GEOPHYSICAL RESEARCH LETTERS, VOL. 12, NUMBER 24, PAGES 2449-2452, DECEMBER 24, 1992
Publisher's Note: the correct volume is 19

SOLAR CYCLE VARIATIONS IN H^+ AND D^+ DENSITIES IN THE VENUS IONOSPHERE: IMPLICATIONS FOR ESCAPE

Thomas M. Donahue
Space Physics Research Lab, Department of Atmospheric, Oceanic and Space Sciences, University of Michigan

Richard E. Hartle
Laboratory for Atmospheres, Goddard Space Flight Center

Abstract. The hydrogen ion concentrations recently observed on Venus, near solar minimum, by the Ion Mass Spectrometer on the Pioneer Venus Orbiter in the anti-solar sector (22:00-02:00 LST) of the ionosphere are more than an order of magnitude less than those previously observed at solar maximum. This strong solar cycle variation has a profound effect on the escape of hydrogen (and deuterium) from Venus; almost all escape occurs during solar maximum. After adjustment for solar cycle variation, a planet-averaged hydrogen escape flux of 0.6-1.4 x 10^7 cm^{-2} s^{-1} is obtained along with a large deuterium fractionation factor of 0.1-0.14. These results suggest at least two plausible scenarios for the evolution of water on Venus: (1) Water vapor on Venus may be approaching a steady state if the escape flux is balanced by endogenous or exogenous sources of water. The source of water must be highly fractionated, with a D/H ratio differing by less than an order of magnitude from the present ratio of 2.4 x 10^{-2}, thus precluding low D/H water from comets, asteroids or a mantle reservoir. (2) The present day D/H ratio of 2.4 x 10^{-2} could be established by Rayleigh fractionation of an early low D/H water reservoir if the escape flux was sufficiently large in earlier times. An early water endowment at least 340 times today's abundance, equivalent to 4.2 to 14 m of liquid water on the surface, would be needed.

1. Introduction

The Pioneer Venus Orbiter (PVO) spacecraft, which explored the thermosphere of Venus between December, 1978 and July, 1980, has recently revisited that region. During the late summer and fall of 1992 the spacecraft was exploring the nighttime atmosphere at altitudes as low as 132 km. 1978-80 was a time of maximum solar activity. In September, 1992, activity was declining toward a minimum. Hence the Venus thermosphere and ionosphere was examined with the same instruments during times of high and low activity. The present paper will contrast the hydrogen ion population of the ionosphere between 150 km and 700 km in the anti-solar sector (22:00 - 02:00 LST) under these very different conditions.

2. Hydrogen Ion Densities at High and Low Solar Activity

Figure 1 shows examples of hydrogen ion densities obtained by the PV Orbiter Ion Mass Spectrometer (OIMS) on orbits 5021 and 5032 (LST 00:47 - 01:57). Ions of mass 2 are also plotted. These are characteristic of conditions during the present epoch. These profiles provide a vivid contrast with conditions in 1978-80 when the densities observed under similar conditions were about 10 times larger at 200 km and 30 times larger at 600 km [Bauer et al., 1985]. Even though some of these data points will need further scrutiny, no fine tuning can change the essential element on which this analysis depends. The general level of the densities will not change. It is very low. Figure 2 shows average profiles for H^+ in filled and depleted ionospheres between 22:00 and 02:00 LST (orbits 4995-5033, 31 cases in all). Averages for the two hours before and after midnight are shown separately. In Figure 3 the VIRA model H^+ densities [Bauer et al., 1985] for 150° - 170° SZA are shown along with the current results.

3. Implications for Hydrogen Escape

We wish to draw attention to the significance of such large variations in H^+ for escape of hydrogen and deuterium from Venus. Until recently four processes have been recognized as contributing currently to escape: classical "Jeans" escape (J), charge exchange between low temperature atoms and high temperature ions (CE), collisions of hydrogen atoms with high speed oxygen atoms produced by dissociative recombination of O_2^+ (O^*), and outflow in the plasma tail (T). The first process is virtually inactive in the cold upper atmosphere of Venus. Calculations of CE by Hodges and Tinsley [1986] and by Rodriguez et al. [1984] give disparate results -- 2.4 x 10^7 cm^{-2} s^{-1} in the first case and 0.4 - 1 x 10^7 cm^{-2} s^{-1} in the second. The latter authors also model a loss by O^* amounting to 1.2 x 10^6 cm^{-2} s^{-1} that contrasts with a recent result of 3.5 x 10^6 cm^{-2} s^{-1} obtained by Gurwell and Yung [1992]. (T) has been discussed by Brace et al. [1987] who produced evidence for O^+ escape in 1984 and argued for an accompanying -- but unobserved -- planet wide average H^+ flux of 5 x 10^6 ions/cm^{-2} s^{-1}. Two remarks need to be made concerning the calculations. First, the ionospheric models on which they were based were constructed with data obtained by the PV orbiter during the solar maximum of 1978-80 (or the solar minimum of 1984 for T). Second, the ionospheric models adapted by the two groups who have calculated CE differ strikingly from each other, and neither corresponds closely to the VIRA empirical model, which is no more than an average of (OIMS and OETP) data obtained during three successive passages of periapsis over the night hemisphere (Figure 3). Obviously, these calculations need to be repeated using H^+ densities obtained from PVO observations. Allowance should be made for changes with solar activity which will reduce the average CE flux by a factor of 2 unless compensating changes in the neutral

Paper number 92GL02927
0094-8534/92/92GL-02927$03.00

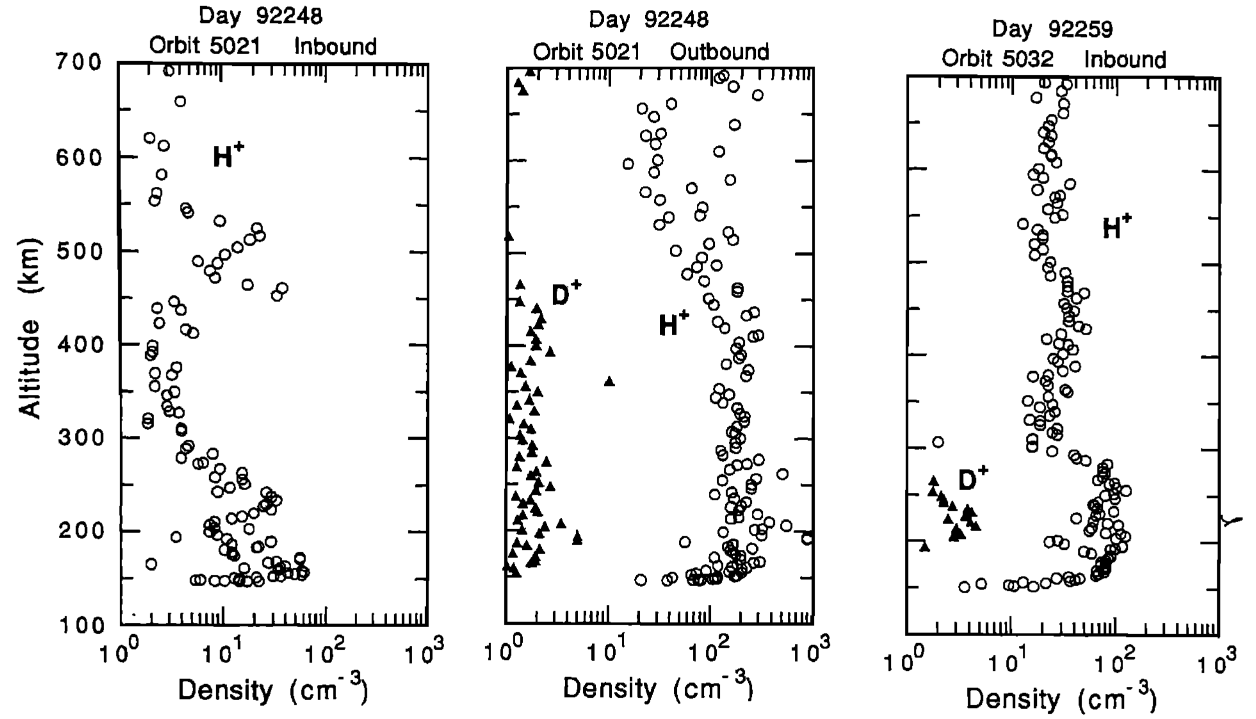

Fig. 1 Mass 1 and Mass 2 ions observed on three orbits in 1992 by the PV OIMS.

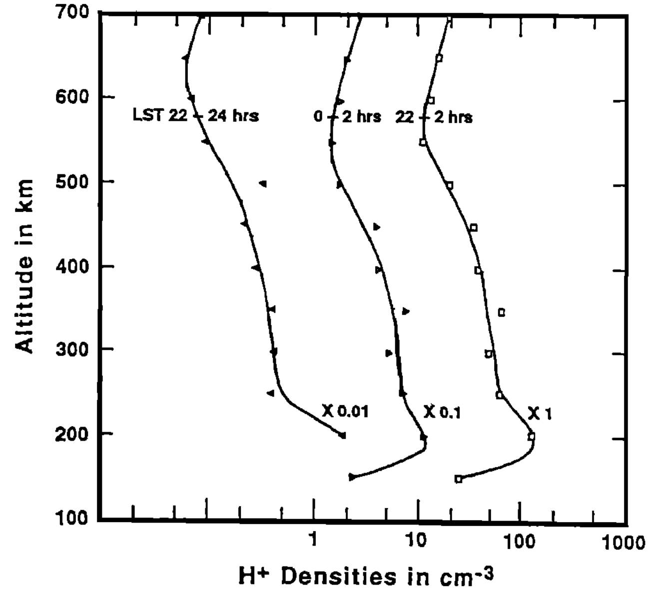

Fig. 2 Average H^+ densities in the midnight sector of Venus, 31 cases from Orbits 4995-5032, 9 August - 14 September, 1992.

density occur. We note that O^* will also vary, because radio occultation data [Kliore and Mullen, 1988] clearly show that there is a large solar cycle modulation in $\mathrm{O_2}^+$ density.

While awaiting the results of these exercises, it may be possible to reconcile the results already published and to adjust them for solar variability by recourse to the PV OIMS results. From Figure 3 it is clear that the Tinsley and Hodges [1986] ion densities above 250 km are too high by a factor of 3 for SZA 150°-180°. A similar comparison at other zenith angles shows that, overall, they are effectively high by a factor of about 2.7 for the entire nightside. Thus their CE probably should be reduced from 2.8 to 1 x 10^7 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Likewise the Rodriguez et al. [1984] fluxes are too low by a factor of 2.3 and 1.9 for the SZA zones 150°-180° and 120°-150°, in which almost all CE is generated. For their Case 3 this changes their CE flux from 3.2 x 10^6 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to 9 x 10^6 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ during solar maximum. Thus, the results of the two calculations may converge at about 10^7 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ if they are performed using the same (observed) H^+ densities.

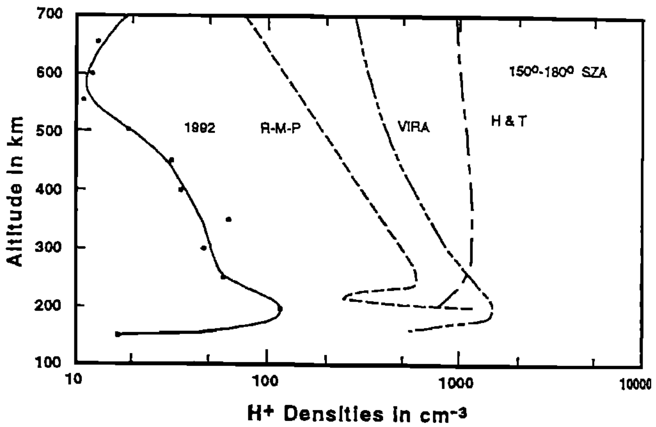

Fig. 3 H^+ densities Solar Zenith Angle 150° - 180°, OIMS and OETP, 1978-80 (VIRA), OIMS 1992 and models used by Hodges and Tinsley (H.T.), [1986] and Rodriguez et al.(R-P-M), [1984].

It is interesting to compare these theoretical fluxes with the recent determination of the upward flux of H^+ in the nightside thermosphere of Venus by Hartle and Grebowsky

[1992]. Data obtained in the dawn (hydrogen bulge) sector between midnight and 2 a.m., 150°-180° SZA show that H^+ (and D^+) ions in this region flow upward between 300 km and the ion exobase at 500 km, accelerated by the charge separation electric field. This occurs in filled ionospheres under quiet solar conditions -- as well as in ionospheric holes. The H^+ flux reaches a local value of 8×10^7 cm^{-2} s^{-1} and the D^+ flux 3×10^5 cm^{-2} s^{-1} at 500 km, with values larger by a factor of 2 -- especially for D^+ -- possible. The midnight region was selected because the lateral flow of ions from the dayside stagnates there, and the vertical flow is not complicated by the effects of day to night transport. There is reason to expect that the outward flow detected here will also be a component of the vertical flow everywhere on the nightside, and be particularly strong in the region of the bulge. Allowing for variation in H^+ density with SZA in the bulge leads to the estimate that this flux would attain a value of about 14×10^7 cm^{-2} s^{-1} between 150° and 120° and drop to about 2.9×10^7 cm^{-2} between 120° and 90°. The average bulge flux would be 7.5×10^7 cm^{-2} s^{-1}. This would correspond to a globally averaged flux of 1.5×10^7 cm^{-2} s^{-1} if it assumed that almost all of the flow occurs in the bulge which covers 20% of the planet's surface.

These upward flowing ions have two possible destinations. One of these is the plasma flow of H^+ and D^+ accompanying the tail ray O^+ flow described by Brace et al. [1987] which we have called T. The other is an analog of the telluric polar wind in which the upward flowing ions are accelerated to escape speed and escape into the solar wind with a flux P. Thus a new process (P) would be added to the four already identified in contributing to escape. We proceed now to estimate the contribution of these five processes to obtain the hydrogen escape flux averaged over the planet and over the solar cycle. We shall also estimate the fractionation factor for each process and for the aggregate of the five.

4. Escape Fluxes and Fractionation Factors

The fractionation factor for D escape relative to H is given by

$$f = \frac{\phi_D}{\alpha \phi_H}, \tag{1}$$

where α is the D/H ratio in the mixed atmosphere [Krasnopolsky, 1985]. With $\alpha = 2.4 \times 10^{-2}$ [Donahue et al., 1982; de Bergh et al., 1991; T.M. Donahue and R.R. Hodges, Jr., unpublished 1992] f is 0.17 (and perhaps considerably larger) for the thermospheric D^+ and H^+ flows obtained by Hartle and Grebowsky [1992]. If the tail ray flow is really a plasma flow, the fractionation factor f_t is merely the ratio of the D^+ and H^+ densities divided by α. Since the density ratio obtained by Hartle and Grebowsky [1992] is 6.2×10^{-3}, it follows that $f_t = 0.26$. If the D^+ and H^+ ions in the Venus wind flow (P) have equal kinetic energies, as they should if they are accelerated by an electric field, f_p will be $f_t/\sqrt{2}$ or 0.15. (We note that the ratio of H^+ and D^+velocities obtained by Hartle and Grebowsky is, in fact, 1.4.) It follows then, that P is 1.2×10^7 cm^{-2} s^{-1} and T is 0.3×10^7 cm^{-2} s^{-1}.

Combining these flux values with the estimate of 0.9×10^7 cm^{-2} s^{-1}, arrived at in Section 3 for CE, and 0.35×10^7 cm^{-2} s^{-1} for O^* calculated by Gurwell and Yung [1992] gives a total flux of 2.75×10^7 cm^{-2} s^{-1} at solar maximum, or a solar cycled averaged flux $\bar{\phi}$ of 1.4×10^7 cm^{-2} s^{-1}. Taking the values derived for f_p and f_t together with 0.02 for f_{ce} and 0.31 for f_{O^*} [Gurwell and Yung, 1992] yields a total fractionation factor of $\bar{f} = 0.14$. Here we have always taken α to be 2.4×10^{-2} or 150 times terrestrial.

Table 1. Escape Fluxes and Fractionation Factors

Process	ϕ cm^{-2} s^{-1}	f	ϕ cm^{-2} s^{-1}	f	f
CE	0.9(1)	0.02(3)	0.9	0.02	0.02
O^*	0.35(2)	0.31(2)	0.35	0(4)	0.31
t	0.3(1)	0.26			
p	1.2(1)	0.15(1)			
total	2.75	0.14	1.25	0.013(5)	0.1
average	1.4		0.6		

(1)This paper; (2)Gurwell and Yung, [1992]; (3)Krasnopolsky, [1985]; (4)McElroy et al., [1982]; (5)Hunten et al., [1982]..

In Table 1 we display the contributions of various mechanisms to the escape flux and fractionation factors that have been associated with these processes. The first two columns give the values suggested in this paper. The next three columns show the effect of neglecting tail ray and Venus wind losses but allowing for the large increase in f_{O^*} proposed by Gurwell and Yung [1992]. From this table it is apparent that only charge exchange, and Jeans escape now seem to discriminate severely against deuterium escape. No matter what combination of processes is considered the fractionation factor is 0.1 or larger, and the effective hydrogen escape flux is severely reduced by solar cycle effects. We shall now discuss the implications of these changes for the evolution of water on Venus.

5. Evolution of Venus Water

Recently there has been a convergence of some measurements of the water vapor mixing ratio in the lower atmosphere toward 30 ppm [Pollack et al., 1992; Donahue and Hodges, unpublished results 1992]. However, some older credible analyses that call for much higher mixing ratios -- up to 200 ppm -- remain unexplained. Thus there is a possibility that the water vapor concentration is variable in space and time and that possibility should still be allowed for in a discussion of the water vapor budget of Venus -- present and past. The rest of the hydrogen inventory is virtually unbounded except by aeronomic constraints. Here we shall consider a possible range of 30 to 100 ppm H_2O equivalent. The time required to exhaust such reservoirs by the escape flux discussed here is given by

$$\tau = H/\bar{\phi}, \tag{2}$$

where H is 8.3×10^{22} atoms cm^{-2} if the water vapor mixing ratio is 30 ppm. For a flux of 1.4×10^7 cm^{-2} s^{-1} τ lies between 190 and 630 My. The characteristic time for decay of the D/H signature as D/H approaches a steady state value in the presence of sources and sinks of water, is

$$\tau_{ss} = \tau/\bar{f} \tag{3}$$

[Krasnopolsky, 1985]. This is between 1.4 and 4.5 Gy. The order of magnitude increase in $\bar{f}$ resulting from the reevaluation of $f_O{}^*$ and the large values of f_t and f_p, therefore, means that it is plausible that the present day water vapor is well on its way toward a steady state if sufficiently strong sources -- endogenous or exogenous -- exist. However, the same high efficiency for deuterium escape which, on the one hand, makes τ_{ss} short, on the other hand, makes the ultimate D/H ratio, given by

$$(D/H)_{ss} = \alpha_s/\bar{f}, \tag{4}$$

[Krasnopolsky, 1985] only 7 times the source value, α_s. Because water in comets very likely has a D/H ratio in the neighborhood of a few times 10^{-4}, this would appear to preclude comets [Grinspoon and Lewis, 1988] as important sources and to require mechanisms for producing a highly fractionated source of water from a mantle reservoir, given the present very high D/H ratio of 2.4×10^{-2}.

On the other hand it would be possible for the presently large value of D/H to be established by simple Rayleigh fractionation of an early water reservoir with a terrestrial like D/H ratio if $\bar{\phi}$ should increase adequately with H. If α/α_0 is 150 and $\bar{f}$ is 0.14 an ancient water supply 340 times larger than the present atmospheric inventory would be required. This is equivalent to 0.14 to 0.47 percent of a full terrestrial ocean. To exhaust the associated hydrogen, $\bar{\phi}$ would have to increase appropriately with increasing water abundance [Kumar et al., 1985].

6. Conclusions

Solar activity has a profound effect on hydrogen escape from Venus; the fractionation factor for deuterium and hydrogen escape is very large and our understanding of the history of water on Venus is very confused. Virtually the only scenario that appears to be excluded by our present understanding of hydrogen and deuterium escape processes is one that involves a steady state in which H and D outflow are balanced by an input of low D/H water from comets, asteroids or a mantle reservoir. However, it would be difficult to underestimate the quality of our present understanding either of the processes or the present hydrogen inventory. Developments are occurring, it remains to be seen whether or not they represent progress.

Conclusions, similar to those reached here regarding the significance of the large fractionation factor generated by process O^* and T, were reached, prior to the preparation of this paper, by D. H. Grinspoon [Unpublished manuscript; International Colloquium on Venus, Aug. 10-12, Pasadena, CA.]

Acknowledgments. The authors wish to acknowledge the contributions of Paul Cloutier and Leonard Cramer of Rice University for supplying OIMS data so efficiently and of Larry Brace for discussion of electron densities. S. Bougher and D.M. Hunten made useful suggestions for improving this presentation. This work was supported by NASA under grant NAG 2-488 and letter of agreement PPO 4880.

References

Bauer, S.J., L.M. Brace, H.A. Taylor, Jr., T.K. Breus, A.J. Kliore, W.C. Knudsen, A.F. Nagy, C.T. Russell, and N.A. Savich, The Venus Ionosphere, Adv. Space Res., 5, 11, 233-267, 1985.

Brace, L.H., W.T. Kasprzak, H.A. Taylor, R.F. Theis, C.T. Russell, A. Barnes, J.D. Mihalov, and D.M. Hunten, The ionotail of Venus: its configuration and evidence for ion escape, J. Geophys. Res., 92, 15-26, 1987.

de Bergh, C., B. Bézard, T. Owen, D. Crisp, J.-P. Maillard, and B.L. Lutz, Deuterium on Venus: Observations from Earth, Science, 251, 547-549, 1991.

Donahue, T.M., J.H. Hoffman, R.R. Hodges, Jr., and A.J. Watson, Venus was wet: A measurement of the ratio of deuterium to hydrogen, Science, 216, 630-633, 1982.

Donahue, T.M. and R.R. Hodges, Jr, The past and present water budget of Venus, J. Geophys. Res., 97, 6083-6091, 1992.

Grinspoon, D.H. and J.S. Lewis, Cometary water on Venus: implications of stochastic impacts, Icarus, 74, 21-35, 1988.

Gurwell, M.A. and Y.L. Yung, Fractionation of hydrogen and deuterium on Venus due to collisional ejection, Planet. Space Sci., in press, 1992.

Hartle, R.E. and J.M. Grebowsky, Planetary loss from light ion escape on Venus, Adv. Space Res., in press, 1992.

Hodges, R.R., Jr., and B.A. Tinsley, The influence of charge escape on the velocity distribution of hydrogen in the Venus exosphere, J. Geophys. Res., 91, 13, 649-658, 1986.

Hunten, D.M., T.M. Donahue, J.C.G. Walker, and J.F. Kasting, Escape of atmospheres and loss of water, in Origin and Evolution of Planetary and Satellite Atmospheres, edited by S.K. Atreya et al., pp. 386-422, University of Arizona Press, Tucson, 1989.

Kliore, A.J. and L. Mullen, The long-term behavior in the main peak of the dayside ionosphere of Venus during Solar Cycle 21, J. Geophys. Res., 94, 13339-13347, 1988.

Krasnopolsky, V.A., Total injection of water vapor into the Venous atmosphere, Icarus, 62, 221-229, 1985.

Kumar, S., D.M. Hunten, J.B. Pollack, Nonthermal escape of hydrogen and deuterium from Venus and implications for loss of water, Icarus, 55, 369-373, 1985.

McElroy, M.B., M.J. Prather and J.M. Rodriguez, Escape of hydrogen from Venus, Science, 215, 1614-1615, 1982.

Pollack, J.B., J.B. Dalton, D. Grinspoon, R.B. Wattson, R. Freedman, D. Crisp, D.A. Allen, B. Bézard, C. de Bergh, L.P. Giver, Q. Ma, R. Tipping, Near-Infrared light from Venus' nightside: a spectroscopic analysis, Icarus, 1992.

Rodriguez, J.M., M.J. Prather, and M.B. McElroy, Hydrogen on Venus: exospheric distribution and escape, Planet. Space Sci., 32, 1235-1355, 1984.

T.M. Donahue, University of Michigan, Space Physics Research Lab, Department of Atmospheric, Oceanic and Space Sciences, Ann Arbor, MI 48109-2143.

Richard E. Hartle, Laboratory for Atmospheres, Goddard Space Flight Center, Greenbelt, MD 20771.

(Received October 13, 1992;
Accepted November 16, 1992.)