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DOPPLER SHIFT OF AURORAL LYMAN α OBSERVED FROM A SATELLITE

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Abstract. The first documentation of Doppler shifted auroral Lyman α emission resulting from incident energetic protons in the auroral regions has been made using nadir VUV satellite spectral observations. The auroral Lyman α emission from high-velocity protons is expected to show a red shifted wavelength displacement based on ground-based observations of Balmer lines. VUV spectra (1100-1900 Å) taken over five sample auroral oval crossings by a nadir-viewing satellite in 1978 consistently show the Lyman α emission displaced toward longer wavelengths with a larger line width. The intensity peaks were shifted up to 4 Å when the geocoronal Lyman α emission profile was subtracted from the Lyman α emission profile observed over the auroral regions. The optical observations infer the auroral proton precipitation with average energies of 34 keV and an energy flux of 0.1 $\mathrm{erg\ cm^{-2}\ s^{-1}\ sr^{-1}}$ when interpreted according to available model calculations. These values agree reasonably well with the average values for the characteristics of nightside incident auroral protons based on previous statistical satellite particle precipitation observations.

Introduction

Doppler shifted hydrogen Balmer series emission in the auroral regions was first observed by a ground-based spectrometer and used to infer the energy of precipitating protons [Meinel, 1951]. Subsequent calculations and discussions have been presented by Chamberlain [1961] and Eather [1967]. Figure 1 shows a Doppler shifted and broadened Balmer β line observed in a proton aurora compared to the line observed in the laboratory [Zwick and Shepherd, 1963]. Auroral protons, typically 10–40 keV, precipitate into the atmosphere and lose energy through charge-exchange and charge-stripping cycles with atmospheric constituents. Relatively recent detailed computations of the profile of the hydrogen spectral line emission were performed for ground-based observations in the directions of the magnetic zenith and horizon [Ponomarev, 1976]. The profile showed a good match to the observed Balmer line spectra [Galperin et al., 1976].

The Lyman α emission line (1216 Å) from proton precipitation can be observed only from space. In this study we present the first observations of the Doppler shifted profile of the auroral Lyman α line deduced from a polar orbiting satellite and infer the average energy and energy flux of the auroral protons by comparing the observed Doppler shift and broadening with the available model calculations. The Lyman α Doppler shift of 10-eV hydrogen atoms on Jupiter was recently reported in the American Astronomical Society meeting, Division of Planetary Sciences [Clarke et al., 1988], as pointed out by the reviewer of this paper.

Observations

The auroral spectral data were obtained by an AFGL UV background experiment flown on the S3-4 satellite in 1978 [Huffman et al., 1980]. On board the satellite, which was in a low-altitude (180-270 km) polar orbit near the noon-midnight meridian plane, was the nadir-viewing 1/4-m, f/5 Ebert-Fastie spectrometer. Fifteen spectra with 8 Å resolution were selected for analysis during periods of strong Lyman emission. All the spectra were taken at a satellite altitude of about 260 km. Table 1 lists the geometrical and geophysical information along with the spectral characteristics from five auroral oval crossings. Figure 2a is an example of the nadir Lyman

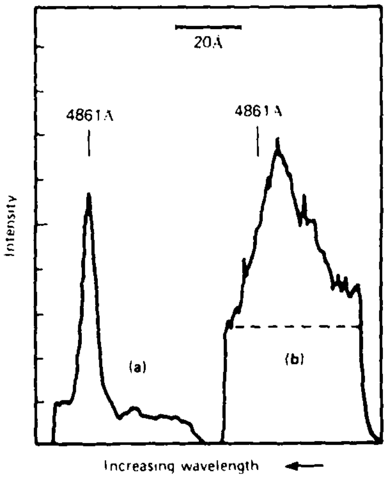

Fig. 1 Examples of hydrogen Balmer β line profiles [from Zwick and Shepherd, 1963]; (a) a hydrogen lamp source, (b) a magnetic zenith profile of a proton aurora.

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TABLE 1. Summary of Lα spectra.

	UT							Intensity (kR)			Spectral profile (Å)			Energy	Energy flux
Date	h	m	s	Kp	AE	GMLAT	SZA	Geo. + Aur.	Geocorona	Aurora	Red shift	Geo. HWFM	Aur. HWFM	(keV)	(erg/cm^{2}s)
5/1	7	18	34	6-	600	-67.9	116.2	3.48	1.85	1.63	2.82	8.02	10.92	28.	0.49
	7	18	56		600	-67.0	117.6	3.29	1.73	1.56	2.47	8.02	11.78	24.	0.42
	7	54	54		500	63.3	95.3	5.76	3.79	1.97	4.44	8.02	9.91	48.	0.88
6/5	10	1	36	3+	500	-72.3	115.8	1.94	1.48	0.46	3.35	8.08	12.28	35.	0.16
	10	1	58			-72.6	117.1	1.95	1.43	0.52	1.55	8.08	12.07	13	0.09
	10	2	20			-72.5	118.5	1.80	1.43	0.37	4.76	8.08	9.89	52.	0.17
	10	3	05			-72.4	119.9	1.85	1.29	0.56	4.40	8.08	12.71	48.	0.25
	10	3	27			-72.2	121.3	1.75	1.24	0.51	3.14	8.08	12.78	32.	0.17
	10	3	49			-71.8	122.6	1.80	1.15	0.65	4.30	8.08	12.84	47.	0.29
6/27	12	57	23	3	550	-61.0	148.1	1.63	0.75	0.88	2.82	7.97	10.34	28.	0.27
	12	57	45			-59.7	149.3	1.63	0.74	0.89	2.95	7.97	11.56	30.	0.28
7/8	6	4	34	3-	250	-69.7	120.7	1.57	1.13	0.44	2.69	8.02	11.02	27	0.13
	6	4	56			-68.7	122.0	1.67	1.08	0.59	3.35	8.02	11.28	35.	0.21
7/14	17	26	38	5+	250	-65.4	114.2	1.35	0.93	0.42	2.46	8.51	10.71	24.	0.11
	17	26	50			-63.9	195.4	1.65	0.93	0.72	3.92	8.51	10.39	42.	0.29
Averages										0.8	3.3			34.	0.3

α line intensity as observed along the entire orbit on May 1, 1978. The geocoronal Lyman α line intensity shows a strong correlation with the solar zenith angle. Figure 2b shows two spectra, one from the proton auroral region and the other from the midlatitude region. The latter is the average of 22 nighttime geocoronal spectra to reduce noise and has the 8 Å half width full maximum (HWFM) line profile. The former has a broader 10 Å HWFM spectral profile with a peak red shifted by 2 Å, indicating that some emission is from high-speed hydrogen moving away from the satellite toward the earth.

Two steps were needed in order to deduce the auroral Lyman α: first, the geocoronal background intensity was estimated by interpolation of the smoothed geocoronal intensities outside the auroral region; second, the geocoronal Lyman α profile with the estimated background intensity was subtracted from the observed Lyman α profile over the proton auroral region as shown in Figures 3a-f. The peak shifts and the HWFM width of the remaining auroral spectra are shown in Table 1; the auroral Lyman α spectrum is broader than that of the geocorona by ~2 Å.

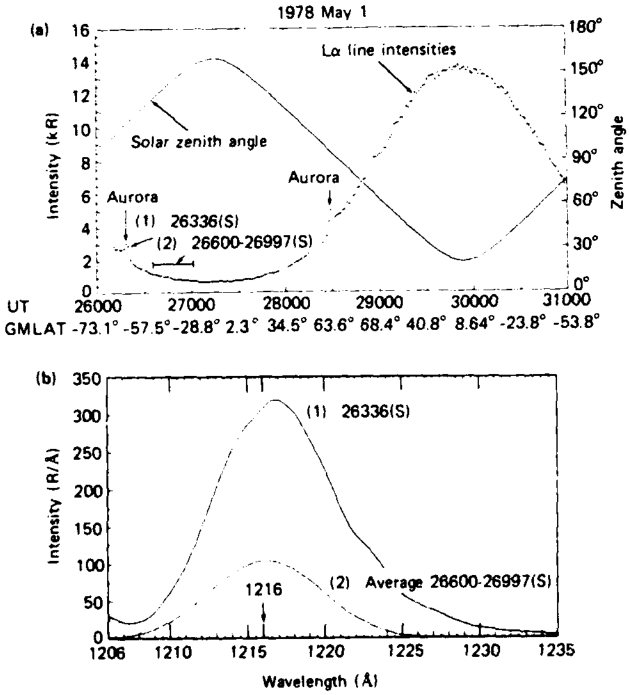

Fig. 2 (a) Observed Lyman α line intensity and solar zenith angle of the S3–4 throughout an orbit. (b) Comparison of the Lyman α profiles taken from auroral and midlatitude regions (the corresponding observation times were indicated in Figure 2a).

Discussion and Conclusions

We used the hydrogen line spectral profiles of auroral protons computed by a Monte Carlo method as our model [Ponomarev, 1976]. The model takes into account the charge-exchange and proton-beam stripping processes in the three dimensional model atmosphere and uses the cross sections of McNeal and Birely [1973]. Figure 4 shows the profile calculated for an isotropic pitch angle distribution as a function of the Doppler velocity in two viewing directions. The centroid of the profile shifts to a more negative Doppler velocity as seen from the ground with increasing energy of the monoenergetic beam. In order to compare this model with our space-based observations, the profiles of Figures 4b and c were transformed for the 1216 Å line and also smeared for 8 Å spectral resolution. Figure 5a shows the increase of both the Doppler shift and the broadening with the increasing energy of the protons as viewed downward from the satellite. In order to reduce the noise level, we averaged six spectra from the same auroral oval pass on July 5 and subtracted the estimated geocoronal Lyman α profile (Figure 5b). Figure 5c illustrates the remaining (i.e., auroral) spectrum and two model spectra calculated for two proton energies. The general shape of the auroral profile matches the calculated 30-keV profile. The observed profile is broader than the 30-keV model profile, as expected, because the energy spectrum of the auroral protons is not a monoenergetic beam and the deduced auroral spectrum is from an average of six spectra. Taking these facts into consideration, the auroral spectrum matches the 30-keV model calculated profile very well.

According to Ponomarev's calculation for isotropic proton precipitation, the spectral peak shift, Δλ, can be related to the proton energy, E_0, by the equation:

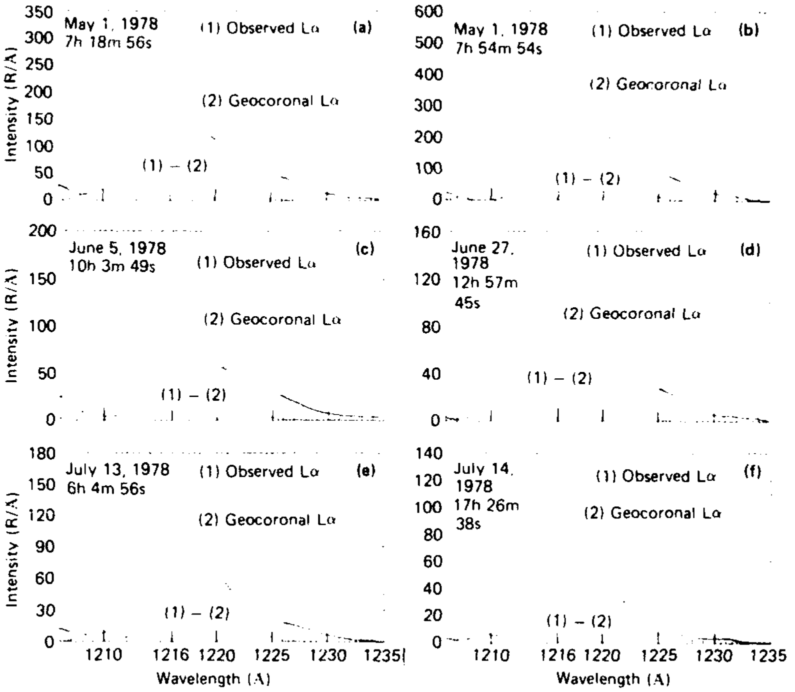

Fig. 3. Examples of Lyman α profiles from an auroral region. The estimated geocoronal Lyman α profile (dotted line) was subtracted from the observed profile to reveal the Lyman α profile from the proton precipitation (designated (1) − (2)).

$$E_0 = 12.321 \times \Delta\lambda - 6.291.$$

Using this equation, the mean energy of auroral protons can be estimated (Table 1). The values are, in general, higher than those from statistical study of ion precipitation measurements reported by Hardy et al. [1988], which are about 20 keV in the midnight region for Kp > 3. However, the DMSP measurement was limited to energies from 30 eV to 30 keV and some spectra were extrapolated to 100 keV to include the high-energy tail of the ion distribution. This extrapolation increased the average energy and the energy flux by less than 30% and 50%, respectively. The Lyman α spectra used here were among the most intense proton emissions in our satellite data set, corresponding to very active periods (up to Kp = 6−). A higher mean energy than the statistical value is expected, because there is no temporal or spatial averaging, which would smooth down the high values. Therefore, the agreement between our inferred and averaged measured proton energy is reasonable.

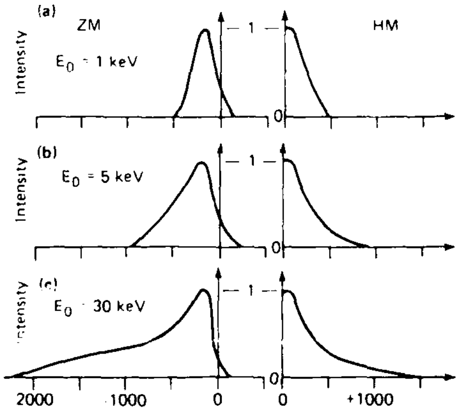

Fig. 4. Hydrogen line profile in the proton aurora as a function of the Doppler velocity computed by the Monte Carlo technique. The geomagnetic zenith (ZM) and horizon (HM) profiles are calculated for an isotropic distribution of the pitch angle for protons of monoenergetic energies of 1, 5, and 30 keV [from Galperin et al. 1976].

For the energy flux estimation, we used the Lyman line emission intensity calculated by Edger et al. [1973] with the emission cross section increased by 22% as suggested by Van Zyl and Newmann [1988]. The estimated energy fluxes are derived using the proton energy inferred from the observed profile (the last column of Table 1). The average value estimated from the observation is ~0.3 erg cm^{-2} s^{-1}. This value would be divided by 3 for the integrated solid angle for comparison with the statistical particle precipitation measurements of 0.1 erg cm^{-2}s^{-1}sr^{-1} reported by Hardy et al. [1988]. Thus, the observed auroral Lyman α profile and emission intensity are consistent with the existing model calculations and ion precipitation measurements. These observations suggest that sensitive high-resolution spectral measurements from a satellite can be used for global imaging of the characteristics of the proton precipitation. However, specific calculations of the resulting Lyman α emission profile expected for different nadir viewing angles, including multiple scattering effects on the emission profile, would be required.

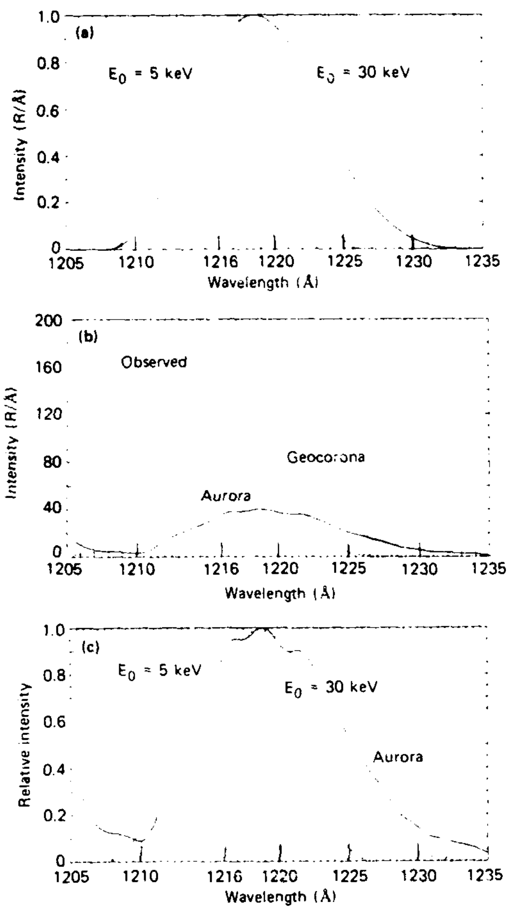

Fig. 5. Comparison of the auroral Lyman α profiles: observed and calculated. (a) Lyman α spectral intensity profile in the proton aurora adapted from model calculations of Ponomarev [1976]. (Figures 4b and 4c are translated from the Doppler velocity to the wavelength.)
(b) Auroral Lyman α spectral intensity profile observed on June 5, 1978. OBSERVED: an average of six consecutive auroral spectra. GEOCORONA: the estimated intensity with a profile of an average of 12 midlatitude spectra from the same orbit. AURORA: OBSERVED – GEOCORONA.
(c) Comparison of observed auroral Lyman α spectral relative intensity profile (AURORA profile in (b)) and model calculation (in (a)).

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