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OBSERVATIONS FROM EARTH ORBIT AND VARIABILITY OF THE POLAR AURORA ON JUPITER

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ABSTRACT

Spatially resolved spectra of Jupiter taken with the *International Ultraviolet Explorer* satellite show enhanced emissions from the polar regions at H Lα (1216 Å) and in the Lyman and Werner bands of H_2 (1175–1650 Å). Two types of variability in emission brightness have been observed in these aurorae: an increase in the observed emission as the auroral oval rotates with Jupiter's magnetic pole to face toward the Earth and a general variation in brightness of more than an order of magnitude under nearly identical observing conditions. In addition, the spectral character of these aurorae (determined by the ratio of H Lα to H_2 brightnesses) appears variable, indicating that the depth of penetration of the auroral particles is not constant.

Subject headings: planets: Jupiter — planets: magnetospheres

The first indications of H_2 Lyman-band emission on Jupiter were recorded in the sounding rocket spectra of Rottman, Moos, and Freer (1973) and Giles, Moos, and McKinney (1976), who observed the whole planet and detected weak emissions between 1250 and 1650 Å. Giles *et al.* tentatively identified these emissions as Lyman bands of H_2 excited by low-energy electrons. Recently the *Voyager 1* and *Voyager 2* UVS experiments have positively identified H_2 Lyman- and Werner-band (875–1150 Å) and H Lα (1216 Å) emissions from Jupiter's polar regions; they conclude from their observing geometry that a source of these diffuse aurorae is the passage of particles through the Jovian upper atmosphere along magnetic field lines which are connected to the Io plasma torus (Broadfoot *et al.* 1979; Sandel *et al.* 1979). Other potential particle sources are the magnetic flux lines from the antisolar Jovian magnetotail (Ness *et al.* 1979), which is the operative mechanism in the case of the Earth's aurora, and flux lines from the satellite Io itself (Dessler and Chamberlain 1979). In fact, Atreya *et al.* (1977), using the *Copernicus* satellite, have reported an enhancement in H Lα emission from a localized region on the planet near the foot of the Io flux tube.

We report here recent observations of Jupiter with the short-wavelength spectrograph of the *IUE* Observatory (Boggess *et al.* 1978; Lane *et al.* 1978) which show highly variable H Lα and H_2 Lyman-band emission from the polar regions. Previous searches from the ground for visible H auroral emission (6563 Å) have been inconclusive (see Dulk, Eddy, and Emerson 1970, and references therein). The localized ultraviolet emissions discussed here permit the first definite identification of diffuse polar aurorae from another planet using an Earth-based observatory.

The large entrance aperture to the *IUE* spectrograph is roughly elliptical in shape, subtending a region 23″ long by 10″ wide. The image of this aperture is focused directly onto the detector camera face at each wavelength, providing spatial imaging over a 10″ by 23″ region. The dispersion direction is roughly along the 10″ minor axis of the aperture. The spatial resolution of the instrument on planetary objects is $\sim$6″. The correction for the sensitivity variation along the slit was obtained from exposures of diffuse geocoronal H Lα emission. In the observations reported here, a series of 15 minute exposures were obtained in the spectral range 1175–1950 Å with roughly 11 Å spectral resolution. By moving the Jupiter image 10″–15″ along the major axis of the aperture (which is constrained to point roughly north-south), north-south maps of the $\sim$36″ diameter Jovian disk were obtained at each of these wavelengths.

Figure 1 (Plate L3) shows a photographic representation of the raw data from the first three sets of exposures, taken on 1978 December 9, 1979 May 19, and 1979 June 7. Emission features from the polar regions at 1608 Å and around 1570 Å were clearly present on 1979 May 19, while these features were weak or nonexistent on the other days. The sum of the two polar spectra taken on 1979 May 19 (SWP 5307 and 5309) is plotted in Figure 2, along with the equatorial spectrum (SWP 5308) recorded on the same day. The equatorial spectrum appears qualitatively different from the polar spectra; this is confirmed by longer exposures of the equatorial region. Similar auroral emissions were detected from the polar regions in 1980 May (see Fig. 2), and weak features due to the H_2 bands were also observed in 1979 February. The auroral spectra are well correlated both in wavelength and relative intensity with the laboratory spectrum (1270–1640 Å) of an H_2 discharge lamp (Fastie and Kerr 1975), also plotted in Figure 2. The H_2 lamp spectrum has been corrected for detector response but not for the transmittance of the MgF_2 optics. The Lyman- and Werner-band emissions in the lamp spectrum are excited by low-energy ($T_e \approx$ 1–10 eV) electrons; the similarity between the planetary and the laboratory spectra indicates that electron impact is a likely excitation mechanism for the Jovian emissions.

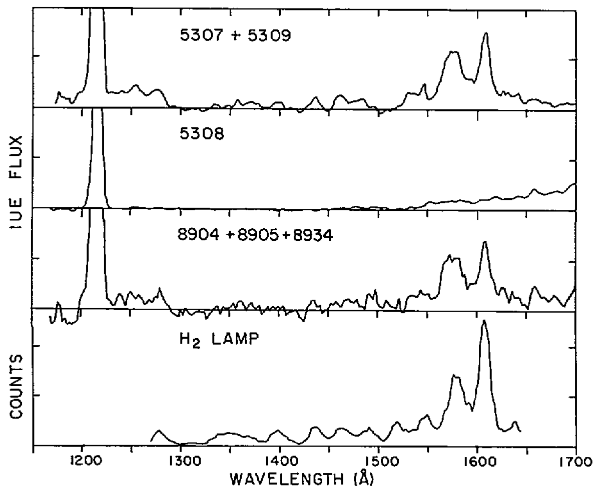

FIG. 2.—Slit-integrated spectra of Jupiter's polar regions (sum of SWP 5307 and SWP 5309) and equatorial region (SWP 5308) in 1979 May, and from the polar regions (sum of SWP 8904, 8905, and 8934) in 1980 May. These spectra are corrected for instrument sensitivity and plotted with different vertical scales. The laboratory spectrum of an H_2 discharge lamp is smoothed to 11 Å resolution to simulate the *IUE* spectral resolution.

A dramatic enhancement in H Lα emission in the polar region was also seen on 1979 May 19 but was absent on 1978 December 9 and 1979 June 7, indicating that it too is auroral in origin. Since Figure 1 was printed to emphasize the emission near 1600 Å and the Lα features appear overexposed, the north-south H Lα intensity distribution (corrected for slit response) is plotted in Figure 3. The *IUE* spatial maps normally show a falloff in the H Lα emission toward the poles similar to the limb darkening reported by Broadfoot *et al.* (1979) and Clarke *et al.* (1980); these emission profiles have been interpreted as predominantly resonantly scattered solar Lα radiation by these authors. However, it is clear from Figure 3 that H Lα brightening at the poles is also a distinct signature for observing Jovian aurorae from Earth orbit.

The north-south spatial extents of the H_2 and Lα emissions are comparable to the 6″ response of the instrument. Therefore, these emissions must have come from regions near the poles much narrower than 6″ in the north-south direction, and the latitudinal extent of the Jovian auroral oval is not measurable with the *IUE*. An east-west asymmetry at Lα was also noted in the 1979 May 19 exposure of the north pole (SWP 5309) in which the 1216 Å flux is enhanced in the eastern half of the aperture, toward Jupiter's north pole. This enhancement in emission may indicate either a localized source or a diffuse source partially filling the aperture (see Fig. 3, top). The data on the southern region (SWP 5307) indicate an auroral source which is diffuse in the east-west direction. To set an upper limit on the size of the observed auroral regions, it is assumed that the strongly emitting region in the southern exposure was 2″ in the north-south direction and the width of the slit (10″) in the east-west direction; the northern region is assumed to have been 2″ north-south and two-thirds the width of the slit (6″.7) east-west. A chart of the auroral brightnesses for all polar exposures to date is given in Table 1, assuming an emitting area 2″ by 10″, except for SWP 5309, as previously noted. The upper limits in H_2 emission brightness quoted in Table 1 represent the total H_2

TABLE 1

JOVIAN AURORAL BRIGHTNESSES

Image Number	Pole	Date	λ_{III}CML (1965) (degrees)	ϕ_{Io} (degrees)	Brightnesses (kR)	
					H Lα	H_2 Bands
SWP 3563......	N	1978 Dec. 9	168	207	...	<3.7
SWP 4442......	S	1979 Feb. 28	0	299	...	~6.6
SWP 5307......	S	1979 May 19	80	165	17	55
SWP 5309......	N	1979 May 19	154	182	42	100
SWP 5450......	N	1979 June 7	321	45	...	<4.7
SWP 5451......	S	1979 June 7	348	51	...	<8.4
SWP 8890......	S	1980 May 2	5	229	...	<4.3
SWP 8892......	N	1980 May 2	72	245	...	<5.0
SWP 8901......	S	1980 May 3	28	44	...	<4.6
SWP 8903......	S	1980 May 3	93	59	...	<8.2
SWP 8904......	N	1980 May 3	125	66	20	28
SWP 8905......	N	1980 May 3	157	74	28	30
SWP 8934......	N	1980 May 5	163	136	16	34

emission which would correspond to a 1608 Å feature brightness equal to 3 σ in the spectral noise level around 1608 Å. Upper limits have been set on the H_2 emission rather than the H Lα emission, since the planetary background is much lower at 1608 Å than at 1216 Å. As a comparison to the *Voyager* data, note that the H Lα auroral brightness reported by Sandel *et al.* (1979) would correspond to 45 kR if spread over a 2″ north-south zone. The main uncertainty in these *IUE* brightnesses is the assumed area of the emitting regions, not the *IUE* flux calibration.

To correlate these emissions with potential auroral sources, Figure 3 shows the regions of the Jovian disk observed with the *IUE* large aperture in the 1979 May 19 exposures. The circular lines near the poles indicate the location, at the top of the atmosphere, of the magnetic field lines connected to the Jovian magnetotail. The lines slightly closer to the equator represent the

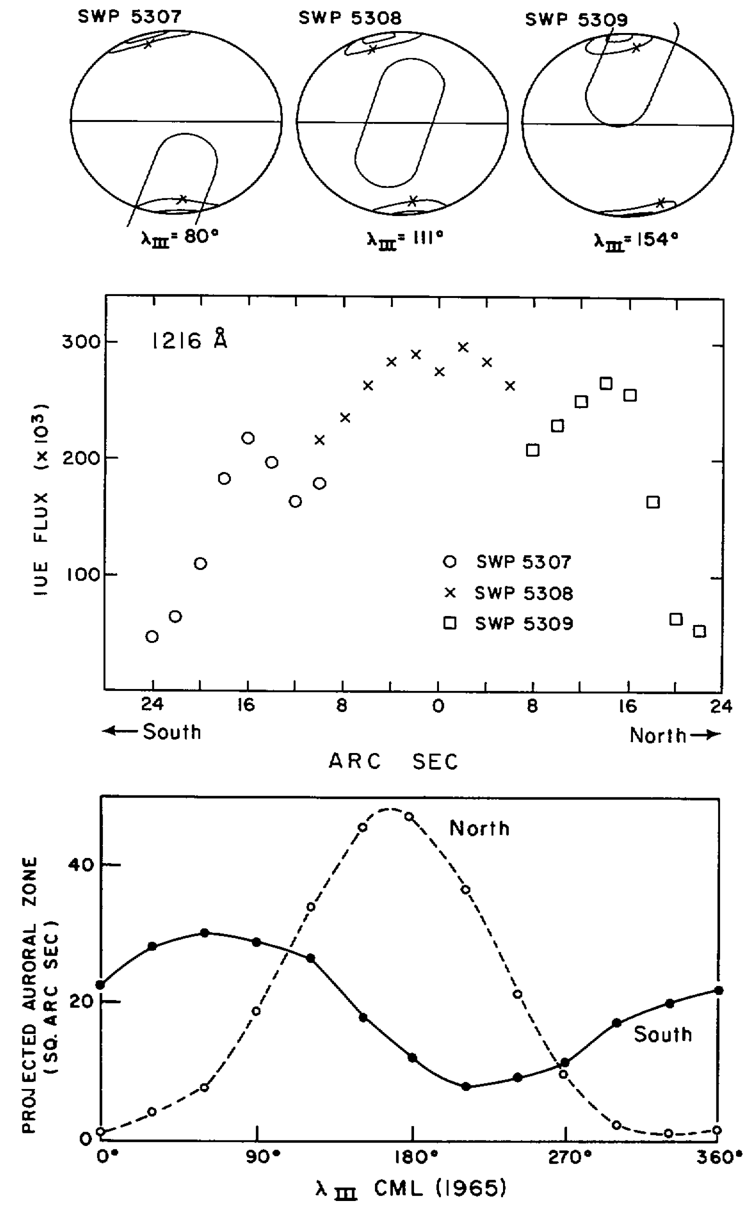

FIG. 3.—(*Top*): The large entrance aperture superposed on the predicted auroral sources at the time of the 1979 May 19 observations, taking into account a 30–40 minute light-time correction between Jupiter and the Earth. Magnetic longitude of the central meridian is indicated in λ_{III}(1965) coordinates. The auroral sources indicated by lines and an X are discussed in the text. (*Center*): North-south intensity variation in the H Lα flux measured in the above observations. This data has been corrected for relative response at different points in the aperture. (*Bottom*): Apparent area of Jupiter's predicted auroral zones poleward of the Io torus field lines (as viewed from the Earth) plotted as a function of longitude.

location of the flux lines connected to the Io plasma torus, which have been suggested as the source of the diffuse aurora (Sandel *et al.* 1979). The position of the foot of the flux tube from Io is indicated by an **X**, following the model of Acuna and Ness (1976); according to the theory of Dessler and Chamberlain (1979), the active region follows the foot of the flux tube of Io by 30°–40° in magnetic longitude (λ_{III}[1965] coordinates) and would have been in our slit. In the observations of 1979 June 7 the observing geometry was generally unfavorable for observing the predicted auroral zones, and no auroral emissions were observed. However, in the north pole observations on 1978 December 9 and 1979 May 19 the observing geometry was nearly identical, and all three potential sources were within the field of view; yet strong emissions were observed only on the latter date. A Lα image obtained from a rocket on 1978 December 1 should also have shown polar enhancement if the aurorae were active—but did not (Clarke *et al.* 1980). These results indicate that other factors, in addition to observing geometry, are important in the production of the Jovian aurorae (e.g., Jupiter's auroral emission may vary dramatically as a function of magnetospheric conditions in the vicinity of Io and its associated plasma torus).

The strength of the auroral signals indicates that the *IUE* satellite can be used for long-term monitoring of the Jovian aurorae to study the dependence on magnetic geometry and to investigate possible controlling mechanisms. One such experiment was performed in the observations of 1980 May 2–5. Table 1 lists the observed emission brightnesses, the longitude of the central meridian on Jupiter, and the position angle ϕ_{Io} of Io in its orbit (measured from superior geocentric conjunction) at the times of all observations. Note that the northern auroral zones (following the model of Ness *et al.* 1979) reach a maximum tilt toward the Earth when λ_{III}CML (1965) is around 170°, and the southern zones when λ_{III}CML is around 70°; this effect is modeled in Figure 3 (bottom), where the observable area of the Jupiter disk poleward of the Io torus field lines is plotted as a function of longitude. There is a good correlation between the appearance of aurorae in exposures SWP 8901–8934 and the visibility of the auroral zones. Furthermore, all of the aurorae observed to date appeared within the longitude range $0° < \lambda_{III}$ CML $< 170°$, although they do not always appear active in that region. No strong correlation has been determined between the position of Io in its orbit and the occurrence of aurorae, other than to note that to date aurorae have been observed only when $60° < \phi_{Io} < 180°$.

Finally, it is significant that the aurorae appear to vary in spectral character as well as in brightness. The ratio of H Lα to the total H_2 brightness is significantly higher in the aurorae of 1980 May than in those observed in 1979 May and also appears to vary between exposures in the 1980 May spectra. At this point in the investigation, the effects of observational geometry cannot be ruled out. However, the enhancement of the H Lα emission may indicate incoming primary particles with relatively lower energies; these would produce aurorae at higher altitudes where both the number density of H increases with respect to that of H_2 and radiation of $\lambda \lesssim 1450$ Å is more likely to escape absorption by methane and other hydrocarbons in leaving the atmosphere.

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REFERENCES

Acuna, M. H., and Ness, N. F. 1976, *J. Geophys. Res.*, **81**, 2917.
Atreya, S. K., Yung, Y. L., Donahue, T. M., and Barker, E. S. 1977, *Ap. J.* (*Letters*), **218**, L83.
Boggess, A., *et al.* 1978, *Nature*, **275**, 377.
Broadfoot, A. L., *et al.* 1979, *Science*, **204**, 979.
Clarke, J. T., Weaver, H. A., Feldman, P. D., Moos, H. W., Fastie, W. G., and Opal, C. B. 1980, *Ap. J.*, in press.
Dessler, A. J., and Chamberlain, J. W. 1979, *Ap. J.*, **230**, 974.
Dulk, G. A., Eddy, J. A., and Emerson, J. P. 1970, *Ap. J.*, **159**, 1123.
Fastie, W. G., and Kerr, D. E. 1975, *Appl. Optics*, **14**, 2133.
Giles, J. W., Moos, H. W., and McKinney, W. R. 1976, *J. Geophys. Res.*, **81**, 5797.
Lane, A. L., *et al.* 1978, *Nature*, **275**, 414.
Ness, N. F., *et al.* 1979, *Nature*, **280**, 799.
Rottman, G. J., Moos, H. W., and Freer, C. S. 1973, *Ap. J.* (*Letters*), **184**, L89.
Sandel, B. R., *et al.* 1979, *Science*, **206**, 962.

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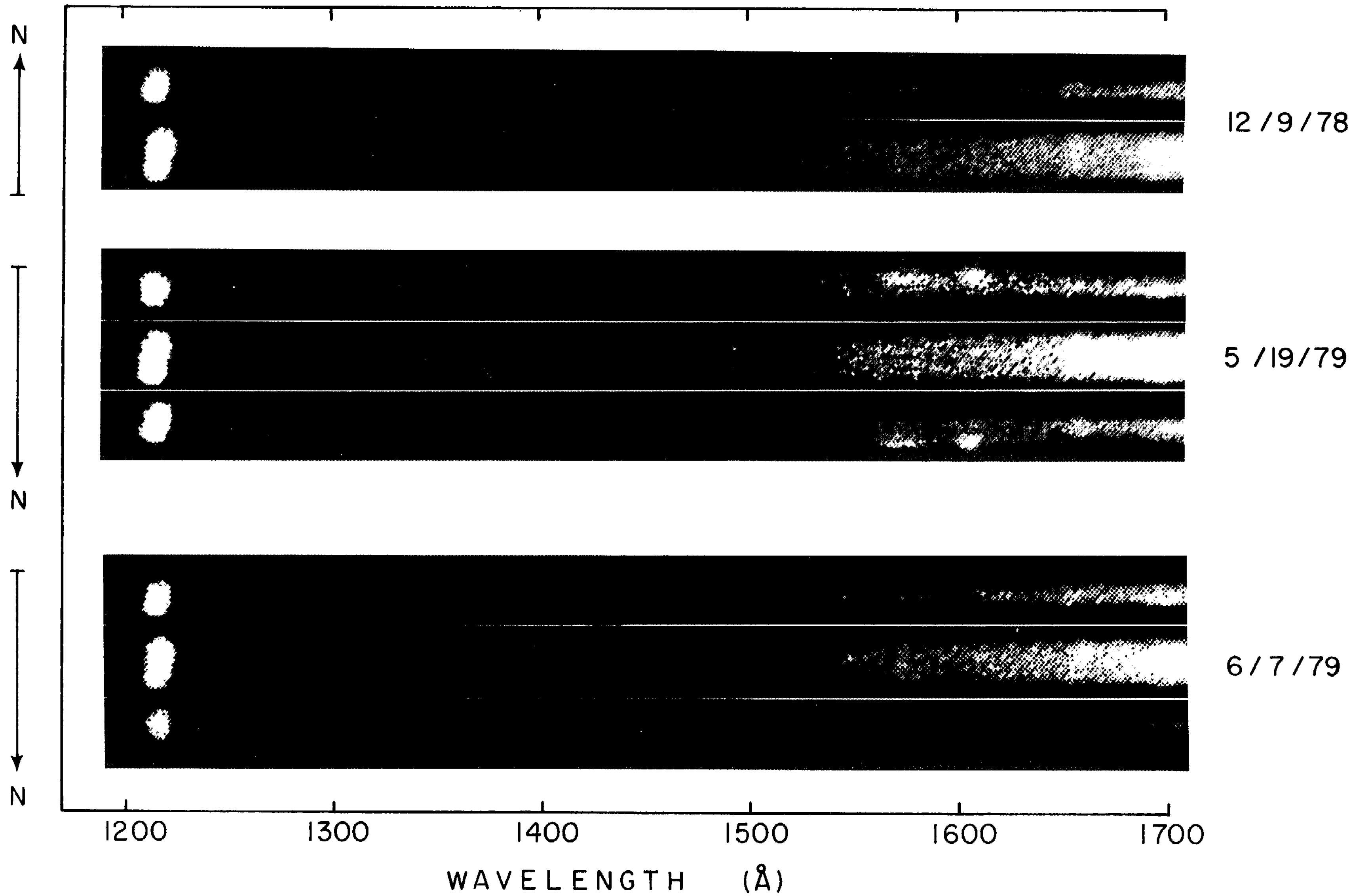

FIG. 1.—Raw data from three sets of north-south spectral maps of Jupiter, shown as photowrite images of the detector camera face reconstructed from the digital data. The H Lα (1216 Å) flux shows clearly the outline of the large entrance aperture and the sharp drop in flux at the edge of the planet.

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