GEOPHYSICAL RESEARCH LETTERS, VOL. 15, NO. 7, PAGES 701-704, JULY 1988

IUE OBSERVATIONS OF NEPTUNE FOR H LYMAN-α EMISSION

John T. Clarke

Department of Atmospheric, Oceanic and Space Sciences
The University of Michigan, Ann Arbor

Abstract: Neptune has been observed on seven occasions with the International Ultraviolet Explorer Observatory (IUE, Boggess *et al.* 1978) in an attempt to detect planetary H Ly-α line emission. The observing technique is the same as previously employed in IUE observations of Uranus, described in detail by Clarke *et al.* (1986), and consists of spatial separation of the planetary emission from background geocoronal and interplanetary H Ly-α emissions within the spectrograph aperture. No emission has been detected from Neptune in any of the observations, with 1 σ upper limits to the planet-averaged surface brightness as low as 180 Rayleighs. Despite poorer sensitivity in observing Neptune from Earth orbit compared to the other planets, the intrinsic brightness is significantly less than the 400-1500 R that would be expected from scaling arguments. This upper limit does not rule out scattered solar H Ly-α emission from a Jupiter-like atmosphere, and it does not rule out auroral emission from an active magnetosphere. The main significance is for the efficiency of the electroglow process on Neptune, and Neptune is significantly less efficient at producing bright aurora and/or electroglow than Uranus. This may further indicate that Neptune has a lower upper atmospheric temperature than Uranus.

Observations

A summary of the observations performed between 1983 and 1987 is given in Table 1. Sensitivity limits to planetary emission are determined mainly by the brightness of the background geocoronal and interplanetary emissions, since each image is timed to bring the total exposure level up to 60-80% of saturation (160-200 DN) for good linearity in the detector response. Images of background emission roughly one arc min from Neptune were obtained on each occasion for scaling and subtraction. The sensitivity of the observing technique has been determined by scaling and subtracting exposures of background emission from each other, and comparing these results with the Neptune images. The uncertainties listed in Table 1 are based on the analysis of Clarke *et al.* (1986) of the reduction procedure for point-like sources (which applies to both Uranus and Neptune), and the values listed in Table 1 have been converted to disk-average surface brightnesses based on the angular size of Neptune at the time of each observation.

Table 1. IUE Observations of Neptune

Date	Exposure Time	Background H Ly-α	Neptune H Ly-α [1]
4/24/83	120 min.	1200 R	$\leq$ 500 R
4/25/83	113 min.	1200 R	$\leq$ 500 R
7/14/83	77 min.	1400 R	$\leq$ 700 R
7/15/83	55 min.	1700 R	$\leq$ 950 R
8/18/86	160 min.	660 R	$\leq$ 180 R
5/21/87	175 min.	770 R	$\leq$ 205 R
8/15/87	150 min.	670 R	$\leq$ 180 R

[1] 1σ upper limits to disk-averaged Neptune emission.

Production of H Ly-α Emission

The three processes expected to lead to H Ly-α emission from Neptune, based on analogy with the 3 other gas giant planets, are i) scattered incident radiation, ii) polar aurora and iii) electroglow (as defined by Broadfoot *et al.* 1986). The H Ly-α radiation incident on Neptune is a combination of direct solar emission (i.e. a line of roughly 1 Å FWHM) and solar photons scattered by interplanetary H atoms (a much narrower line Doppler-shifted by the velocity of the interplanetary gas with respect to Neptune). Resonant scattering of direct solar emission is modeled in Figure 1, following the procedure described in Clarke (1982). The solar line profile at 20 AU and $\theta = 0°$ from Wu and Judge (1979) has been extrapolated to 30 AU assuming equal absorption by interplanetary H from 20 to 30 AU as between 10 and 20 AU. The solar flux at 1 AU is taken to be 2.1 x 10^{11} ph/cm^2-sec as an average of the values measured by SME

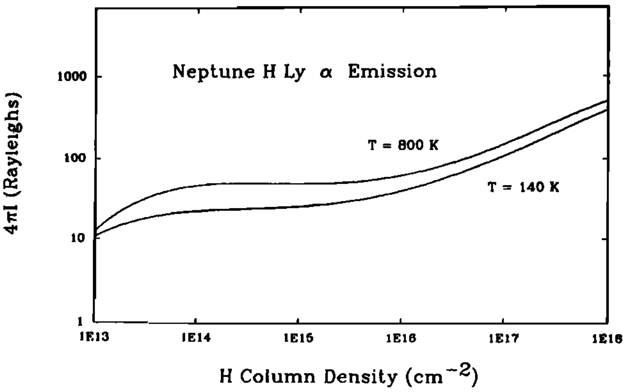

Fig. 1. Curves of growth for resonant scattering of incident solar H Ly-α emission as measured at Neptune. These values must be decreased by 30-50% (the interplanetary absorption) for comparison with IUE data. In addition to the calculated emission, scattering of the interplanetary emission will compete with direct solar scattering at column densities above roughly 10^{16} (see text).

Paper number 8L6813.
0094-8276/88/008L-6813$03.00

(G. Rottman, pers. comm.) during the 3 most recent IUE observations. The two extreme cases are for an isothermal upper atmosphere at 140K determined from stellar occultation data (French *et al.* 1983) and a hot upper atmosphere (assuming the Uranus exobase temperature, 800K) with most scattering taking place in the hot corona. The unusual shape of these curves of growth is due largely to the mapping of the planetary line onto the solar line, which has a deep absorption by interplanetary H roughly .05 Å from line center and a peak 0.2 Å from line center.

Scattering of interplanetary emission may be added to this plot when the Voyager UVS has measured the interplanetary radiation field at 30 AU. Since the interplanetary emission is a redistribution of the solar flux rather than a source, it is unlikely to modify the curves in Figure 1 by a large factor. For comparison, the total resonant scattering at Uranus has been modeled as 100-500 Rayleighs by Yelle and Sandel (1986), assuming an atmospheric column of H atoms on the order of 10^{15} to 10^{17} cm^{-2}, which is optically thick enough to broaden the atmospheric line and scatter much of the Doppler-shifted interplanetary emission. Between Jupiter and Uranus Yelle and Sandel derive a roughly 1/R(AU) scaling in the intensity of the extended interplanetary emission, which would correspond to 70-300 R from Neptune if this scaling relationship continues beyond 20 AU. From Figure 1 this corresponds to an H column of roughly 10^{17}cm^{-2}, which is consistent with the other three giant planets. Rayleigh scattering of incident H Ly-α radiation by H_2 has been clearly detected only on Uranus (Yelle *et al.* 1987), where the process is important due to the very deep column of H_2 (10^{24} cm^{-2}) above the level of hydrocarbon absorption. Existing observations of the CH_4 abundance on Neptune (Orton *et al.* 1987) suggest that the atmosphere is more similar to Jupiter's with a vertical column corresponding to unit optical depth for absorption at 1216 Å of 10^{21} cm^{-2} (Romani and Atreya 1988), so that a significant amount of Rayleigh scattered emission is not expected from Neptune.

Polar aurora have been detected on the other 3 giant planets and the polar aurora are expected to be the most variable of the three emission components. The brightnesses of the spatially-resolved polar auroral H Ly-α emissions from Jupiter and Saturn, when converted to disk averages from IUE data, are roughly 0-700 R from Jupiter and 0-600 R from Saturn. Weaker auroral emission by a factor of three from Neptune is not ruled out by these observations, although the indication is that Neptune may have a less active magnetosphere than either Jupiter or Saturn. It has also been suggested by Suess and Dessler (1985) that Neptune may be beyond the solar wind bow shock at times of solar minimum, and the absence of the solar wind at Neptune could exclude the presence of an Earth-like aurora independent of the strength of Neptune's magnetic field.

The emission observed from Uranus should provide a reasonable analogy for the emission expected from Neptune. H Ly-α emission was observed from Uranus with the IUE over four years preceding the Voyager encounter (Clarke *et al.* 1986). The disk-average brightness ranged from 800-2400 R, with observed variations of a factor of two over as little as 6 hours time. The Voyager UVS detected 1500 R of H Ly-α extended over the sunlit hemisphere near closest approach, and up to 50% variations in the disk-averaged brightness when further away (Broadfoot *et al.* 1986). This diffuse emission was interpreted as predominantly electroglow, first identified by Shemansky and Smith (1986) and defined by Broadfoot *et al.* (1986) as charged particle excited emission with a local energy source. More recently, Yelle *et al.* (1987) have interpreted the 1500 R emission observed by the UVS as predominantly Rayleigh-scattered solar radiation. Allowing for 30% absorption by interplanetary H atoms between Uranus and the Earth (cf. curve of growth in Clarke 1982) and a 20% calibration difference between the UVS and IUE (Skinner *et al.* 1987), the 1500 R UVS measurement (near Uranus) corresponds to 800 R as measured by the IUE (at 1 AU). This is near the minimum brightness observed over four years by IUE, and is consistent with the full level of solar-scattered emission plus a minimum amount of auroral and electroglow emissions at that time. The unusually high solar wind pressure and low magnetospheric plasma densities during the Voyager encounter suggest that it was a relaxation phase following a magnetic storm and compression of the magnetosphere (Voigt *et al.* 1987), which is consistent with the lack of bright aurora at that time.

The fast variations of as much as 1400 R (above the minimum level of 800-1000 R) observed by IUE before the Voyager encounter were interpreted as evidence of auroral emission and therefore an active magnetosphere (Clarke *et al.* 1986). Weak spatially-resolved polar auroral emissions from the sunlit hemisphere at the time of closest approach of the UVS have also been reported by Sandel (1986). The question is now how much of the variable emission is electroglow (i.e. diffuse over the planet) and how much is localized polar aurora. As originally argued (Clarke 1982), an increase of 1000 R on a time scale of hours to days is much more plausibly due to localized charged particle excitation than to any planet-wide process. In addition, the tilted and offset magnetic field of Uranus with nearly an order of magnitude difference in field strength between sunlit and dark hemispheres (Connerney *et al.* 1987) makes pitch angle diffusion loss into the sunlit hemisphere much more efficient than at magnetic conjugate points in the dark hemisphere at the current epoch, and is also likely to give rise to intense ionospheric currents through magnetospheric convection. It therefore seems likely that the rapidly variable component of the Uranus emission is due to localized emission processes, which happened to be relatively weak at the time of Voyager closest approach. Equally variable emission of up to 1kR might thus be expected from aurora and/or electroglow on Neptune.

To summarize, expectations for Neptune are: a constant level of scattered radiation of 200-300 R or less, a constant or slowly varying level of equatorial electroglow which is difficult to predict (but is probably less than the 500-1000 R observed at Uranus), and a much more variable contribution by localized aurora of up to 600 R at the peak (by analogy to Jupiter and Saturn).

Atmospheric Heating

It has been proposed that there is a functional relationship between the the heating of the outer planet upper atmospheres and the electroglow emission brightness. Hunten and Dessler (1977) first proposed soft electron excitation to explain the

Table 2. Relative Planetary Temperatures and Brightnesses

Planet	$1/R^2$	Surface B	Composition	FUV Airglow	$T_{(exobase)}$
Venus[1]	1.9	none	CO_2	10 kR[2]	280K
Earth[1]	1.0	0.3 G	N_2, O	20 kR[2]	800-1400K
Mars[1]	0.43	none	CO_2	5 kR[2]	180-350K
Jupiter	0.034	4 G	H_2, H	4-8 kR[3]	1200K
Saturn	0.011	0.2 G	H_2, H	1-3 kR[3]	400-800K
Titan	0.011	none	N_2	0.1 kR[4]	190K
Uranus	0.0027	0.25 G	H_2, H	1-3 kR[3]	800K
Neptune	0.0011	?	H_2, H	$\leq$ 0.4 kR[3]	?

[1] D. Anderson, Personal communication

[2] OI 1304 Å (photo-electron excited)

[3] H Ly-α (particle excited fraction) and H_2 Lyman and Werner (non-polar)

[4] N_2, N*I* and N*II*

high thermospheric temperature of Jupiter. Table 2 compares the observed average temperatures of the planets holding substantial atmospheres with the variation in solar input energy ($1/R^2$ normalized to 1.0 at the Earth), the surface magnetic field strength, and the emission brightness of the electroglow (or dayglow) emission. The inner planet emission brightnesses include photoelectron excitation and the particle excited fractions on the outer planets are discussed in Clarke, Hudson and Yung (1987). It is very clear that the exobase temperatures do not correlate with the amount of input solar flux (based on the comparison with $1/R^2$). Some process intrinsic to the planet must therefore be doing the heating. There appears to be a bi-modal distribution in temperature between those planets with a 800-1000K corona, and those without (200-300K). Venus, Mars and Titan are without high temperature corona and also have no internal magnetic fields, and every planet with a substantial magnetic field also has a corona. This does not appear to be solely a difference in atmospheric composition or planetary size between the different planets, since the Earth has a magnetic field and also sustains a corona, while Titan has no field and no corona at the same distance R as Saturn. Although this is an empirical demonstration, the evidence supports a relationship between upper atmospheric heating and processes which depend on a magnetic field, such as Joule heating related to aurora and diffuse ionospheric currents.

One recent theory for the production of the electroglow involves field-aligned currents generated by an ionospheric dynamo (which requires a magnetic field to function, cf. Clarke, Hudson and Yung 1987). Theoretically, it is believed that the heating of the H_2 atmospheres is controlled by auroral currents and by collisions in the acceleration of superthermal photoelectrons and ions by anomalous resistivity. The strength of these currents depends mainly on neutral wind speed, the conductivities of the ionosphere, and magnetospheric activity. There is empirical evidence (see Table 2) that the diffuse emission brightness of the outer planets scales approximately as the exobase temperature, and certainly not as $1/R^2$. The dynamo theory predicts significantly enhanced ionization as well as excitation of the FUV emissions, which suggests that weaker electroglow on Neptune could also mean a relatively lower ionospheric density. It is already clear that Neptune departs from the trend of the other planets in its lack of detectable dayside emission, and this may indicate a lower temperature (and lower ionospheric density) for Neptune. This matter is especially relevant to the question of atmospheric drag on the Voyager spacecraft during its close pass through Neptune's upper atmosphere.

Summary

Adding the estimated emissions from scattered sunlight, polar aurora and electroglow, the planet-averaged H Ly-α emission brightness of Neptune might be expected to lie in the range 400-1500 R, compared to the range 800-2400 R observed from Uranus by the IUE. The 1 σ upper limit from recent IUE observations is as low as 180 R, so that a 2-8 σ detection would be expected for a Uranus-like planet at the distance of Neptune. The upper limit *is* consistent with the predicted solar-scattered emission from a Jupiter-like upper atmosphere and a less active but significant amount of auroral emission (i.e. the observations do not rule out an active magnetosphere). The principal significance of this limit is that the very bright electroglow and/or auroral emissions observed from Uranus are *not* present at Neptune. Finally, the emission that *is* present may appear 30-50% brighter than the IUE limits when measured by Voyager due to absorption by interplanetary hydrogen.

Acknowledgements. I wish to thank the IUE Observatory staff for assistance in the acquisition and reduction of the IUE data, and Jayant Murthy for assistance in reducing the IUE data. This research was supported by NASA grant NAG 5-1030 to the University of Michigan.

References

Boggess, A. *et al.*, "The IUE Spacecraft and Instrumentation", *Nature*, *275*, 377, 1978.

Broadfoot, A. L. *et al.*, "Ultraviolet Spectrometer Observations of Uranus", *Science*, *233*, 74, 1986.

Clarke, J.T., "Detection of Auroral H Ly-α Emission from Uranus", *Astrophys. J. Lett.*, *263*, L105, 1982.

Clarke, J. T. *et al.*, "Continued Observations of the H Ly-α Emission from Uranus", *J. Geoph. Res.*, *91*, 8771, 1986.

Clarke, J. T., M.K. Hudson and Y.L. Yung, "The Excitation of the Far Ultraviolet Electroglow Emissions on Uranus, Saturn, and Jupiter", *J. Geophys. Res.*, *92*, 15139, 1987.

Connerney, J.E.P., M.H. Acuna and N.F. Ness, "The Magnetic Field of Uranus", *J. Geophys. Res.*, *92*, 15329, 1987.

French, R.G., J.H. Elias, D.J. Mink and J.L. Elliot, "The Structure of Neptune's Upper Atmosphere: The Stellar Occultation of 24 May 1981", *Icarus*, *55*, 332, 1983.

Hunten, D. M. and A. J. Dessler, "Soft Electrons as a Possible Heat Source for Jupiter's Thermosphere", *Planet. Space Sci.*, *25*, 817, 1977.

Orton, G.S., D.K. Aitken, C. Smith, P.F. Rouche, J. Caldwell and R. Snyder, "The Spectra of Uranus and Neptune at 8-14 and 17-23 Microns", *Icarus*, *70*, 1, 1987.

Romani, P.R. and S.K. Atreya, "Methane Photochemistry and Haze Production on Neptune", *Icarus*, in press, 1988.

Sandel, B. R., "Voyager UVS Observations of Aurora on Uranus", *Conference on Outer Planet Magnetospheres*, U. of Iowa, 1986.

Shemansky, D.E. and G.R. Smith, "The Implication for the Presence of a Magnetosphere on Uranus in the Relationship of EUV and Radio Emission", *Geophys. Res. Lett.*, *13*, 2, 1986.

Skinner, T. E., et al., "Temporal Variation of the Jovian H I Lyman - Alpha Emission (1979 - 1986)", *J. Geophys. Res.*, *93*, 29, 1988.

Suess, S.T. and A.J. Dessler, "Probing the Local Interstellar Medium", *Nature*, *317*, 702, 1985.

Voigt, G.-H., K.W. Behannon and N.F. Ness, "Magnetic Field and Current Structures in the Magnetosphere of Uranus", *J. Geophys. Res.*, *92*, 15337, 1987.

Wu, F.M. and D.L. Judge, "Modification of Solar Lines Propagating Through the Interplanetary Medium", *J. Geophys. Res.*, *84*, 979, 1979.

Yelle, R. and B. Sandel, "Uranian H Ly-α Emission: The Interstellar Wind Source", *Geo. Res. Lett.*, *13*, 89, 1986.

Yelle, R.V., L.R. Doose, M.G. Tomasko and D.F. Strobel, "Detection of Raman-scattered Ly-α Emissions From the Atmosphere of Uranus", *Geo. Res. Lett.*, *14*, 483, 1987.

John T. Clarke, Department of Atmospheric, Oceanic and Space Sciences, The University of Michigan, Ann Arbor, MI 48109-2143.

(Received: April 6, 1988;
Revised: May 4, 1988;
Revised: June 3, 1988;
Accepted: June 7, 1988.)