JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. A8, PAGES 14,515–14,521, AUGUST 1, 1995

On removing molecular ions from Venus

J. G. Luhmann[1]

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California

W. T. Kasprzak and J. M. Grebowsky

NASA Goddard Space Flight Center, Greenbelt, Maryland

Abstract. Acceleration or "pickup" of exospheric atomic oxygen ions by the interplanetary convection electric field is a generally accepted mechanism for the observed removal of O^+ from Venus. However, heavier escaping molecular ions (e.g., O_2^+, CO_2^+, N_2^+, CO^+, and NO^+) in high abundances were also detected in the wake by the Pioneer Venus Orbiter (PVO) neutral mass spectrometer (ONMS) operating in its ion mode. It was recently demonstrated that pickup of O^+ at low velocities from the terminator upper ionosphere could explain some characteristics of the Venus ionospheric "tail rays." Since the PVO ion mass spectrometer data indicate that a significant molecular ion component also contributes to the terminator ionosphere above the collisional region ($\geq$ 250 to 300 km altitude), we apply the tail ray model to study both the associated low-altitude O^+ flows and the behavior of heavier ions of similar origin. The predicted flow vectors show dawn/dusk asymmetries similar to those in the ONMS observations. Further, the heavier ions achieve higher peak energies, thus improving their chances of detection by the ONMS which has an energy threshold of $\sim$36 eV in the spacecraft frame. The appeal of this explanation is that no exotic or complicated interpretations are required, and that a broad set of diverse observations fit a common scenario. The same mechanism could in principle be operating at Mars where molecular ions were also detected in the wake on Phobos 2.

Introduction

It was recently proposed [*Luhmann*, 1993] that the Venus wake structures known as ionospheric tail rays [*Brace et al.*, 1987] can result from the penetration of the solar wind convection electric field into the oxygen-dominated high (>250 km) altitude terminator ionosphere. At altitudes where collisions are infrequent the electric field maps along the inner magnetosheath field lines threading the upper ionosphere. There it can become the dominant force, exceeding the antisolar pressure gradient force that drives day-to-night transport at lower altitudes. In this case the upper ionosphere ions can be accelerated or "picked up" by the same physical mechanism that leads to solar wind scavenging of the O^+ ions created in the high-altitude exosphere. While the exospheric ions are accelerated to high (> 1 keV) energies and thus exhibit marked asymmetries controlled by the solar wind convection electric field due to their large gyroradii [e.g., *Phillips et al.*, 1987; *Intriligator*, 1989; *Moore et al.*, 1990], the picked up upper ionosphere ions have low ($\sim$ 10s of eV) energies and show insignificant finite gyroradius effects mirroring the low local flow speeds and compressed, draped magnetic field. This concept is of interest both because it obviates the need to invoke other, more exotic planetary ion pickup processes to explain the tail rays, and also because it allows us to more simply and accurately estimate the solar wind scavenging rate. However, it also has implications for other observations obtained on the Pioneer Venus Orbiter (PVO).

Here we show that the same model can account for the properties of Venus' nightside superthermal ion flows as detected by the PVO neutral mass spectrometer (ONMS) in its ion mode of operation [*Kasprzak et al.*, 1982, 1987, 1991], including the vector magnitudes and directions and the abundances of heavy molecular ions in those flows. If the ONMS ion flows are regarded as tail ray ions observed at low altitudes, the observed dawn/dusk asymmetries in the flow pattern can be understood in terms of the effect of the average interplanetary magnetic field draping pattern. Moreover, the escape of heavy molecular ions is a natural consequence of their regular presence in the collisionless region of the terminator upper ionosphere where they are exposed to the same accelerating field as the O^+. This model should in principle apply to any unmagnetized planet having an ionosphere, including Mars, where ionospheric atomic and molecular ions were similarly observed in the low-altitude wake on the Phobos 2 spacecraft [*Lundin et al.*, 1990].

---

[1] Now at Space Sciences Laboratory, University of California, Berkeley.

Paper number 95JA00538.
0148-0227/95/95JA-00538$05.00

Model Description

Details of the magnetic and convection electric field descriptions underlying the tail ray model used here are given by *Luhmann* [1993]. In brief, the Venus low-altitude wake fields are described by a simple three-dimensional comet tail model that produces the field draping of an induced magnetotail by virtue of a localized decrease in the plasma velocity. The free parameters in the model allow control of the minimum flow speed and scale of the draped field region, and thus of the severity of field draping. These parameters were adjusted to simulate the observed wake magnetic fields above the region where the nightside ionosphere plasma substantially affects the fields (e.g., where plasma pressure becomes comparable to the field pressure) and inside of a nominal tail boundary at $\sim 1.2\ R_V$ from the tail axis (1 R_V $\sim$6053 km.) (The parameters can be varied within a modest range without a substantial change in the results.) For the chosen parameters the flow speeds near the terminator in the region of the upper ionosphere are several 10s of km/s. The characteristic pickup energies obtained for O^+ test particles arising from a source in this region were a few 10s of eV, regardless of whether the initial ion velocities were set at zero or $\sim$1 km/s tailward as observed by *Knudsen et al.* [1980] with the PVO Retarding Potential Analyzer. It should be noted that the results are not affected if the terminator source region is supplied by ion production and preacceleration at smaller solar zenith angles. While this model is not self-consistent, it can lend some insights provided that the test particles do not undergo collisions or significant wave-particle interactions, and that the underlying fields are adequately described.

Figure 1 shows some of the ion trajectories from the tail ray model, which assumed an interplanetary magnetic field (IMF) perpendicular to the upstream solar wind flow, for O^+ originating at a terminator altitude near 1.1 R_v. Although only O^+ trajectories are shown here, they closely resemble those for heavier ions (e.g., O_2^+, CO_2^+), with the exception that small increases in the amplitudes of the gyrational motions occur for the latter. Field lines in the plane of the IMF are shown in Figure 1c for reference. Some of the ion trajectories starting near the (magnetic) equatorial region end where they intersect the collisional atmosphere instead of escaping down the tail (these ions thus constitute an energized precipitating nightside component). For this perpendicular IMF case the O^+ ions from the terminator symmetrically converge toward the magnetic meridian plane (the plane of the induced tail current sheet), but appear to flow essentially antisunward in the orthogonal plane. Gravity, included in the forces in the equation of motion, aids the focusing of the ions toward the meridian plane. The focusing action is always in the projection containing the upstream magnetic field. Considering the constantly varying IMF orientation, collected observations of these ions should show a combination of converging and antisunward flows. However, since the IMF is on average in the ecliptic plane, a preference for convergent flows is expected to appear in statistical analyses of equatorial projections.

ONMS Observations of Nightside Superthermal Ions

Kasprzak et al. [1982, 1987, 1991] described the PVO neutral mass spectrometer (ONMS) ion mode of operation. The measurements are restricted in the sense that superthermal ions can be detected only if their energy in the spacecraft frame is in excess of 36 eV along the ONMS axis (which points ~ 25° from the southward pointing spin axis). This threshold is independent of species mass. On the nightside, in the planetary frame, the minimum energy for the registration of the predominant species O^+ is ~ 30 eV, which is equivalent to a velocity of about 20 km/sec. The component of the ion motion in the ecliptic plane can also be determined from the spin modulated data. From the spacecraft attitude it can be inferred whether the superthermal ions are directed sunward or antisunward or converging to the antisolar point. Figure 2a shows

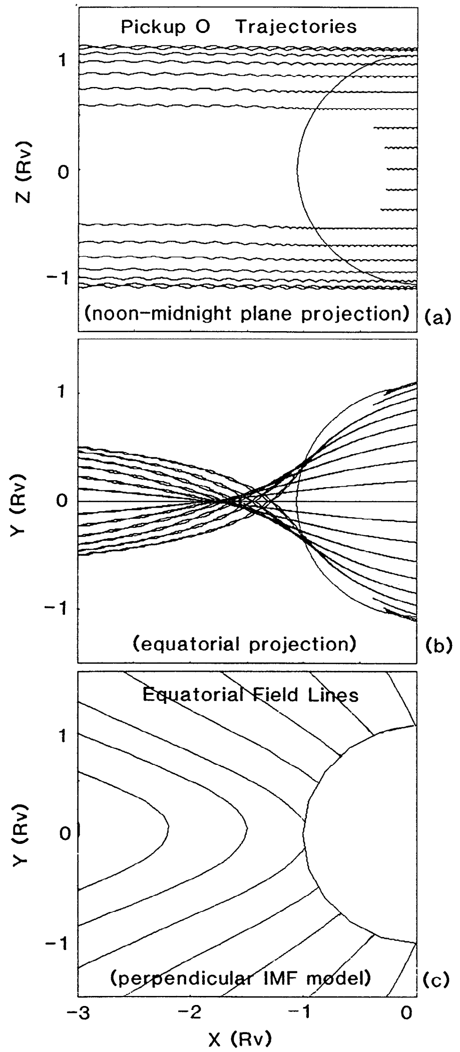


Figure 1. (a, b) Orthogonal views of sample O+ trajectories launched from the terminator in the tail ray model of *Luhmann* [1993]. (c) "Equatorial" plane magnetic field lines for the same model.

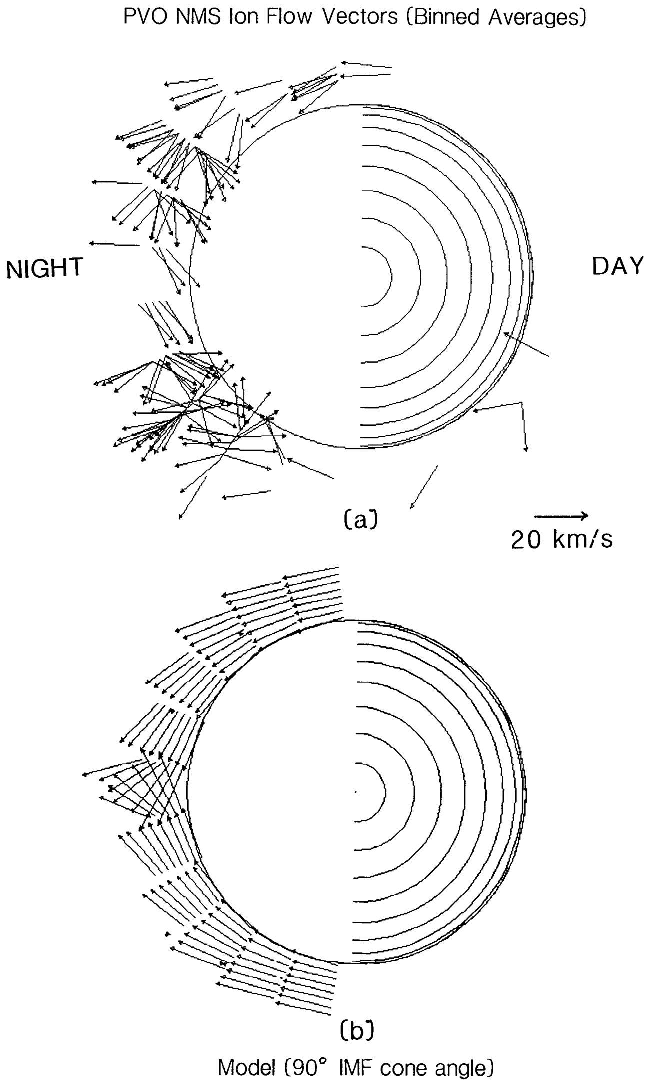


Figure 2. (a) Averaged superthermal ion flow vectors derived from the ONMS O^+ data. The measured vectors are assumed to have magnitudes of ~20 km s^{-1} due to the energy threshold of the ONMS in ion mode. They are projected onto the equatorial plane after binning in 15° solar zenith angle and 250 km altitude bins. (b) Model display corresponding to Figure 2a derived from the test particle calculation described in the text.

observed "average" nightside superthermal ion flow vectors projected onto the Venus equatorial plane and scaled to 20 km/sec. These were derived [*Kasprzak and Niemann*, 1988] by binning the inferred ion velocities from PVO orbits 901-1350 and 1576-1800 in 250 km (altitude range) by 15° (solar zenith angle) bins and plotting the vectors at the bin centers. The data cover the altitude range from ~ 600 km to ~ 3000 km. Note that on the dawn side (top of Figure for retrograde Venus) the vectors suggest a net antisolar flow of the hot ions. The duskside flow pattern (bottom of Figure) is relatively disordered.

The composition of the superthermal ion flows is primarily O^+, but significant fractions of molecular ions are also detected. *Kasprzak et al.* [1991] described the composition of the ONMS superthermal ion population in terms of the ratios of other species to O^+. Compositional analysis in the ONMS ion mode is difficult because the overall response of the detector is a function of ion mass, energy, and effective instrument angle of attack. *Kasprzak et al.* [1991] estimate that the sensitivity of the instrument at 40 amu is ~ 2-3 times lower than at 16 amu, depending on the ion energy. No calibration factors have been applied to the data to correct for these responses. Typical flux ratios of molecular contributions relative to O^+ found by *Kasprzak et al.* [1991] range between ~10^{-2} and 1 for the detected species with masses 4, 14, 28, 30, 32, and 44 amu, corresponding to He^+, N^+, N_2^+, CO^+, NO^+, O_2^+, and CO_2^+ (mass 1 cannot be measured). The average and median values of the ratios are given by those authors but are considered uncertain due to the instrument response and the irregular structure in the ion populations. O^+, the dominant superthermal species, constitutes roughly 1% of the total ionospheric density in the region where it is measured.

Model Comparisons

Average vectors analogous to those in Figure 2a were modeled by launching 2800 O^+ ions from the terminator

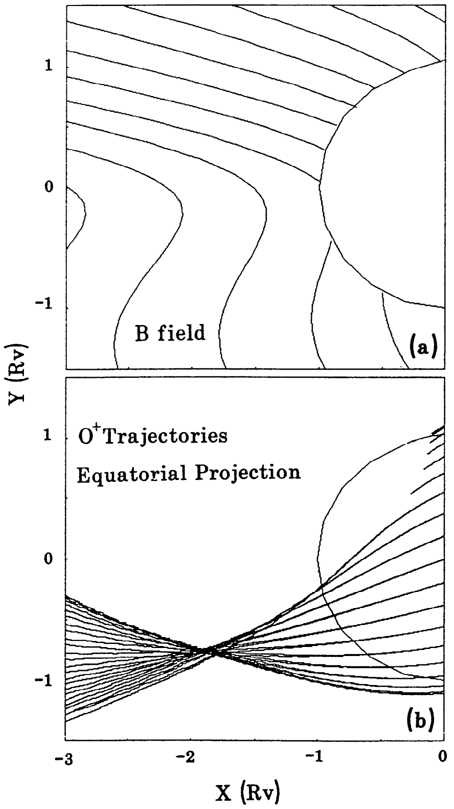
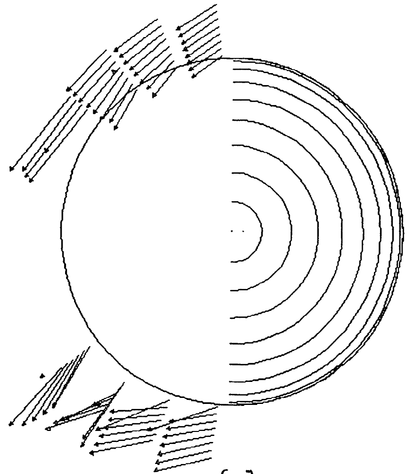
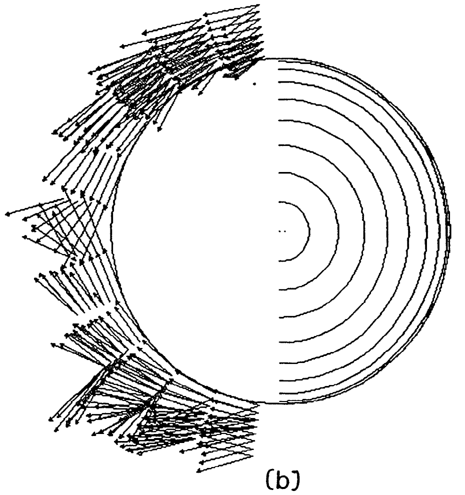


Figure 3. (a) IMF B_x component of the magnetic field model. (b) Sample O^+ ion trajectories for the magnetic field model.



(a)
Model (40° IMF cone angle)



(b)
Model (mixed IMF cone angles)

Figure 4. (a) Calculated averaged O^+ flow vectors corresponding to those in Figure 2 for the revised field model shown in Figure 3. The IMF "cone angle" is the angle between the Venus-Sun axis and the IMF. It is the same as the Parker-Spiral angle for an IMF in the equatorial plane. (b) Same as Figure 4a but for a mixture of IMF cone angles within ± 45° of the nominal average 40° value.

plane in the altitude range between 250 and 2250 km. As in work by *Luhmann* [1993], the initial test particle velocities were taken as 1 km/s antisunward, and the density of starting points had a radial falloff. The IMF was assumed to lie in the equatorial plane, perpendicular to the solar wind flow, in the direction opposite Venus' orbital motion ($+y$ in VSO coordinates). The velocities along the trajectories were recorded at each time step and then sorted according to their locations in the altitude-solar zenith angle bins used by *Kasprzak and Niemann* [1988]. Averages of the vector components along the trajectories passing through each bin produce the equatorial plane projections shown in Figure 2b. Unlike Figure 2a, Figure 2b displays considerable symmetry with respect to the Venus-Sun axis, although the velocities appear to be of comparable magnitude. The impression from this simulation of the ONMS data is that the flow is antisolar and converging toward midnight. This symmetry can be broken by introducing the effect of the Parker spiral IMF on the tail draping pattern [e.g., *McComas et al.*, 1986]. At Venus the average IMF direction is about 40° from radial (with respect to the Sun). When this modification is introduced by adding a uniform magnetic field component antiparallel to the Venus-Sun axis, the new model field lines and ion trajectory examples appear, as in Figure 3. The revised flow vector results in Figure 4a show departures from the symmetrical antisolar flow pattern in the observed sense. If results from a combination of IMF angles within 45° of the nominal Parker spiral angle are superposed, as in Figure 4b, the model vectors also exhibit the observed greater variability in the dusk sector.

This model can be used to estimate energy or spectral properties of the proposed low-altitude pickup ion population as well. The energy distribution for the hot ion population as a whole (most of which escapes) can be calculated from the trajectory "data" by counting the total number of trajectory points, or time steps, at which a particle is found in a given energy interval. Related results presented in the earlier tail ray paper [*Luhmann*, 1993] show that for O^+ the characteristic energies are in the few 10s of eV range at essentially all locations in the present flow and field model (which applies only to the low-altitude wake). Flux scales are arbitrary because their magnitudes are controlled by the (variable) source density at the terminator. Figure 5 shows the spectra obtained for O^+, O_2^+, and CO_2^+ for both perpendicular and 40° angle IMFs. The perpendicular IMF case gives higher energy ions because the pickup electric field ($\mathbf{E} = -\mathbf{V}\times\mathbf{B}$ where $\mathbf{V}$ is the (antisolar) velocity in the model and B is the draped magnetic field) is on average greater for that wake magnetic field configuration.

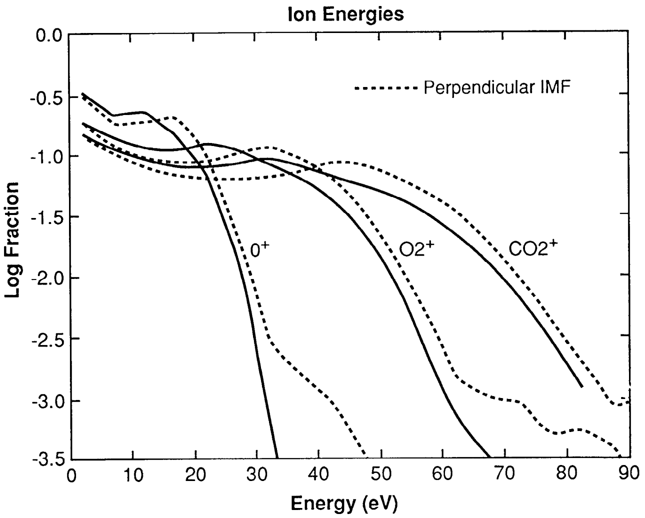


Figure 5. Calculated energy spectra for the test particle ions of mass 16, 32, and 44 amu for an IMF perpendicular to the solar wind flow (dashed line) and at 40° to it (solid line).

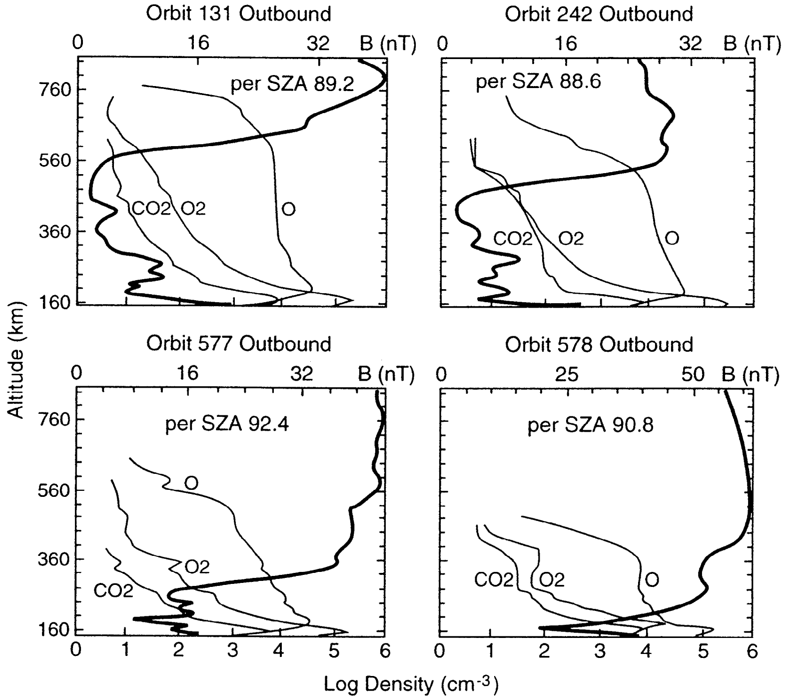


Figure 6. Four examples of ionospheric composition altitude profiles derived from the PVO INMS measurements near the terminator. The corresponding magnetic field magnitude profiles obtained with the PVO magnetometer (solid lines) show where the solar wind electric field can map into the ionosphere. The ionosphere is collisionless above ~250 km.

One implication of the proposed model is that the composition of the superthermal nightward ion flows should reflect the ion composition in the terminator source region. The PVO ion mass spectrometer [*Taylor et al.*, 1980] measured altitude profiles of the ionospheric constituents throughout the PVO low-altitude mission (also see the review by *Brace and Kliore* [1991]). Terminator profiles, four of which are reproduced in Figure 6, show significant densities of ions other than O^+ above the collision-dominated region starting near 250 km. The corresponding magnetic field profiles, obtained from the PVO magnetometer, indicate where the solar wind convection electric field can map along draped field lines into the terminator upper ionosphere. The depth to which it can map depends on the solar wind conditions. In the present model the ions in the magnetized regions are subject to Lorentz forces that are larger than the cross-terminator pressure gradient forces, thereby producing the superthermal nightward flows observed by the ONMS. The model energy spectra have a bearing on the perceptions of ion composition obtained from the ONMS ion data. In addition to escaping O^+ *Kasprzak et al.* [1991] found ~20% O_2^+ and a comparable amount of CO_2^+ in their detected ion populations for solar zenith angles greater than 120°. As illustrated by Figure 7, these are somewhat higher than the corresponding contributions of molecular ions detected near ~250 km at the terminator by the ion mass spectrometer, although their mass distribution is comparable. (Only masses 28, 30, and 32 are compared here to diminish the effect of the nonuniform ONMS response described above.) The pickup acceleration mechanism may provide the key to understanding this apparent "overabundance" in the escaping heavy ions observed by the ONMS. Since the pickup electric field imparts the same velocity (in the moving plasma frame) to all ions, the more massive ions acquire higher energies. If the minimum ion energy requirement for ONMS detection

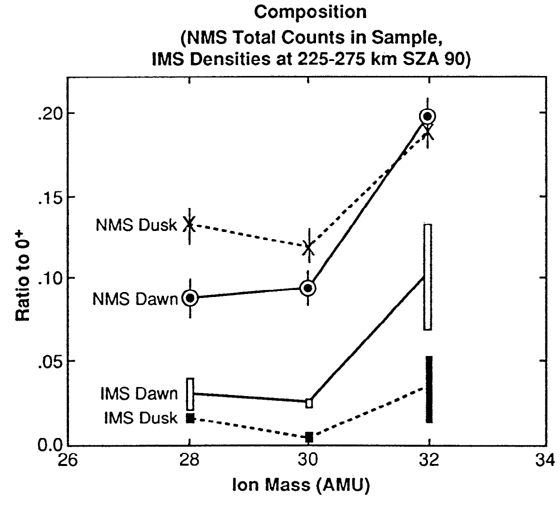


Figure 7. Ratios of escaping mass 28, 30, and 32 ions (probably N_2^+, CO^+, NO^+, and O_2^+) to O^+ in the ONMS superthermal ion data for solar zenith angles > 120°, and for average IMS densities in the altitude range 225-275 km at the terminator (solar zenith angle 90°).

on the nightside is ~30 eV, 25 eV, and 20 eV O^+, for O_2^+, and CO_2^+, respectively, it can be seen from Figure 5 that more of the heavier ions will be registered relative to their proportion. Thus the compositional observations of *Kasprzak et al.* [1991] do not require acceleration from the deep nightside ionosphere where molecular species are more abundant relative to O^+.

Another implication of the model is that the heavy ion contribution to the scavenged ionospheric population should increase as the solar wind pressure becomes stronger, or the ionosphere becomes weaker (e.g., near solar minimum), because the magnetic field (and hence mapped electric field) will reach lower average altitudes. In Figure 8 we test this prediction by comparing the total molecular ion contribution in the same data as used for Figure 7 to the F10.7 cm flux as an indicator of solar EUV intensity. The anticorrelation found in this display, though weak and having significant scatter, is consistent with this prediction and opposite to the trend for the O^+ flux versus EUV found by *Kasprzak et al.* [1991].

Concluding Remarks

The question of whether the energy contained in the observed escaping ions can be supplied by the solar wind can be considered if we presume a particular cross section for the energy transfer. For example, if we assume that the involved boundary layer magnetosheath plasma comes from solar wind streamlines within ~0.1 R_v of the stagnation streamline, ~4 x 10^{27} eV s^{-1} is supplied by a 400 km s^{-1} solar wind flow. Typical fluxes of the escaping heavy ion population were ~10^5 - 10^8 cm^{-2} s^{-1} according to *Kasprzak et al.* [1991]. Suppose we assume that these emanate from a ring-shaped area 1000 km in thickness around the terminator. (This is the approximate thickness of the region of the observed ONMS ion flows and is thus an overestimate for individual cases.) At ~40 eV per ion, these fluxes would then correspond to ~5 x 10^{23} -5 x 10^{26} eV/s, well within the limit carried by the assumed solar wind energy "source". If the thickness of the source ring is narrower the energy requirements are even more modest. On the other hand, if a layer of the entire observed upper ionosphere (seen in Figure 6) with O^+ density ~10^4 cm^{-3} was accelerated to 40 eV without substantial spatial divergence, the fluxes would be much higher than those detected by the ONMS. Thus the actual source region must be in the gradient layer where the densities are lower, or for some reason the pickup efficiency may be limited. The ultimate test of this concept requires the use of a much more sophisticated treatment such as a global version of the hybrid simulation of *Brecht and Ferrante* [1991] with heavy ions loaded at the inner boundary.

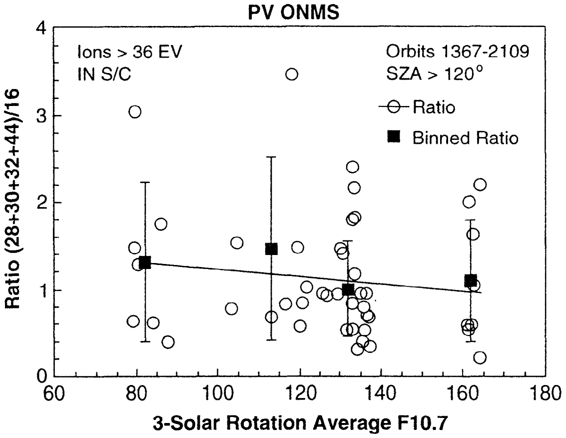


Figure 8. Superthermal heavy ion to O^+ ratio versus F10.7 flux. Averages in F10.7 bins of 20 are shown by the solid squares. The best-fit line to the raw data is also indicated.

In summary, it is expected that both thermal O^+ ions and molecular ions observed in the upper (collisionless) terminator ionosphere of Venus can be accelerated or picked up by the solar wind convection electric field that maps into the magnetosheath-ionosphere boundary. Both the inferred flow vectors and the measured composition of the superthermal ions observed in the wake by the Pioneer Venus Orbiter neutral mass spectrometer in its ion mode are consistent with the idea that the ions are escaping from the terminator upper ionosphere as part of the tail rays. Terminator upper ionosphere ions at weakly magnetized Mars are likely to suffer a similar fate.

Acknowledgments. J. L. was supported in this effort by NASA grant NAGW-3426 from the Venus Data Analysis Program.

The Editor thanks K. Szegö and another referee for their assistance in evaluating this paper.

References

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, 1987.

Brace, L. H., and A. J. Kliore, The structure of the Venus ionosphere, in *Venus Aeronomy*, edited by C. T. Russell, *Space Sci. Rev., 55*, 81, 1991.

Brecht, S. H., and J. R. Ferrante, Global hybrid simulation of unmagnetized planets: Comparison of Venus and Mars, *J. Geophys. Res., 96*, 11,209, 1991.

Intriligator, D. S., Results of the first statistical study of Pioneer Venus Orbiter plasma observations in the distant Venus tail: Evidence for a hemispheric asymmetry in the pickup of ionospheric ions, *Geophys. Res. Lett., 16*, 167, 1989.

Kasprzak, W. T., and H. B. Niemann, Fast O+ ion flow observed around Venus at low altitudes, *NASA Tech. Memo., 100717*, Dec. 1988.

Kasprzak, W. T., H. A. Taylor, L. H. Brace, and H. B. Niemann, Observations of energetic ions near the Venus ionopause, *Planet. Space Sci., 30*, 1107, 1982.

Kasprzak, W. T., H. B. Niemann, and P. Mahaffy, Observations of energetic ions on the nightside of Venus, *J. Geophys. Res., 92*, 291, 1987.

Kasprzak, W. T., J. M. Grebowsky, H. B. Niemann, and L. H. Brace, Superthermal >36 eV ions observed in the near-tail region of Venus by the Pioneer Venus Orbiter neutral mass spectrometer, *J. Geophys. Res., 96*, 11,175, 1991.

Knudsen, W. C., K. Spenner, K. L. Miller, and V. Novak, Transport of O+ ions across the Venus terminator and implications, *J. Geophys. Res., 85*, 7803, 1980.

Luhmann, J. G., A model of the ionospheric tail rays of Venus, *J. Geophys. Res., 98*, 17,615, 1993.

Lundin, R., et al., Plasma composition measurements of the Martian magnetosphere morphology, *Geophys. Res. Lett., 17*, 877, 1990.

McComas, D. J., H. E. Spence, C. T. Russell, and M. A. Saunders, The average magnetic field draping and consistent plasma properties of the Venus magnetotail, *J. Geophys. Res., 91*, 7939, 1986.

Moore, K. R., D. J. McComas, C. T. Russell, and J. D. Mihalov, A statistical study of ions and magnetic fields in the Venus magnetotail, *J. Geophys. Res., 95*, 12,005, 1990.

Phillips, J. L., J. G. Luhmann, C. T. Russell, and K. R. Moore, Finite Larmor radius effect on ion pickup at Venus, *J. Geophys. Res., 92*, 9920, 1987.

Taylor, H. A., Jr., H. C. Brinton, S. J. Bauer, R. E. Hartle, P. A. Cloutier, and R. E. Daniell Jr., Global observations of the composition and dynamics of the ionosphere of Venus: Implications for the solar wind interaction, *J. Geophys. Res., 85*, 7765, 1980.

J. M. Grebowsky and W. T. Kasprzak, NASA Goddard Space Flight Center, Code 915, Greenbelt, MD 20771. (e-mail: grebowsky@pacf.dnet.nasa.gov;kasprzak@pacf.dnet.nasa.gov)

J. G. Luhmann, Space Sciences Laboratory, University of California, Berkeley, CA 94720. (e-mail: jgluhmann@sunspot.ssl.berkeley.edu)

(Received August 2, 1994; revised January 27, 1995; accepted February 9, 1995.)