. We use a code which solves the coupled transport equations for *p* and H [*Galand et al.*, 1997], including the collisional angular redistribution as described by *Lanchester et al.* [2003]. Given an incident *p* flux, it predicts the H emission Doppler profiles, auroral emission rates (when the emission cross section is known) and ion production rates. It also calculates the source function of the secondary electrons (the proto-electrons) produced in the proton beam. The integrated brightness of H<sub>3</sub> at the time of the conjunction is 255 R (see Table 1). This is higher than the observed value, indicating strong extinction due to the haze. An atmospheric extinction coefficient for the clear conditions was estimated by *Lummerzheim et al.* [1990] to be 1.49. To reconcile the model with the data, a further factor of 1.7 is needed, which is reasonable for hazy conditions.

[13] The 1N bands of N<sub>2</sub><sup>+</sup> are also excited in *p*/H collisions with N<sub>2</sub>. We assume the set of cross sections for production of the N<sub>2</sub><sup>+</sup> 1N(0,0) band as used in the model [*Galand et al.*, 1997], and Franck-Condon factors, which give the 1N(0,2) brightness of 17.7 R. Finally, the source function of proto-electrons obtained from the proton transport code is used as an input to the electron transport code to give N<sub>2</sub><sup>+</sup> 1N(0,2) and O<sup>+</sup> 4P-4D<sup>0</sup> intensities of 1 R and 0.01 R respectively.

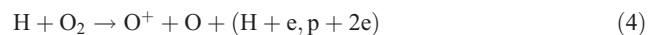
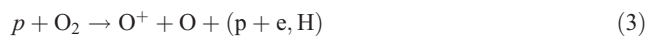
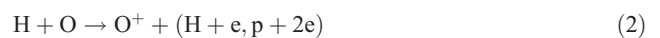
[14] It is clear from Table 1 that the electron impact processes contribute very little to the O<sup>+</sup> 4P-4D<sup>0</sup> brightness. The *p* precipitation is responsible for the dominant part of the emissions in the observed spectral intervals. Assuming

the extinction of 2.5, the observed N<sub>2</sub><sup>+</sup> 1N(0,2) is ca 60% brighter than modelled, which is a good agreement considering the uncertainties involved.

## 5. Excitation of the O<sup>+</sup> Lines by *p*/H Impact

[15] The brightness of O<sup>+</sup> lines due to the e<sup>-</sup> precipitation is an order of magnitude below the observed. Excitation by the protoelectrons is negligible, because of the very fast fall-off of their energy spectra, leaving only a small part of the population above the threshold for O<sup>+</sup> 4D<sup>0</sup> state excitation (39.3 eV). This leaves most of the emissions unaccounted for by the e<sup>-</sup> excitation.

[16] The O<sup>+</sup> lines are excited in *p*/H impact on O and O<sub>2</sub>:



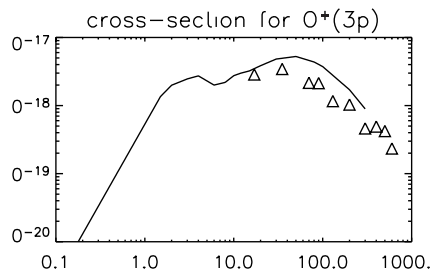
There are very few studies of excitation of high lying states of O<sup>+</sup> in *p*/H collisions. *Wilhelmi and Scharner* [2000] studied UV and visible fluorescence from O and O<sub>2</sub> in *p* impact, and published emission cross-sections for the 539 Å emission for *p* energies above 17 keV. This line originates from the lower state of the 4P-4D<sup>0</sup> multiplet (see Figure 1), which is populated, along with direct excitation, by cascading from 3*p* (4S<sup>0</sup>, 4P<sup>0</sup>, 4D<sup>0</sup>) states. The cascading is significant, as 3*p* → 3*s* transitions (including 4P-4D<sup>0</sup>) are readily seen in the visible fluorescence spectrum. Thus, this 539 Å cross-section is the upper limit for the 4P-4D<sup>0</sup> emission cross-section. In a recent theoretical study *Kirchner et al.* [2000] calculated the cross section for excitation of O<sup>+</sup>(3*p* 2,4P) in equation (1) for *p* energies above 1 keV using the basis generator method in the framework of the independent particle model. This cross-section includes all 3*p* 2,4P states: the six in Figure 1 and other states with excited O<sup>++</sup> core. Even though the cross-section does not include cascading from higher levels, it is clearly the upper limit of the 4P-4D<sup>0</sup> emission cross-section. Both cross-sections are shown in Figure 5. We used the cross-section of *Kirchner et al.* [2000] (log-log extrapolated below 1 keV) for processes (1) together with the modelled altitude profile of *p* intensities to estimate the upper limit of 4.1 R for the brightness of the O<sup>+</sup> multiplet. We also made a

**Table 1.** Observed and Modelled Emissions for the Event

Brightness [R]	H <sub>3</sub>	1N(0,2)	O <sup>+</sup>
SIF observation 17:02 UT	102	13.0	11.9
Modelled (no extinction)			
Electron precipitation	0.0	1.75	0.5
<i>p</i> /H precipitation	254.9	17.65 <sup>a</sup>	0.6–3 <sup>b</sup>
Proto-electrons	0.0	1.0	0.01

<sup>a</sup>Estimated from 1N(0,0) using the Franck-Condon factors.

<sup>b</sup>Estimated range - see text.



**Figure 5.** Cross-section for production of O<sup>+</sup> in 3p state, calculated by Kirchner *et al.* [2000] (extrapolation below 1 keV). Triangles - experimental cross-section for 539Å line for p impact on O [Wilhelmi and Schartner, 2000].

calculation taking the cross-section below 1 keV equal to that at 1 keV (rather than extrapolating). The predicted upper limit to 4P-4D<sup>0</sup> brightness from equation (1) only increased to 4.7 R. An estimate of the brightness produced in process (3) can be obtained by using twice the cross-section for p + O, resulting in 2.2 R. These values should be decreased by a ratio of 4P-4D<sup>0</sup> brightness to the total brightness of all 3p → 3s transitions. We speculate that this ratio is at least 0.1, but probably does not exceed 0.5. Thus, a brightness of the order of 1 R is to be compared to the observed value of 12 R, which in turn should be increased to account for extinction (see discussion above). This means that the published cross-sections for the p processes alone cannot account for the observed brightness.

[17] It is useful to consider the total production rate of O<sup>+</sup> in the proton transport model. The total column production rate of  $2.56 \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$  is dominated by process (1), contributing  $2.0 \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$  (90% being due to electron capture). Process (2) amounts to  $3.6 \cdot 10^8 \text{ cm}^{-2}\text{s}^{-1}$ , and processes (3) and (4) to  $1.1 \cdot 10^8 \text{ cm}^{-2}\text{s}^{-1}$  and  $0.84 \cdot 10^8 \text{ cm}^{-2}\text{s}^{-1}$  respectively. Observations suggest a column emission rate of over 20 R, which is  $2 \cdot 10^7 \text{ photons cm}^{-2}\text{s}^{-1}$ . Processes (3) and (4) cannot be responsible for this rate, since this would imply that 10% of O<sup>+</sup> ions produced by dissociative processes are in the 3p<sup>4</sup>D<sup>0</sup> state, which is too much to be realistic. Thus, either up to 1% of O<sup>+</sup> produced in p collisions with O emit the 4P-4D<sup>0</sup> multiplet, or it is emitted by up to 5% of O<sup>+</sup> ions resulting from H impact on O. The former is more plausible, but still implies that the cross-section of equation (1) is significantly larger than assumed above. Assuming the experimental data of Wilhelmi and Schartner [2000] are reliable, cross-sections below 17 keV are the likely cause for the disagreement. With the total cross-section for electron capture in p + O collisions being almost constant for p energies below 10 keV at  $10^{-15} \text{ cm}^2$  [Hamre *et al.*, 1999], the branching of 1% as discussed above implies 4P-4D<sup>0</sup> emission cross-section of ca  $10^{-17} \text{ cm}^2$  for that energy range, which is difficult to reconcile with the calculations by Kirchner *et al.* [2000].

## 6. Summary

[18] In the presented event p precipitation is the dominant source of the N<sub>2</sub><sup>+</sup> 1N and O<sup>+</sup> 4P-4D<sup>0</sup> emissions. Modelled H<sub>3</sub> and N<sub>2</sub><sup>+</sup> 1N brightnesses are consistent with the observations, allowing for extinction due to the hazy conditions.

The ratio of the O<sup>+</sup> 4P-4D<sup>0</sup> multiplet to the N<sub>2</sub><sup>+</sup> 1N(0,2) band is enhanced in proton aurora compared to normal electron aurora. The existing ionization-3p-excitation cross-section, together with the modelled p intensities, put an upper limit on the predicted 4P-4D<sup>0</sup> brightness, which is an order of magnitude below the observed value. To explain the observed brightnesses, about 1% of all produced O<sup>+</sup> ions must emit a 4P-4D<sup>0</sup> photon. Electron capture and ionization by p collisions with O are the dominant processes for O<sup>+</sup> production in the event. Emission cross-section of the order of  $10^{-17} \text{ cm}^2$  for p energies below 10 keV would be consistent with the observations.

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