GEOPHYSICAL RESEARCH LETTERS, VOL. 16, NO. 6, PAGES 587-590, JUNE 1989

DOPPLER SHIFTED H Ly α EMISSION FROM JUPITER'S AURORA

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Abstract. IUE observations of the aurora on Jupiter have been performed with high spectral resolution in a search for Doppler shifted H Ly α emission produced through charge exchange by fast precipitating protons, as observed in the Earth's aurora. No emission has been observed corresponding to proton energies greater than 200 eV, placing a strict upper limit on the contribution of KeV - MeV protons to the production of Jupiter's aurora. However, a large fraction of the H Ly α emission has appeared Doppler-shifted mainly toward the blue by roughly 50 km/sec, corresponding to a kinetic energy of 10-20 eV for a fast proton or H atom, and there are higher velocity wings on the line extending out to equivalent energies of 150-200 eV. The blue shift indicates motion up out of the atmosphere, and we suggest that the emission results from the in situ acceleration of ionospheric protons in Jupiter's auroral ionosphere by analogy to the ionospheric potentials observed in the Earth's auroral zones. These observations demonstrate that the acceleration of ionospheric plasma in an H_2 atmosphere can lead to bright Ly α emission, with implications for the production of the outer planet airglow emissions. The observed Doppler shift represents a significant fraction of the escape velocity, and the upflowing protons and H atoms may contribute substantially to the low energy plasma in Jupiter's magnetosphere if the plasma motions are at high altitudes.

Introduction

The contribution of proton precipitation to the Earth's aurora was first studied by ground-based high resolution spectroscopy of Doppler-shifted Balmer (H α) emission (Meinel 1951). The excitation process is charge exchange of incident fast protons with atmospheric molecules leading to Doppler shifted emission. By obtaining spectra viewing vertically up roughly parallel to the B-field lines in a bright aurora, and then viewing perpendicular to the B-field lines through the same aurora, the field-aligned trajectory of the auroral protons was determined. The maximum observed blue-shift of the H α emission corresponds to a proton energy of 50 KeV, which is roughly the energy necessary for a magnetospheric proton incident on the upper atmosphere to penetrate to the observed height of the auroral layer. Doppler-shifted Ly α emission from proton precipitation has also been observed from the Earth's aurora recently in down-looking observations with a space-borne spectrometer (Ishimoto et al. 1989), demonstrating that Ly α observations may also be used to study auroral proton precipitation.

The first theoretical estimate of the contribution of proton precipitation to Jupiter's aurora was by Heaps, Edgar, and Green (1975). A further theoretical study following the first Voyager encounter suggested the presence of strong proton aurora on Jupiter's nightside (Goertz 1980). Since that time evidence has been gathered for the contribution of heavy ion precipitation from the Io torus, principally the observation of X-ray emission which is most likely produced by K-shell excitation of O and S ions (Metzger et al. 1983). However, the lack of S and O recombination lines in the FUV H_2 auroral emission spectrum suggests that the FUV aurora are largely electron-excited (Waite et al. 1988). It therefore appears that many different kinds of charged particles may be contributing to the excitation of Jupiter's various auroral emissions.

H Ly α emission may result from fast protons either through charge exchange or through collisions of the resulting fast H atoms. H Ly α emission can also be produced by electron impact through excitation of H and dissociative excitation of H_2. It has also been proposed that in situ acceleration of ionospheric plasma in H_2 atmospheres may lead to FUV emissions through the acceleration of superthermal particles by anomalous resistivity (Clarke, Hudson, and Yung 1987), and that these emissions could be characterized by Doppler-shifted Ly α emissions corresponding to proton energies of a few to 50 eV. If this mechanism works at all, it would most likely be observed at auroral latitudes, since the observed corotation of much of the plasma in Jupiter's magnetosphere implies strong ionospheric currents at high latitudes (Kennel and Coroniti 1979). Anticipating both large and small Doppler shifts (from precipitating and ionospheric protons, respectively), we have undertaken a series of IUE high dispersion observations of the H Ly α emission from Jupiter's aurora. Previous low dispersion IUE spectra of Jupiter's aurora have been presented by Clarke et al. (1980) and Skinner et al. (1984), and the IUE Observatory has been described by Boggess et al. (1978).

Observations and Data Reduction

IUE observations of Jupiter's aurora at high dispersion have been performed over the period December 1986 - September 1988 (see Table I). Image SWP 29880 employed the short wavelength large aperture (SWLA) for maximum sensitivity, whereas all other observations were with the small aperture (SWSA) for optimal spectral resolution. During each small aperture observation the large aperture was open for a measurement of the geocoronal and interplanetary H Ly α emissions at high dispersion, and this background emission has been used to establish the absolute wavelength reference for the Jovian emission observed in the small aperture. In each case there is a correction to the wavelength reference for the motion of the IUE with respect to Jupiter, which includes components of the velocities of the Earth orbit (20-30 km/sec) and the IUE orbit (1-2 km/sec) along the line of sight. The observations reported in this paper were at or near the central meridian of Jupiter, and contain no correction for the rotation of Jupiter. The spectra were extracted from the line by line data sets using

Paper number 89GL00829.
0094-8276/89/89GL-00829$03.00

Table I IUE Observations of Jupiter

SWP Image	Date	Magnetic Latitude	System III Longitude	IUE line of sight velocity	Background Ly α 4πI	Maximum auroral Ly α Doppler shift	SWSA auroral[3] Ly α 4πI	SWLA total H_2 4πI
16091	1/22/82	+80°	210-315°	-32[1] km/s	2.2 kR	+45[1] km/s	5.2 kR	-
29880	12/14/86	N. pole[2]	180°	+30	1.3 kR	+160/-200	5.6 kR[2]	-
32390	11/24/87	+60°	145-240°	+19	2.3 kR	+/- 17	9.8 kR	76 kR
32469	12/6/87	-70°	350-85°	+24	1.0 kR	-28	5.8 kR	42 kR
32470	12/6/87	+60°	110-215°	+24	1.4 kR	-31	7.3 kR	40 kR
32813	1/29/88	+60°	320-50°	+29	.63 kR	-23	5.0 kR	<10kR

[1] Positive value indicates motion away from observer (i.e. redshift).
[2] Data measured in SWLA.
[3] Auroral Ly α after subtraction of geocoronal and interplanetary background emissions.

standard IUE RDAF procedures, with extraction widths appropriate to the different aperture sizes. The H_2 bands that are easily detected in low dispersion spectra of Jupiter's aurora are dispersed into many lines at high dispersion, and only the strong H Ly α line is detected. Both the apparent wavelength separation of the small and large apertures, and the instrumental resolution to monochromatic emission, were determined from archived spectra of geocoronal emission in which the line of sight interplanetary gas motion was near zero (see Figure 2).

The latter four small aperture exposures in Table I were each interrupted for a 15 min. large aperture low dispersion spectrum to measure the brightness of the auroral H_2 emission with respect to past observations and to confirm the pointing of the small aperture. In each case the large aperture in low dispersion was centered at the same latitude in the auroral zone as the small aperture in high dispersion, and the camera was read out only after both SWSA (high) and SWLA (low) images were exposed. The short SWLA exposures were obtained when 180° (32390 and 32470) or 0° (32469 and 32813) longitudes crossed the central meridian (and aperture). The auroral H_2 emission brightnesses in Table I are from the low dispersion spectra in the SWLA, converted to the equivalent brightness of a 5.5 by 8.9 arc sec emitting region. The 3 arc sec SWSA Ly α brightness values are systematically lower than the auroral Ly α brightnesses observed in the SWLA in the same exposure, implying that the emitting region is larger than the 3 arc sec SWSA. It has previously been demonstrated that the FUV auroral emission region is extended in longitude, with peak emissions centered at λ_{III} = 180° (north) and λ_{III} = 0° (south) (Clarke et al. 1980, Skinner et al. 1984).

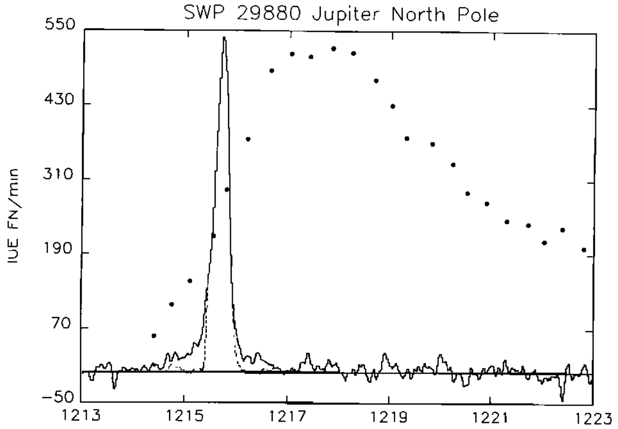

Fig. 1. IUE spectrum (solid line) of Jupiter's north auroral zone, with the line profile of the Earth's H α auroral emission toward the magnetic zenith from Meinel (1950) plotted as points on the same velocity scale and normalized to the same peak intensity. The Earth Hα line profile has been reversed about zero wavelength to represent observations from above the atmosphere looking down; the dashed lines at the base of the IUE line profile indicate the instrument response to monochromatic emission.

Pointing for all small aperture spectra (including the archived image) was accomplished by offset from one of the Galilean satellites, calculated from the JPL ephemeris NAIF. The pointing of the SWSA on each auroral emission region is estimated to have been better than 2-3 arc sec. Northern exposures were centered at +60° (magnetic) latitude and southern exposures at -70° latitude, except for SWP 16091 centered on +80° latitude. In SWP 32390 the SWSA tracked the Jovian meridian at λ_{III} = 180° across the disk as Jupiter rotated (to maximize the signal level), leading to a variation in the angle between the line of sight and Jupiter's magnetic field over the course of the exposure. Since ample signal was obtained in SWP 32390, in the three following exposures the SWSA was held on the central meridian at a fixed magnetic latitude, so that the line of sight remained nearly constant as the auroral zone rotated under the aperture.

H Ly α Spectra

Unlike the Doppler-shifted H α emission observed from the Earth's aurora, no emission with a red-shift greater than 160 km/sec or with a blue-shift greater than 200 km/sec is apparent in the initial Jovian auroral spectrum (Figure 1) or in any of the spectra listed in Table I. Although the auroral Ly α line is centered at the rest wavelength of Jupiter's atmosphere, there *is* significant emission extending out to these limiting velocities at the level of 10-15% of the peak, with somewhat more blue-shifted than red-shifted emission. The large aperture IUE spectrum in Figure 1 has the highest signal level of the observations to date, with a spectral resolution of roughly 0.3 A. Although the brightness of the aurora during this exposure was not measured in low dispersion, the SWLA was centered on 180° longitude (the central longitude of the northern aurora). The aperture-integrated and background-subtracted Ly α brightness of 5.6 kR suggests a moderate level of auroral emission by comparison with other observations (this corresponds to 13 kR from a 5.5 x 8.9 arc sec auroral emission area). A 3 σ upper limit of 100 Rayleighs/ 0.3 A is obtained for any red-shifted Ly α emission with a line of sight velocity of 160 km/sec or greater. In other words, no Earth-like proton aurora has been observed on Jupiter to date.

By contrast to the lack of highly Doppler-shifted emission, every small aperture exposure has shown a substantial part of the H Ly α emission Doppler-shifted by a small amount from rest wavelength. Examples of small aperture spectra are plotted in Figure 2, with clearly blue-shifted emission from both the northern and southern aurora observed near the longitudes of

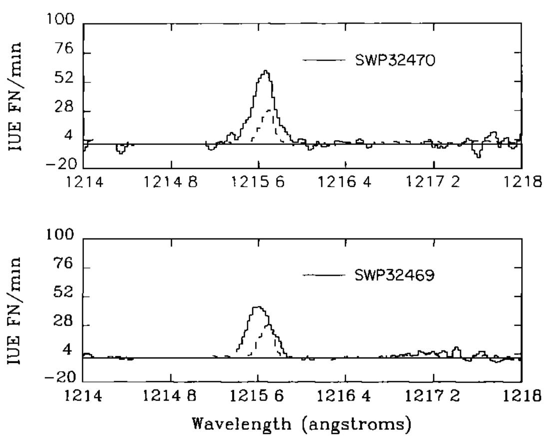

Fig. 2. IUE SWSA spectra of Jupiter's auroral H Ly α line profiles (solid lines), compared with the instrument resolution (dashed lines) determined by observations of geocoronal emission. The geocoronal intensities have been scaled up to the observed intensity at rest wavelength to show the fraction of Doppler-shifted emission.

peak auroral emission. The aurora were moderately bright during these exposures, as determined from the low dispersion spectra. In SWP 32390 the Ly α line profile shows both blue-shifted and red-shifted emissions, with again roughly 1/2 of the emission shifted by the SWSA resolution of 0.14 A or more from line center. As a control, SWP 32813 was centered on $\lambda_{III} = 0^\circ$ and $+60^\circ$ latitude, which is 180° from the longitude of brightest aurora. Although no auroral H_2 emission was detected at low dispersion in SWP 32813, there still appears a substantial amount of blue-shifted Ly α emission at high dispersion. Finally, image SWP 16091 at $+80^\circ$ latitude shows predominantly *red*-shifted emission, with roughly 1/2 of the emission shifted from rest wavelength. This spectrum was obtained roughly 6 years before the present observations and at a similar longitude to SWP 32813, but at higher latitude. The appearance of red or blue-shifted emission may therefore depend on position on the planet (and possibly line of sight), or simply be variable with time.

Interpretation

The dominant blue-shift of the auroral Ly α emission, representing motion up out of the atmosphere, implies the acceleration of ionospheric plasma leading to the observed emission(not precipitating particles). The low energy of 10-20 eV for a proton at the observed blue-shift is consistent with this process, as opposed to the KeV-MeV energies of Jovian magnetospheric protons. We therefore identify the motions as produced by electric potentials in the auroral ionosphere, analogous to plasma motions in the Earth's auroral ionosphere. We will refer to the observed line of sight velocities in the following discussion, since we do not distinguish between field-aligned and cross-field components. The several kR brightness of the Doppler-shifted emission implies a power of as much as 10^{13} Watts for this process (assuming a 5% production efficency), which is a substantial perturbation on the ionospheric energy budget. The presence of downward flows at high latitudes and upward flows at lower latitudes is the qualitative configuration required to enforce corotation of magnetospheric plasma (Kennel and Coroniti 1979), and the presence of Doppler-shifted emission in the absence of auroral H_2 emissions in SWP 32813 supports an ionospheric motion (rather than auroral precipitation). However, further observations will be required to establish the vector motions (as opposed to the line of sight velocities presented here).

The excitation of these emissions presents some puzzles. We can rule out dissociative excitation of H_2 by electron impact as the dominant process, partly from the asymmetric line shapes and partly from the observed Doppler-shifted emission in SWP 32813 in the absence of H_2 bands. Fast H_3^+ or H_2^+ may also produce Ly α by dissociative excitation in collisions with H and H_2(Dunn et al. 1962). Both ions have been observed in the Jovian magnetosphere (Hamilton et al. 1981), although these processes are not well characterized for the production of Ly α emission. Processes to produce fast excited state H atoms (H^*) and Ly α radiation based on proton acceleration are:

(1) H^+(fast) + H_2 -> H^*(fast) + H_2+
(2) H(fast) + H_2 -> H^*(fast) + H_2
(3) H^+(fast) + H -> H^*(fast) + H^+
(4) H(fast) + H -> H^*(fast) + H

The cross section for proton charge exchange with H_2 decreases toward lower energies, and in the range 10-50 eV the H atom goes predominantly into the ground state. Cross section measurements for (1) are less than 10^{-19} cm^2 at proton energies below 100 eV, and for (2) roughly 1-2 x 10^{-17} cm^2 below 50 eV (Van Zyl, Gealy, and Neumann 1989). Reactions (3) and (4) could have Ly α emission cross sections as large as 10^{-16} cm^2 by analogy with low energy H^+ and H impact on rare gas atoms (Van Zyl and Gealy 1987). In the collisional environment of Jupiter's ionosphere, accelerated protons will form a beam of H atoms and protons through charge exchange and stripping reactions (Gealy and Van Zyl 1987). The production of Doppler-shifted emission may be dominated by the fast H atoms through (2) and (4), in which case there is a two step process: 1) ionospheric protons are accelerated in situ and charge exchange into fast neutral H atoms, while 2) the resulting fast H atoms are excited through collisions with H and H_2. In this picture the Doppler-shifted emission indicates the magnitude and direction of an ionospheric plasma motion.

The Jovian observations do not appear to represent a simple polar wind of ionospheric plasma toward the magnetotail, since the observed motions are down at high latitudes (connected to the magnetotail) and up at lower latitudes (connected to the Io torus and middle magnetosphere). The Jovian data appear closer to the case of high altitude electric field acceleration of H^+ and O^+ in the Earth's aurora (Mozer et al. 1980). At the Earth H^+ and O^+ ions are created and energized by parallel electric fields or plasma wave processes to the escape velocity, and are subsequently observed as large ion outfluxes in the topside ionosphere and magnetosphere within the cusp and auroral zone regions (Chappell et al. 1987). At high altitudes, proton conics (Klumpar 1979) have been observed in association with electrostatic ion cyclotron turbulence at frequencies close to the proton gyrofrequency (Kintner et al. 1979). These currents are predominantly carried by upward drifts of low energy ionospheric electrons, and the critical drift required to excite the ion-cyclotron instability was studied by Kindel and Kennel (1971). At Jupiter associated current densities in the auroral ionosphere may be over an order of magnitude larger, and such processes may thus occur in the Jovian ionosphere as well.

We will examine the case of current driven instabilities in the following calculation, but we do not rule out the existence of other instabilities and acceleration processes. Lockwood (1984) investigated the stability of the Earth's auroral ionosphere to oxygen cyclotron waves. Using the Lockwood (1984) study as a rough guide, values of the observed near-auroral zone ionospheric profile of Voyager 2, and modeled neutral densities (Waite et al. 1983), we obtain critical current densities on the order of 100 μA-m^{-2}. This leads to an altitude for the critical height below which the instability is quenched of approximately 2000 km in the Jovian auroral ionosphere, where the H^+ density is 5×10^4 cm^{-3} (from Voyager 2 high latitude occultation data) and the H density is 10^8 cm^{-3}. As an example, assuming that Ly α is produced with a cross section of 10^{-16} cm^2, the observed emission brightness of 6.6 kR can be reproduced if 10% of the ions undergo the transverse heating process and lead to Ly α production. The improbably high fraction of 10% of the ions accelerated to supersonic velocities suggests that the acceleration region is more extended in altitude than our calculation assumes. For the sake of argument, however, assuming the H^+ density of 5×10^4 cm^{-3}, a 10% population of fast protons, and a velocity of 6.2×10^6 cm/sec (i.e. 20 eV), there would be an upward flux of 3×10^{10} cm^{-2}-sec^{-1} particles. Accurate values of the cross sections for (2), (3), and (4) will be required before the observed brightness of the emissions can be more reliably related to proton and H atom fluxes in the ionosphere.

The identification of bright FUV hydrogen emission resulting from the in situ acceleration of ionospheric plasma provides support for the mechanism underlying the dynamo theory of the outer planet diffuse FUV emissions (Clarke, Hudson, and Yung 1987). The measured upward motion of the protons/H atoms of 20-30 km/sec also implies a potentially substantial supply of plasma and neutral atoms to the magnetosphere. Assuming the motion is along field lines at 60° latitude the line of sight motion is 0.7 of the field-aligned velocity, implying velocities of 30-40 km/sec compared with the escape velocity of 57 km/sec. A large flux of protons and H atoms may be introduced into the magnetosphere from the auroral zones if the excitation occurs at high altitudes.

Conclusions

We have established an upper limit of 100 R/0.3 A to the contribution of energetic proton precipitation (E > 130 eV) to the production of Jupiter's aurora. However, roughly 1/2 of the auroral H Ly α emission appears Doppler shifted by 30-60 km/sec predominantly toward the blue. We interpret this emission as resulting from the in situ acceleration of ionospheric protons in the auroral zone(with a possible contribution from H_3^+ and H_2^+), forming a beam of upflowing 10-20 eV protons and H atoms which produce fast excited state H atoms through collisions with ambient H and H_2. The several kR of emission by this process requires a considerable amount of energy, and in turn suggests a substantial modification of the auroral ionosphere. The observed velocities also represent a significant fraction of the escape velocity, raising the possibility of a large outflow of H atoms and ions into the Jovian magnetosphere from the auroral zones. Finally, an observation of red-shifted emission at higher latitudes may represent a return flow from the magnetosphere, and the sense of the observed flows is consistent with those expected from the enforcement of corotation of magnetospheric plasma.

Acknowledgements. We thank the IUE Observatory staff for assistance in the acquisition and reduction of the IUE data, and the RDAF's at GSFC and U. Colorado for assistance in the reduction of the spectra. We acknowledge helpful conversations with B. Van Zyl. This work was supported by NASA grant NAG 5-1030 to the University of Michigan.

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(Received: March 16, 1989;
Revised: April 10, 1989;
Accepted: April 11, 1989)