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Visible Aurora in Jupiter's Atmosphere?

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The darkside limb pictures obtained by the imaging experiment on Voyager 1 have been reexamined. It is concluded that the observed luminosity is very likely due at least in part to Io torus aurora. If the effective wavelength of the emission lies in the 4000- to 5000-Å region, the slant intensity is estimated to be about 20 kR. The observed double structure may be due to a number of causes such as horizontal structure in auroral emission, aurora plus twilight or photochemical airglow plus aurora.

Aurora on Jupiter was unambiguously detected in the extreme ultraviolet by means of the UV spectrometer on Voyager 1 by *Broadfoot et al.* [1979]. Further data from Voyager 2 were reported by *Sandel et al,* [1979]. Although the spatial resolution attained by this instrument is not high, the observed enhancements in the Lyman and Werner bands of H_2 and $L\alpha$ are clearly associated with the polar cap regions and in particular with the footprints of the Io plasma torus. In addition to these observations there was also evidence for aurora or airglow emission in darkside limb pictures obtained by the wide-angle camera of the imaging experiment [*Smith et al.,* 1979]. Two such pictures were obtained and one of these was reproduced as Figure 10 of Smith et al. The purpose of this paper is to update the very brief tentative interpretation of these results given by Smith et al.

The second picture of the darkside polar limb is shown as Figure 1. This picture is composed of three separate exposures of 53 s each plus three slews of 11 s each. Analysis of the pointing directions during this picture and the one reproduced as Figure 10 by Smith et al., herein presented as Figure 2, has shown that the slew directions for Figure 1 were approximately perpendicular to the limb, whereas for Figure 2 the slews were almost parallel to the limb. As a consequence the three limb images appear separately on Figure 1 whereas on Figure 2 they are almost superposed. The preliminary interpretation (Smith et al.) of Figure 1 as showing three separate auroral layers at different heights must consequently be abandoned. On the other hand, the double structure of the emitting layer of Figure 2 appears to be real and indeed careful examination of Figure 1 shows that this structure is repeated in each of the three component exposures.

For the explanation of the double structure of Figure 2 there are, in principal, two possibilities: (1) Vertical structure, i.e., two horizontal uniform layers at different heights; (2) Horizontal structure, i.e., two features at the same height, one above the limb, the other silhouetting the limb from beyond, in the manner of the well-known bands of terrestrial aurora.

These hypotheses must be considered in the light of the fact that the limb as determined by occulation of a star [*Cook et al.,* 1979*a*] coincides closely with the bottom of the lower feature. This would imply that the lower layer extends right down to the haze layer. If the upper layer extends over the limb, its height (lower border) is measured to be approximately 500 km above the haze layer. If the upper layer is assumed to be the same auroral emission region observed by the EUV spectrometer, the location would necessarily lie approximately 10° over the horizon, since the emission originates near the exobase region at about 1700 km according to the analysis by Shemansky et al. (manuscript in preparation, 1981).

In the case of horizontal structure, the upper feature of Figure 2 could be a band or layer located near the limb, whereas the lower feature could be a band at the same height but further away and partially eclipsed by the horizon.

The locations of the emission of Figure 2 fit quite well with the foot of the Io torus as given by *Acuna and Ness* [1976]. The latitude-longitude net corresponding to Figure 2 has been given by *Cook et al.* [1979*b*]. From the viewpoint at which the pictures were taken, the foot of the torus lies very close to the limb over just the range that the emission is seen in the pictures. Thus the hypothesis that at least one of the luminous layers is due to the torus aurora satisfies the important test of physical location.

An estimate of the intensity of the emission was made from Figure 2. From the camera calibration and the digital image listing the brightest parts of the limb emission of Figure 2 were determined to be 2175 S_{10} units (10th magnitude stars per square degree). The wavelength distribution of 'auroral' emission in the visible region is not known, and consequently, it is not possible unambiguously to calculate an intensity. The observations, however, imply that

$$\int s(\lambda)B_a(\lambda)\,d\lambda = 2175 \int s(\lambda)B_s(\lambda)\,d\lambda \qquad (1)$$

where $s(\lambda)$ is the camera relative sensitivity, $B_a(\lambda)$ is the auroral differential brightness, and $B_s(\lambda)$ is the differential brightness of a source brightness equal to one S_{10} unit.

From *Allen* [1963] we know that $B_s(\lambda)$ is 0.0036 R/Å at 0.55 μm, while the spectral distribution of B_s can be taken as that of the solar spectrum. The camera relative sensitivity $s(\lambda)$ is given by *Smith et al.* [1977]. Thus the right-hand side of (1) was computed to be 13.6 kR. This would be the intensity of the emission if it were due to a feature at the wavelength of

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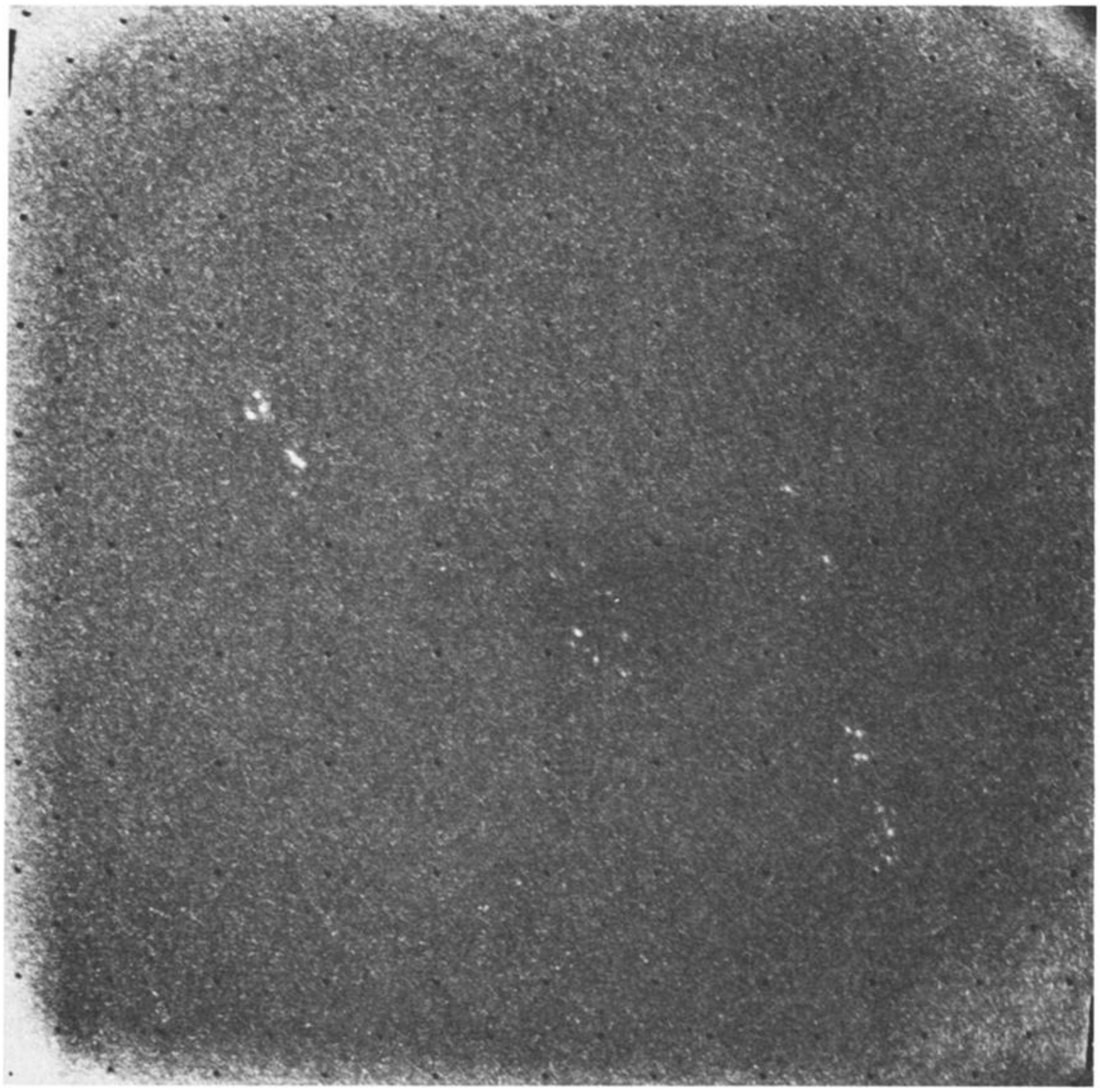

Fig. 1. Darkside multiple image view of Jupiter taken about 6 hours after closest approach by Voyager 1 with the wide-angle camera while the spacecraft was in eclipse. Jupiter's north pole is on the limb near the top right-hand corner of the picture.

peak sensitivity of the camera (~4200 Å). If most of the signal were due to Hβ, its intensity would be about 22 kR.

The possible origins and locations of the luminous layers will now be discussed on the basis of these observations. Let us examine the hypothesis that the upper layer is the torus aurora. The excitation of H_2 and H by electrons gives rise to emission in the 4000- to 6000-Å region through a number of discrete and continuum transitions. We do not consider all of the excitation processes here but include those which are known to provide a significant contribution to the radiative spectrum. Three basic source processes provide emission from excited neutral hydrogen:

(R1) $e + \mathrm{H} \rightarrow \mathrm{H} + h\nu + e$

(R2) $e + \mathrm{H}_2 \rightarrow \mathrm{H} + \mathrm{H} + h\nu + e$

(R3) $e + \mathrm{H}_2 \rightarrow \mathrm{H}_2 + h\nu + e$

We discuss each of these sources below. However, we note at the outset that the excitation conditions considered here are relatively simple and are meant only to demonstrate that there may well be enough emission in the visible region to account for the observations. It is assumed for example that H_2 is excited mostly from the $X\ {}^1\Sigma_g{}^+\ v = 0$ level, whereas the state may show some vibrational development if it occurs close to the exobase as indicated by the EUV observations. We assume in the calculations given below that the exciting electron flux has an E^{-n} differential energy flux distribution similar to that of an average earth aurora with $n = 1.4$. The exact nature of the electron energy distribution is not critical to this rough calculation unless the primary electrons are predominantly in the near-threshold energy region.

$$e + \mathrm{H} \rightarrow \mathrm{H} + h\nu + e$$

Electron excitation of optically thin atomic hydrogen gives rise to strong lines in the Lyman series in the EUV and relatively weak emission in the Balmer and higher series. However, under optically thick conditions the Lyβ and higher members of the Lyman series are converted through flourescence into Balmer series transitions at longer wavelengths. The strong Lyman series lines are optically thick close to the source region even at the exobase on Jupiter (Shemansky et al., manuscript in preparation, 1981). Statistical equilibrium for the atomic hydrogen system calculated by the method described by *Shemansky and Smith* [1981] is shown in Table 1 on an absolute scale for a zenith observation, based on the

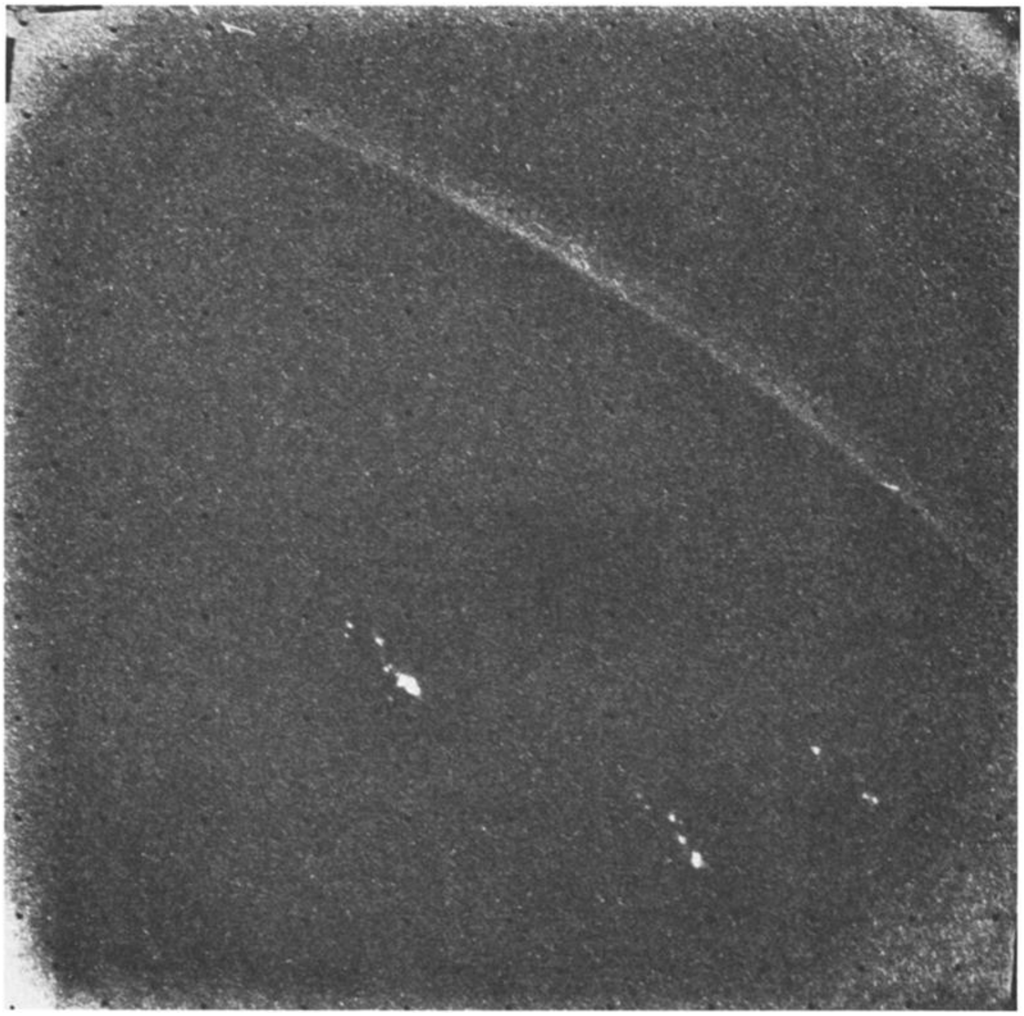

Fig. 2. Similar picture obtained just before that of Figure 1. (This is a reproduction of Figure 10 of *Smith et al.* [1979]).

EUV measurements of auroral Lyα [*Broadfoot et al.*, this issue]. The energy dependent collision strengths for the calculation were obtained from calculations of *Baluja et al.* [1978] for the $n = 2$ levels and from Shemansky et al. (manuscript in preparation, 1981) for $n > 2$. A further contribution to the 4000- to 6000-Å region is supplied by the H (1s-2s) two photon continuum [see *Osterbrock,* 1974], also given in Table 1.

$$e + H_2 \rightarrow H + H + h\nu + e$$

The cross-section for dissociative excitation of Lyα (1216 Å) emission has been measured by *Mumma and Zipf* [1971] and by *Carrière and de Heer* [1972]. *Karolis and Harting* [1978] have measured the cross-section for production of Hα and Hβ. The intensities for this process are estimated (Table 1) by using the 80 kR measured intensity of the H_2 Lyman and Werner bands [*Broadfoot et al.*, this issue], and cross-sections adopted by Shemansky et al. (manuscript in preparation, 1981).

$$e + H_2 \rightarrow H_2 + h\nu + e$$

Electron excitation of H_2 produces continuum emission in the $a\ {}^3\Sigma_g{}^+ - b\ {}^3\Sigma_u{}^+$ transition. The distribution of emission has been calculated by using the formulation of *Coolidge et al.* [1936] and *James and Coolidge* [1939]. The excitation has been placed on an absolute scale using the measured cross-section by *Böse* [1978] in the 2820- to 3450-Å region. The *Böse* [1978] measurements appear to be consistent with the total cross-section calculations of *Rescigno et al.* [1976]. The estimated intensity in the 4000- to 6000-Å region is given in Table 1.

The Fulcher α bands ($d\ {}^3\Pi_u - a^3\Sigma_g{}^+$) have a significantly large cross-section for electrons according to the measurements by *Möhlmann and de Heer* [1976] and contribute an estimated 1 kR to the 4000- to 6000-Å region (Table 1). We have neglected a number of other weaker singlet and triplet systems that, in total, may contribute additional measureable emission.

The total emission rate in the 4000- to 6000-Å region based on the transitions discussed above is approximately 5 kR (Table 1). An enhancement factor of 4 at the limb appears to be reasonable given the geometric configuration at Jupiter. If we assume that the upper layer is the torus aurora, the emission layer located at 1700-km altitude as noted above would require a layer position approximately 10° over the horizon. If the majority of the emission is generated within a vertical scale height region as one would normally expect, the layer would have a thickness of ~200 km (T = 1000 K). The path length in the excitation region would then be ~ 1100 km, a factor of 5 longer than a zenith observation. *Sandel et al.* [1979] estimated an auroral zone width of 6000 km so that a 1000-km path would be entirely inside the source region. Un-

TABLE 1. Estimated Zenith Intensities (kR) for Electron Excitation of Hydrogen on Jupiter

Excitation	Intensities, kR
a. $e + H \rightarrow H + h\nu + e$, optically thick to the Lyman series	
Lyα (1216 Å)	32*
Ly$\beta \rightarrow$ Hα (6560 Å)	3.4
Ly$\gamma \rightarrow$ Hβ (4860 Å)	1.1
Ly$\delta \rightarrow$ Hγ (4340 Å)	0.44
Ly$\epsilon \rightarrow$ Hδ (4101 Å)	0.23
Hα (6560 Å)	0.53
Hβ (4860 Å)	0.16
Hγ (4340 Å)	0.07
Hδ (4101 Å)	0.03
Two Photon continuum:	
6000 Å	4.5 total optically thin
$\int I_\lambda d_\lambda$	9.5 total optically thick
4000 Å	0.34 optically thick
b. $e + H_2 \rightarrow H + H + h\nu + e$	
Lyα (1216 Å)	8*
Hα (6560 Å)	0.6
Hβ (4860 Å)	0.12
c. $e + H_2 \rightarrow H_2 + h\nu + e$	
$a\,^3\Sigma_g^+ - b\,^3\Sigma_u^+$ continuum	
6000 Å $\int I_\lambda d_\lambda$ 4000 Å	1.2
$d\,^3\Pi_u - a\,^3\Sigma_g^+$ Fulcher α bands	
5000–6000 Å	1.0
Total Emission Rate	
4000–6000 Å	4.7

*The calculations are placed on an absolute scale by the Voyager EUV observations of 40 kR Lyα (1216 Å) and 80 kR H_2 Lyman and Werner band (850–1700 Å) emission [*Broadfoot et al.*, 1981]. See text.

der these circumstances the zenith brightness of 5 kR calculated for the 4000- 6000-Å region on the basis of the EUV observations, could easily account for the limb emission.

We have not included possible particle excitation by protons or fast neutral hydrogen [see *Ford and Thomas*, 1972] in the above discussion. However, we note that protons or fast neutral hydrogen cannot directly excite the triplet states of H_2. In addition, the excitation of atomic hydrogen emission by these processes does not appear to produce relative intensities significantly different from the electron excitation process [see *Birely and McNeal*, 1972; *Hughes et al.*, 1972].

The lower luminous band discussed above could be another band of aurora further beyond the horizon. In this case it would have to be intrinsically brighter than the one above the limb. This is not necessarily inconsistent with the data of Sandel et al. who measured the average brightness in an assumed 6000-km wide zone of torus aurora. They did not have the capability to resolve structure on a smaller scale. The lowest layer could also be the visible region twilight effect due to scattered radiation from the dayside.

CONCLUSION

We thus conclude that at least one of the limb emissions on the darkside imaging experiment pictures are very likely due to torus aurora. The reason for the double structure is not clear but it may be due to horizontal structure in the aurora or to additional effects of airglow and twilight processes.

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