GEOPHYSICAL RESEARCH LETTERS, VOL. 13, NO. 1, PAGES 2-5, JANUARY 1986

THE IMPLICATION FOR THE PRESENCE OF A MAGNETOSPHERE ON URANUS IN THE RELATIONSHIP OF EUV AND RADIO EMISSION

D. E. Shemansky and G. R. Smith*

Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

* On Leave of Absence to Northwest Community College, Powell, Wyoming

Abstract. Two apparent contradictory sets of facts exist concerning the presence of a magnetosphere at Uranus. The Voyager planetary radio astronomy experiment has not detected a Uranus signal at a range <0.7 AU, whereas IUE satellite observations show relatively strong emission indicating the presence of substantial particle excitation of the atmosphere. The character of the EUV emission implies the presence of an ionosphere, and mass-loading of the extended system comparable to that of Saturn. If the ingredient for production of an active magnetosphere is present, the non detection of radio emission then suggests that Uranus has a very weak or non existent magnetosphere. The apparent paradox of an excited atmosphere in the absence of an active magnetosphere may possibly be explained in terms of the peculiar characteristics of the excited sunlit equatorial exospheres of Jupiter and Saturn. We suggest that 1) the observed Uranus EUV emission may be a similar phenomenon to those observed in the sub-solar equatorial regions of Jupiter and Saturn, which appear to be disconnected from auroral or magnetospheric activity, and 2) the Uranus intrinsic magnetic field is probably weak or nonexistent because of the availability of substantial mass for producing an active magnetosphere as derived from the nature of the EUV emission. We predict a substantial escape rate of atomic hydrogen (~2 x 10^{28} s^{-1}).

Introduction

A recent highly significant report by Kaiser and Desch (1985) indicating that non-thermal radio emissions from Uranus were not detectable from the Voyager spacecraft at a range of less than 0.7 AU, suggests that the planet may have significantly different magnetospheric characteristics than Jupiter and Saturn. From this point of view it is remarkable that H Lyα emission apparently derived from a non thermal source has been observed as a strong persistent feature on Uranus over the past four years (Clarke et al., 1985 hereafter referred to as CDM). This emission must originate from a particle excitation process, as CDM have pointed out. The absence of any correlational effects with solar wind activity and the fact that solar resonance scattering and ionizing radiation can supply only a small fraction of the required energy, strongly suggests that Uranus is in some way internally generating the particle excitation and associated heating of the atmosphere. This scenario is reminiscent of the peculiar characteristics of the particle excited equatorial atmospheres of Jupiter and Saturn. Both of these planets show high altitude excitation of the sunlit equatorial atmospheres extending well into the exospheric region (Shemansky and Ajello (1983), Shemansky 1985, Yelle et al., 1985,hereafter referred to as SA, SH, YSSK respectively. In each case the process is apparently stimulated by solar radiation, but the energy deposition rate far exceeds solar input. Furthermore, most of the H Lyα emission in each case is caused by direct excitation of atomic hydrogen by electrons, rather than the resonance scattering process assumed in earlier work (see SA; SH; YSSK). Thus all three planets, Jupiter, Saturn, and now Uranus, show strong particle excited atomic hydrogen emission. Our knowledge of Jupiter and Saturn is much more extensive compared to the few critical facts on Uranus. However, the source mechanism in the equatorial regions of the two closer planets is not understood. Shemansky and Smith (1984) have pointed out some of the consequences, if a process similar to the equatorial phenomena of Jupiter and Saturn also occurs on Uranus. The recent results cited above appear to increase the probability that the Uranus EUV emission may be more closely related to these phenomena than to an auroral effect.

There is a significant natural difference among the three outer planets in respect to the excitation of an exospheric or high altitude hydrogenic atmosphere as pointed out by Shemansky and Smith (1982, 1984), which arises in the different strengths of the gravitational field. The electron impact dissociation of H_2 and subsequent reactions produces an atomic product with substantial kinetic energy. The energy distribution of the dissociation products is such that the escape fractions are ~0% at Jupiter, ~10% at Saturn, and ~80% at Uranus. Shemansky and Smith (1982, 1984, 1985) have suggested that the extended hydrogen cloud occupying the Saturn magnetosphere originates in the exosphere of the planet rather than from Titan. At Uranus, the loss rate of atomic hydrogen could be comparable to that at Saturn, in spite of its smaller size. The outflow of neutral particles may then be important to the interaction of the planetary system with the solar wind. We discuss the process and related evidence in further detail in the following text.

The Importance of the Ratio of Atomic to Molecular Emission

The ratio of atomic to molecular emission in the hydrogenic atmospheres of the outer planets varies over a wide range depending on the nature of the exciting process and the altitude of the source. The primary controlling factor is the mixing ratio of atomic and molecular species $[H]/[H_2]$, which varies substantially with atmospheric altitude. At Saturn the ratio $[H]/[H_2]=1.0$

Paper number 5L6772.
0094-8276/86/005L-6772$03.00

TABLE 1

Exobase Production Rates and Escape of Atomic Hydrogen from the Outer Planets[a]

	Jupiter	Saturn	Uranus
(1)	1.6×10^{30}	3×10^{29}	2×10^{28}
(2)	5.1×10^{9}	1.7×10^{9}	5×10^{8}
(3)	19.	6.	2.3
(4)	0	~10	~80
(5)		1.6×10^{9}	8×10^{8}
(6)		3×10^{28}	1.6×10^{28}
(7)		10^{11}	
(8)		2×10^{4}	2×10^{4}
(9)	5-7.3	2.8-5.3	$\gtrsim 2.$
(10)	3.0×10^{9}	1.0×10^{9}	4.0×10^{8}

[a] These estimates exclude auroral activity (see text).
(1) Dissociation production rate (s^{-1}); (2)(cm^2s^{-1})
(3) HI escape energy (eV);(4) Escape yield (%)
(5) Loss rate (kg yr^{-1}); (6) (atoms/s)
(7) Loss lifetime for 200 km am H_2 (yr)
(8) Exobase ion densty (cm^{-3});(9) Y_{IS} (Eq.1)
(10)Ionization Rates (ions $cm^{-2}s^{-1}$)

at an altitude of 3860km ($[H_2]=2.5x10^5cm^{-3}$); $[H]/[H_2]=0.1$ at 2840 km ($[H_2]=2.4x10^7cm^{-}3$, exobase) (Smith et al. 1983). The abundance of atomic hydrogen is controlled by the high altitude equatorial excitation (dissociation) process on both Jupiter and Saturn (SH; Smith et al., 1983). The ratio of atomic to molecular emission brightness,

$$Y_{IS} = I(H\ Ly\alpha)/I_S\ (H_2\ Ly + Wr), \qquad (1)$$

where I(H Lyα) is the observed brightness of the H Lyα line, and $I_S(H_2$ Ly + Wr) is the calculated source brightness of the H_2 Lyman and Werner bands based on the observed band emissions, depends primarily on the reactions

(R1) $e + H(1s) \rightarrow H(2n) + e,$
(R2) $e + H_2 \rightarrow H(2n) + H(xn) + e,$
(R3) $e + H_2(\sigma) \rightarrow H_2(\sigma^*,\pi^*) + e.$

A smaller contribution is provided by

(R4) $h\nu + H(1s) \rightarrow H(2p),$

where hν is derived from the solar H Lyα line. According to CDM the value of Y_{IS} for the disk averaged Uranus emission is $Y_{IS}>2.$(Table 1). The Voyager observations of Jupiter and Saturn sub solar equatorial emissions show values $Y_{IS}=2.8-7.3$, as given in Table 1 (see SH,YSSK). Values of this magnitude require the dominance of R1, which can occur only in the vicinity of the exobase and high altitudes. The aurora at Saturn is dominantly at high altitude with Y_{IS}~1. (see SA), whereas very confined "hot spot" spectra (see Sandel et al. 1982) give values as low as $Y_{IS}=0.18$, close to the limit determined by reactions R2 and R3 (Shemansky et al., 1985). The observational facts thus bring out the following points. 1) The Uranus EUV emission is consistent with the Jupiter and Saturn equatorial phenomena, characterized by strong exospheric excitation. 2) The characteristic electron temperature of the Jupiter and Saturn sources is Te=30-60 eV (SH). The Voyager Planetary Radio Astronomy (PRA) experiment would have difficulty detecting a collisionally dominated process at low mean particle energies, with no available mechanism for producing coherent or resonant radio emission. Variability of the Saturn equatorial emission, mostly in the H Lyα line, is similar in modulation magnitude to that measured at Uranus (Table 1, CDM).

Escape of Atomic Hydrogen

The suggestion on the basis of the Y_{IS} values indicated in the IUE observations (CDM), that the Uranus emissions are produced mostly in the exospheric region of the atmosphere, immediately leads to the implication that the escape flux of atomic hydrogen will be substantial. The rate of dissociation of H_2 by reaction with electrons can be directly calculated from the measurement of H_2 band emission rates (Shemansky and Smith 1982; SH), if we obtain a measure of the electron temperature. At Saturn the production rate of dissociated hydrogen has been estimated (Shemansky and Smith, 1982) at $P_H \sim 3. \times 10^{29}\ s^{-1}$. A rough estimate based on known reactions ending in an atomic hydrogen product indicates that ~10% of P_H is above the escape energy (5.7 - 6.3 eV). This estimate of P_H is based on a measured constant value of $I_S(H_2$ Ly + Wm) ~ 1kR (SA; YSSK), at the Saturn sub solar equator. If we assume Y_{IS} = 3 at Uranus, the mean value I(H Lyα) = 1.2 ± 0.450 kR (CDM) implies I_S (H_2 Ly + Wm) ~0.4 kR. A yield of 1.2 H atoms per H_2 (Ly + WR) photon (see SH), gives a value $P_H = 2 \times 10^{28}\ s^{-1}$, for Uranus. A rough estimate of the energy distribution of the atomic hydrogen fragments for Te = 50 eV, indicates that ~80% of P_H is above the ~2.3 eV escape energy. Table 1 gives estimated rates and other relevant quantities for Jupiter, Saturn and Uranus, based on the assumptions discussed above. The quantities discused above are based on examination of H_2 physical chemistry obtained from a wide range of published literature.

The reactions leading to H atoms with energies in the range of a few eV can only be summarized in this letter. Dissociation is produced through electron excitation of both singlet and triplet states of H_2, occuring in a large number of branches, and through recombination reactions involving H_2^+ and H_3^+. SH gives rate coefficients for many of the reactions along with extensive references to relevant publications. Additional information may be found in Schiavone et al. (1975), Carnahan and Zipf (1977), Ryan et al. (1979), relating to the energy distribution of the dissociation fragments from excitation of singlet H_2 states. Recent work on cross sections may be found in Shemansky et al. (1985) and Van Zyl et al. (1985). Basic information on the characteristics of the H_2 triplet systems may be found in Corrigan (1965), Chung and Lin (1978), Lishawa et al. (1985). The continuum Franck-Condon factor for the excitation of the triplet H_2 b state in the present calculations has been obtained from M.A. Khakoo and S. Trajmar (private communication 1985). Relevant information on recombination reactions is found in Carney and Porter (1976), Mitchell et al. (1983), Kulander and Guest (1979), Peart and Dolder (1974), Michels and Hobbs (1984). The estimated escape rate of atomic hydrogen at Uranus is $P_{HE} \sim 1.6 \times 10^{28}$ s^{-1}, of the same order as the value for Saturn (Table 1). On this basis the assumed process in the high atmosphere of Uranus would be the dominant

TABLE 2

Energy Deposition in the Equatorial Subsolar and Auroral Regions of Jupiter, Saturn and Uranus

	Jupiter	Saturn	Uranus
E_p[a]	0.37	0.13	~0.06
E_S[b]	0.05	0.016	0.004
E_{SW}[c]	0.02	0.005	0.001
$E \cdot A$[d]	9.	2.	0.15
$E_A \cdot A$[e]	50.	0.4	—
Production of radiation (%)	~50	~50	~50
Fraction of Radiation absorbed in CH_4 and C_2H_2(%)	~25	~25	
Local heating (%)	~50	~50	~25

a) Energy deposited in particle excitation;units of ergs $cm^{-2}s^{-1}$. These calculations exclude auroral energy deposition.

b) Solar photoionization deposition;units of ergs $cm^{-2}s^{-1}$

c) Solar wind influx; units of ergs $cm^{-2}s^{-1}$

d) Total deposition equatorial; units of 10^{12} Watts

e) Total deposition aurora; units of 10^{12} Watts

source of magnetospheric particles by a substantial factor (cf. Hill 1984; Cheng 1984; Cheng and Hill, 1984).

Discussion and Summary

Two outstanding facts point to the possibility that the observation of strong EUV emission from Uranus may not be auroral in nature as opposed to the assumption of CDM and earlier authors. First, the PRA experiment on the Voyager spacecraft has not detected non-thermal electron activity at close range (<0.7 AU). Second, CDM detect no correlation effects of the relatively strong EUV emission with solar wind activity.

We suggest that the EUV emissions may be more closely related to the non-auroral excitation of the low latitude sunlit atmospheres of Jupiter and Saturn. Although there are some striking differences between the Jupiter and Saturn phenomena, there is an apparent common dependence on solar stimulus. Moveover, in each case the H Lyα line is controlled by electron excitation; solar H Lyα resonance scattering plays only a small role in the observed emission (SA, SH, YSSK). The phenomena apparently show no dependence on auroral activity and occur mainly in the high altitude atmospheres with heavy involvement in the exosphere. In each case the three outer planets must supply most of the energy deposited in the sub solar regions through an internal process. The magnitude of the deposition is such that it is a controlling factor for high altitude atmospheric temperature (see Smith et al., 1983), and for the $[H]/[H_2]$ mixing ratio. Energy deposition and partitioning estimates for the three planets are given in Table 2. The Saturn equatorial phenomenon energetically dominates auroral deposition by a large factor; the auroral disk averaged H Lyα emission at Saturn is only ~0.2kR, an order of magnitude lower than the disk averaged brightness of Uranus (Table 2). It seems very unlikely that given the present matrix of physical facts, Uranus would show an precipitating flux density ~2 orders of magnitude greater than that measured at Saturn. We conclude that the Uranus EUV emission phenomenon is basically compatible with the character of the excited sunlit low latitude atmospheres of Jupiter and Saturn.

The most striking effect of such a process on Uranus is the relatively greater fraction of dissociated H_2 that escapes from the system. On an absolute basis the escaping mass could be comparable to the corresponding loss process on Saturn (Table 1). A strong magnetic field at Uranus under these circumstances should develop a rather active magnetosphere given the apparent availability of particles for loading the system. The implication of an undetectable radio signal then seems to be that Uranus has at most a very weak intrinsic magnetic field. The dominant physical entity interacting with the solar wind in the Uranus system may then be the outflowing atomic hydrogen. A rough calculation of the distribution of hydrogen at the sub solar side of the planet on the basis of a crude approximation to the atomic hydrogen energy distribution is shown in Figure 1. At 5 R_U the estimated atomic hydrogen density is [HI]~ $10cm^{-3}$at 0°.0 colatitude, with a scale height of 1.5 x 10^5 km. If we assume a solar wind velocity of 4 x 10^7 cm s^{-1} (Barnes and Gazis 1984), and a negligible magnetic field, the solar flux will be significantly depleted only at ranges <$1.5R_U$ from the planet center.

Thus we raise the possibility that the strong EUV radiation from Uranus may not be auroral in origin, with little or no dependence on a magnetosphere as an energy source. The argument is based on phenomena of this kind observed at low latitudes on Jupiter and Saturn. However, we note that the orientation of the rotational axis of Uranus introduces a significant configuration (see discussion by Curtis, 1985) and temporal difference with the two closer planets. Both Jupiter and Saturn show local time (dawn - dusk) effects in the equatorial emission structure. In the case of Uranus the rotation of the atmosphere does not produce a modulation in the deposition of solar flux; the Uranus day is ~84 years. Although the processes apparently requires the stimulus of solar ionizing radiation, the energy source is basically unexpla-

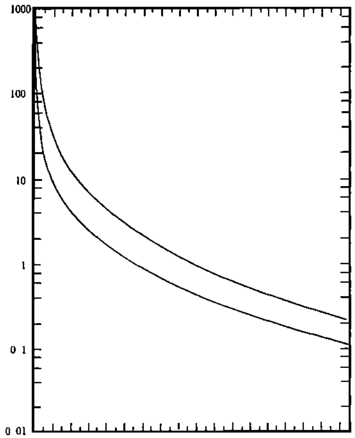

Fig. 1 Rough estimate of atomic hydrogen distribution at Uranus, caused by high altitude electron-H_2 dissociation reactions. Upper curve is calculated at 0.°0 colatitude; lower curve is for 90° colatitude.

ined. A possible mechanism compatible with the character of the deposition of energy is electric field driven current systems producing relatively low energy Druyvesteyn electrons, with energy derived ultimately from atmospheric dynamics (see SH and earlier discussion by Hunten and Dessler 1977). However, we have no theoretical base for such a mechanism at this point.

Acknowledgements: The authors wish to thank E. C. Stone and D. M. Hunten for stimulating discussion. This work is supported by NASA, Division of Planetary Sciences, grants NAGW-649, and NAS7-918 (JPL contract 95729).

Note: M. K. Kaiser, in a private communication, has reported that radio signals from Uranus remain undetected by PRA at a planet-spacecraft range <0.47 AU.

REFERENCES

Barnes, A. and P. R. Gazis, The solar wind at 20-30AU, "Uranus and Neptune", NASA CP-2330, 1984, edited by J. T. Bergstrahl, p. 527.

Carnahan, B. L. and E. C. Zipf, Dissociative excitation of H_2, HD, and D_2 by electron impact, Phys. Rev. A, 16, 991, 1977.

Carney, G. D. and R. N. Porter, H_3^+: Ab initio calculation of the vibration spectrum, J. Chem. Phys. 65, 3547, 1976.

Cheng, A. F., Magnetosphere, Rings, and Moons of Uranus, in "Uranus and Neptune", NASA CP-2330 1984, edited by J. T. Bergstrahl, p. 541.

Cheng, A. F., and T. W. Hill, Do the satellites of Uranus control it's magnetosphere? in "Uranus and Neptune", NASA CP-2330 1984, edited by J. T. Bergstrahl, p. 557.

Chung, S. and C. C. Lin, Application of the close-coupling method to excitation of electronic states and dissociation of H_2 by electron impact, Phys. Rev. A, 17, 1874, 1978.

Clarke, J. T., S. Durrance, W.Moos, J. Belcher, A. Pradhan, and T. Skinner, An overview of four years of observations of the H Lyα emission from Uranus and tests for correlation with the solar wind density, Bul. Am. Astron. Soc. 17, 745, 1985.

Corrigan, S. J. B., Dissociation of molecular hydrogen by electron impact, J. Chem. Phys. 43, 4381, 1965.

Curtis, S.A., Possible nightside source dominance in nonthermal radio emissions from Uranus, Nature 318,47, 1985.

Hill, T.W., Magnetospheric structures; Uranus and Neptune, in "Uranus and Neptune", NASA CP-2330, 1984, edited by J. T. Bergstrahl, p. 497.

Hunten, D.M. and A. J. Dessler, Soft electrons as a possible heat source for Jupiter's thermosphere, Planet. Space Sci. 25, 817, 1977.

Kaiser, M. L. and M. D. Desch, Voyager search for Uranian radio emissions, Bul. Am. Astron. Soc., 17, 743, 1985.

Kulander, K. C. and M. F. Guest, Excited electronic states of H_3 and their role in the dissociative recombination of H_3^+, J. Phys. B, 12, L501, 1979.

Lishawa, C. R., J. W. Feldstein, T. N. Stewart, and E. F. Muschlitz, Excitation of continuum radiation in collisions of (1) electrons and (2) metastable argon atoms with H_2 and D_2, J. Chem. Phys. 83, 133, 1985.

Michels, H. H., and R. H. Hobbs, Low-temperature dissociative recombination of e + H_3^+, Astrophys. J., 286, L27, 1984.

Mitchell, J. B. A., J. L. Forand, C.T. Ng, D. P. Levac, R.E. Mitchell, P.M. Mul, W. Claeys, A. Sen, and J. Wm. McGowan, Measurement of the branching ratio for the dissociative recombination of H_3^+ + e, Phys. Rev. Lett, 51, 885, 983.

Peart, B., and K. T. Dolder, Collisions between electrons and H_3^+ ions V. Measurements of cross sections for dissociative recombination, J. Phys. B., 7, 236, 1974.

Ryan, S. R., J. J. Spezeski, O. F. Kalman, W. E. Lamb, L.C. McIntyre,, and W. H. Wing, Time-of-flight study of H(2s) and D(2s) produced by electron impact on H_2, D_2, and HD: evidence for predissociation, Phys. Rev. A, 19, 2192, 1979.

Sandel, B. R., D. E. Shemansky, A. L. Broadfoot, J. B. Holberg, G. R. Smith, J. C. McConnell, D. F. Strobel, S. K. Atreya, R. P. Pomphrey, S. Linick, Extreme ultraviolet observations from the Voyager 2 encounter with Saturn, Science 215, 548, 1982.

Schiavone, J. A., K. C. Smyth, R. S. Freund, Dissociative excitation of H_2 by electron impact; Translational spectroscopy of long lived high Rydberg fragment atoms, J. Chem. Phys. 63, 1043, 1975.

Shemansky, D. E., An explanation for the H Lyα longitudinal asymmetry in the equatorial spectrum of Jupiter: an outcrop of paradoxical energy deposition in the exosphere, J. Geophys. Res. 90, 2673, 1985.

Shemansky, D. E. and J. M. Ajello, The Saturn spectrum in the EUV - electron excited hydrogen, J. Geophys. Res. 88, 459, 1983.

Shemansky, D. E., J. M. Ajello, and D. T. Hall, Electron impact excitation of H_2: Rydberg band systems and the benchmark dissociative cross section for H Lyman-Alpha, Astrophys. J., 196, 765, 1985.

Shemansky, D. E., and G. R. Smith, Whence comes the "Titan" hydrogen torus (abstract), EOS. Trans. AGU, 63, 1019, 1982.

Shemansky, D. E. and G. R. Smith, Hydrogen blow-off from Uranus; an extropolation from Jupiter and Saturn, Bul. Am. Astron. Soc., 16, 660, 1984.

Shemansky, D. E., G. R. Smith, and D. T. Hall, Extended atomic hydrogen cloud in the Saturn system and a possible analogous distribution at Uranus (abstract), EOS, Trans. AGU,66,1108, 1985.

Smith, G. R., D. E. Shemansky, J. B. Holberg, A. L. Broadfoot, and B. R. Sandel, Saturn's upper atmosphere from the Voyager 2 EUV solar and stellar occulations, J. Geophys. Res., 88, 8667,

Van Zyl, B., M. W. Gealy, and H. Neumann, Excitation of low-energy H atoms in H + Ne collisions,Phys. Rev. A, 31, 2922, 1985.

Yelle, R., B. Sandel, D. E. Shemansky, and S. Kumar, The altitude variation of EUV emissions and evidence for proton precipitation at low latitudes in the Saturian atmosphere,J. Geophys. Res., submitted, 1985.

Donald E. Shemansky, Lunar and Planetary Laboratory,3625 E. Ajo Way, Tucson, AZ 85713
Gerald R. Smith, Northwest Community College, Powell, Wyoming 82435

(Received December 2, 1985;
Accepted December 3, 1985)