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IONOSPHERIC FLOW AND ESCAPE OF IONS FROM TITAN AND VENUS

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ABSTRACT

Knowledge gained from measurements and models is used to study the high-speed plasmas interacting with the atmospheres and ionospheres of Titan and Venus. Considering the similarities of the interactions, comparative analysis is used to support the interpretations of observations made at each body. Ionospheric flow, inferred to exist by analysis of measurements made from the Pioneer Venus Orbiter, supports the interpretation of similar flow in the ionosphere of Titan. The concept of cold ion escape from the ionosphere of Venus is supported by the Voyager 1 observation that cold ions escape down the magnetic tail of Titan. Pickup O^+ ion energy distributions observed at their source in the ionosheath of Venus are shown to be influenced by finite gyroradius effects. The signatures of such effects are expected to be retained as the ions move into the wakes of Titan and Venus.
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INTRODUCTION

A considerable fraction of atmospheric loss at Venus and Titan is in the form of plasma escape. This is due in part to the fact that the ionospheres of these unmagnetized bodies interact directly with the high-speed plasmas flowing around them. We use the similarities of the interactions to reinforce both our earlier and present interpretations of measurements made at each body from different measurement sites and instruments. In particular, the implications of ion measurements made by the Plasma Science Instrument (PSI) on Voyager I as it flew through the ionotail of Titan are related to those of the ion measurements in the ionosphere, ionosheath, and distant ionotail of Venus. The latter measurements were made by the Orbiter Ion Mass Spectrometer (OIMS) and the Orbiter Plasma Analyzer (OPA) onboard the Pioneer Venus Orbiter (PVO). These measurements are used to reinforce the concept that some of the "cool" ions of ionospheric origin escape down the ionotails of each body. Further support of this picture comes from measurements by the CELIAS CTOF instrument onboard SOHO, where observations of "cool" ions in the absence of "hot" pickup ions were made in Venus' wake at 1 AU. Because the gyroradius of pickup O^+ in the ion source region of Venus is much larger that the scale height of the neutral O source, it is argued that the resulting O^+ flux distribution peaks at energies less that the maximum possible O^+ pickup energy. This finite gyroradius effect is consistent with the pickup O^+ ion distributions observed by the OPA in the source and wake regions of Venus and supports the interpretation of the presence of finite gyroradius effects in the PSI measurements of heavy pickup ions at Titan.

TITAN

The PSI onboard Voyager 1 made ion measurements as it flew by Titan on its way through the magnetosphere of Saturn (Bridge et al., 1981). The plasma science instrument had four Faraday cups, three of which were pointing sunward and the forth, the D cup, pointed approximately towards the corotational direction of Saturn's magnetospheric plasma. During the flyby, magnetometer measurements indicated that Titan essentially possesses no intrinsic magnetic field (Ness et al., 1981). Saturn's rotating magnetospheric plasma was found to interact directly with Titan's atmosphere and ionosphere and produced a magnetic tail in its wake, similar to the solar wind interaction observed at Venus. As Voyager 1 approached Titan, pickup H^+ ions were identified (Hartle et al., 1982), just outside the magnetic tail, by the sudden H^+ flux dropout above their cutoff energy, which is 2 times the plasma speed times the sine of the angle between the magnetic field and the plasma velocity. As the spacecraft flew through the magnetic tail of Titan, only the D cup observed ion fluxes (Figure 1), signifying that the plasma was flowing away from Titan (note that the sloped, straight lines in the figure are the noise levels of the PSI). The best-fit analysis of these spectra indicated an ion density of ~10 cm^{-3}, flow speed of ~4 km s^{-1} and a temperature of 1–2 ev, which is much cooler than the plasma outside Titan's tail. All of the above features led to the speculation that these "cold", escaping ions were of ionospheric origin (Hartle et al., 1982). The most likely mass of these ions was 28 amu, the mass of the ion thought then to be the dominant topside ion in the ionosphere; i.e., H_2CN^+.

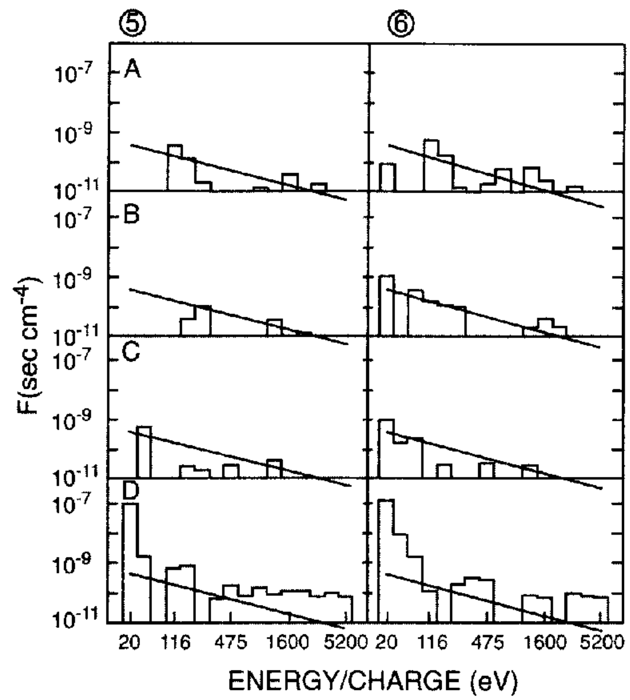

Fig. 1. Flux measurements in A, B, C and D cups of the PSI at 2 points in the magnetic tail of Titan. The A, B, and C cups point sunward while the D cup points into the flow of Saturn's rotating magnetospheric plasma.

These measurements caused us to think that if the escaping ions are of ionospheric origin, then there should be signatures of such upward flow in Titan's ionosphere. Confirmation of this idea will have to wait at least until the Cassini mission. In the interim, we have applied the idea to the ionosphere of Venus, where *in-situ* measurements were made in the ionosphere of Venus during the PVO mission.

VENUS

Ions can escape from a number of places at Venus; e.g., pickup ions born above the ionopause, ions flowing upward from the nightside ionosphere, and those flowing from the dayside ionosphere to the nightside, where a fraction escape from the planet. The *in-situ* measurements of ion composition, densities and temperatures in the ionosphere and pickup ions in the ionosheath during the PVO mission provide the opportunity to look for signatures of such ion escape at their sources.

Day to Night Flow

Day to night transport of O^+ has been known for some time to be essential in maintaining observed levels of O_2^+ and O^+ in the nightside ionosphere (see review, Brace et al., 1995). Such a process entails both vertical and horizontal ion flow in the dayside ion source region. Vertical flow is treated in the following while the horizontal flow has been analyzed extensively by Knudsen et al. (1982). Vertical ion flow was not measured directly in the ionosphere of Venus by instruments on the PVO mission. However, an algorithm has been developed to extract vertical ion speeds from PVO altitude profiles (Hartle and Grebowsky, 1993) of ion and electron densities, temperatures, and their gradients measured by the OIMS, the Orbiter Electron Temperature Probe (OETP) and the

Orbiter Retarding Potential Analyzer (ORPA). Also used are the magnetic field measurements of the Orbiter Magnetometer (OMAG). This technique was first used in the nightside ionosphere to obtain vertical ion wind speeds of H^+ and D^+, from which a strong polarization electric field was shown to be the principal force accelerating the ions upward (Hartle and Grebowsky, 1995). This process has proved to be a major escape flux for hydrogen and deuterium, contributing significantly to the loss and evolution of water on Venus (Hartle et al., 1996).

The algorithm can also be applied to the heavier constituents of the day and night side ionospheres. The dayside ionosphere is known to exist in at least two dynamic states, compressed and extended. In the former, there is evidence that the solar wind ram pressure is high enough to cause the topside ionosphere to flow downward, resulting is a lower ionopause and a shorter scale height for the dominant ion, O^+ (Bauer and Hartle, 1974). When the algorithm is applied to an extended ionosphere, typically occurring when the ionopause is higher than about 500 km, upward flow is found. This is the case for orbit 418, where upward winds shown in Figure 2 are found for O^+, O_2^+, and C^+. (Note: the vertical winds were evaluated near the subsolar point so that the effects of horizontal winds on the calculation were minimized.) These profiles are typical of upward winds obtained when the dayside ionosphere is extended in the presence of low solar wind ram pressures. The downward flow of O^+ obtained from the highly compressed ionosphere of orbit 184 (ionopause below 300 km) is contrasted in Figure 3 against the upward O^+ flow of orbit 418.

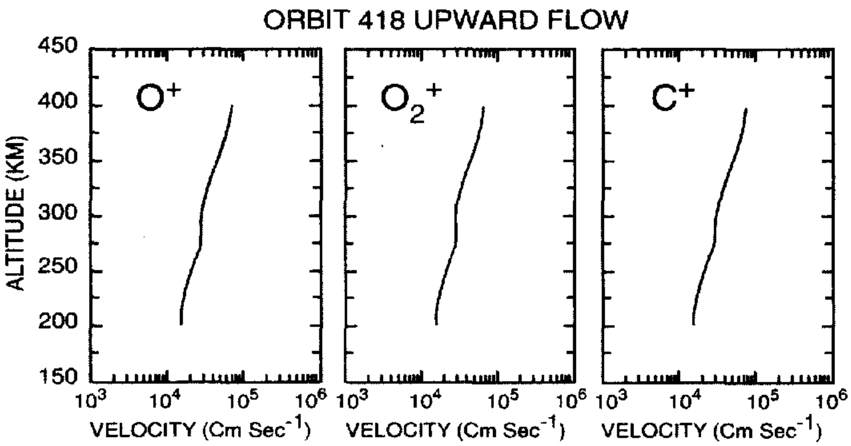

Fig 2. Upward flow speeds of O^+, O_2^+ and C^+ in dayside ionosphere of Venus near subsolar point.

When the analysis for the extended ionosphere is carried to altitudes higher than in Figure 2, the upward wind speed decreases due to an increase in the horizontal magnetic field intensity producing a downward magnetic pressure. This represents a qualitative tendency only, because the structured, strong vertical gradients of parameters in this region do not permit good quantitative values of ion wind speeds with the current data set. Nevertheless, it is clear that the ions slow down with increasing altitude while horizontal flow increases to conserve ion flux. Altogether, the deflection of upward flow toward the nightside by the magnetic barrier is consistent with a fountain-like flow field confined to the cavity below the ionopause suggested earlier by Cravens and Shinagawa (1991).

Considering this day to night flow picture, Brace et al., (1995) estimated that the dayside O^+ flux into the nighttime ionosphere, during times of uncompressed ionospheres, could considerably exceed the flux required to maintain the night O_2^+ layer. They suggested that the excess would escape as relatively cold plasma down the ionotail or as a cloud of plasma that has broken away from the dayside ionopause region.

Night Flow

Earlier, using this algorithm on the nightside, we obtained vertical ion wind speeds of H^+ and D^+, from which a strong polarization electric field was shown to be the principal force accelerating the ions upward (Hartle and Grebowsky, 1995). This process has proved to be a major escape flux for hydrogen and deuterium, contributing significantly to the loss and evolution of water on Venus (Hartle et al., 1996). The upward flow of H^+ and D^+ occurs in the presence of downward flowing O^+, which maintain the nightside O_2^+ layer. However, when the algorithm is applied at altitudes well above the O_2^+ peak, we frequently find the flow reversals as shown in Figure

4, with upward O^+ flow toward the ionotail at high altitudes. The profiles in this figure were generated from data in the midnight to 2:00 am sector that was averaged over Venus years 1, 2 and 3. The altitude of the flow reversal is highly sensitive to the spatial gradients. This is shown in Figure 4, where the range of altitudes is due to about a 10 percent variation in the O^+ scale height from its average observed value, which is used for the central reversal.

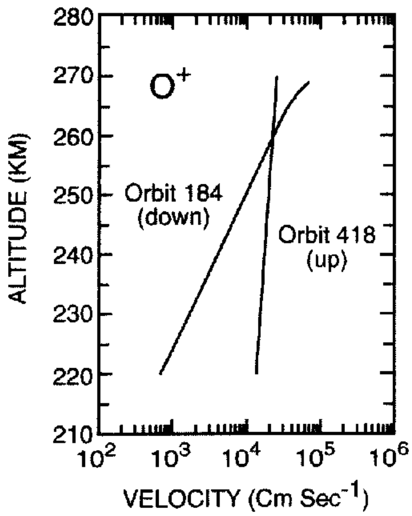

Fig 3. Downward subsolar region flow speed of O^+ for compressed ionosphere compared with upward speed for compressed ionosphere.

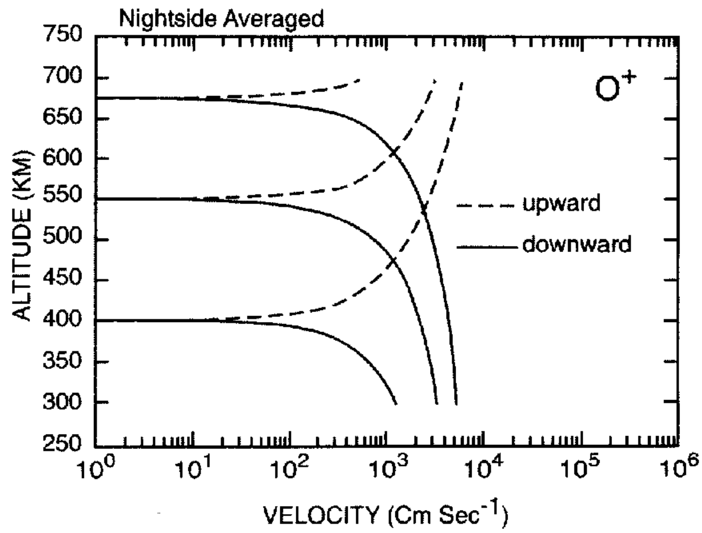

Fig 4. Upward and downward flow speeds of O^+ depicting flow reversal in midnight sector of Venus'.

The day to night flow of heavy ions like O^+, which can exceed the flow necessary to maintain the nightside ionosphere, coupled with the observed inference of upward flow of O^+ directly from the nightside ionosphere suggests the presence of a global ion flow pattern which includes the flow of ionospheric ions away from the nightside ionosphere into the ionotail of Venus. These "cold" ionospheric ions flowing into the ionotail are expected to be accelerated to solar wind speeds by the motional electric field as the draped magnetic field straightens out and merges with the interplanetary field.

Ionotail

The possible presence of these cold escaping ions and/or pickup ions have been sought using OPA measurements in the distant ionotail during PVO apoapsis passes at about 12 Venus radii, R_v (e.g., Intriligator,1989; Slavin et al., 1989). Measurements of O^+ are possible when the plasma wind speed is low enough so that the heavy ions' energies are within the instrument's upper energy limit. The energy widths of the O^+ ions observed in the distant tail are much broader than those expected for the cold ions of ionospheric origin. Consequently, only pickup ions have been identified on the apoapsis passes (Intriligator, 1989; Slavin et al., 1989). However, the presence of cold ions could be inferred from those instances in the central region of the ionotail where there is complete absence of a plasma signal (Intriligator, 1989). Although the pickup O^+ ions are "hot" relative to ionospheric ions, they have not been observed to have measurable fluxes at the *maximum* possible pickup ion energy, which is $(1/2)16m_p(2\ v_p\sin\alpha)^2$ or $64\sin^2\alpha$ times the proton energy and an equivalent speed of $8\sin\alpha$ times the proton bulk speed, where m_p is the proton's mass, v_p its bulk speed and α is the angle between the plasma velocity and the magnetic field. The precise energy and speed is the result of where and how they were born, a point that is addressed below.

Although ionospheric ions were not observed in Venus' wake at 12 R_v by the OPA, O^+ and C^+ ions were observed at 1 AU by the CTOF detector of the CELIAS mass spectrometer instrument [Grunwaldt et al., 1997] on SOHO. These measurements were made when SOHO passed through the predicted position of the plasma wake of Venus, suggesting that the ions were of Venusian origin. Furthermore, the observed ion energy distributions yielded a "cool" temperature of 5600 K/amu, which implied to Grunwaldt et al. (1997) that the ions originate in the "cool" ionosphere of Venus and are not the "hot" pickup ions formed in the corona of the planet. This result was made clear when they showed that their observed interstellar pickup He^+ flux distributions had a much wider energy width than those of O^+ and C^+.

PICKUP IONS

The energy distributions of pickup ions have been measured at Titan and Venus. We consider those measured at Venus first because a fraction of the observations were made in the source region. Flux distributions of pickup O^+ and ambient, shocked solar wind H^+ observed by the OPA in the ionosheath above the dayside ionopause are shown in Figure 5. The O^+ flux was measured as a function of ion energies per unit charge, but is plotted here as a function of equivalent proton speeds. This example typifies the structure of the flux distributions in the dayside ionosheath source region. In this example, the H^+ bulk speeds are about 70 km s^{-1} and the corresponding peak speed for O^+ is about 190 km s^{-1}. Although a range of peak speeds have been observed by the OPA in the O^+ source region, none have been identified to have equivalent speeds anywhere near 8 times the bulk speed of the ambient H^+ plasma (this of course does not consider those cases where the peaks may exist but were not observed because they occur above the energy limit of the OPA). In many cases this is expected because the $\sin\alpha$ is much less than 1. However there are a number of places where $\sin\alpha$ is near 1; e.g., in the sub-solar wind meridian plane.

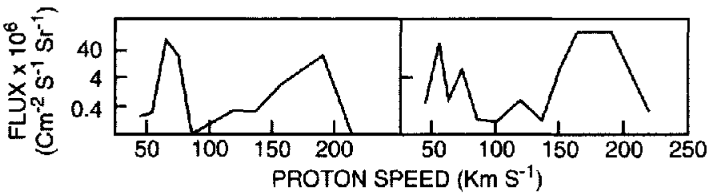

Fig 5. H^+ and O^+ ion flux observed by OPA in the O^+ source region in the dayside ionosheath of Venus.

The O^+ peak is not expected to occur at the maximum possible pickup energy when the O^+ gyroradius is large, because finite gyroradius effects become important. Pickup O^+ ions are born in the dayside ionosheath where the parent hot O corona extends well above the ionopause (Nagy et al.,1990). Electron impact, photoionization, and charge exchange form O^+ from O, which is then picked up by the flowing ionosheath plasma. The O^+ gyroradius varies from 560 km to 5,000 km when the ionosheath plasma speeds are between 100 km s^{-1} and 300 km s^{-1} and the magnetic field ranges from 10 nT to 30 nT. In the 500 km to 1,000 km height range the respective hot O scale heights are about 200 km to 500 km. Thus, the ratio of the O^+ gyroradius to the hot O scale height spans the range 1.1 to 25. Most of the ions (an e-folding amount) at a given observation point were born about an O scale height upstream. Consequently, because the O^+ gyroradius is much larger than an O scale height, the ions have only traversed part of their cycloidal trajectory and therefore the bulk of the them have not accelerated to their full potential by the time they reach the observation point. Ions that come from several scale heights away from the observation point certainly attain their maximum velocity, but their weight in the flux distribution is exponentially diminished. This naturally produces a peak flux that occurs at energies less than the maximum possible energy. Applying this concept to the pickup O^+ ions observed in and near the ionotail at PVO apoapsis, it becomes clear that O^+ ions born with large gyroradii should have flux peaks that do not occur at the maximum possible energies, simply because finite gyroradius effects would have distributed the ion velocities this way at birth.

At Titan, the principal ions observed to be picked up in this moon's ion exosphere by Saturn's rotating magnetospheric plasma are H^+, N^+ and/or N_2^+. As mentioned previously, abrupt flux dropouts above their cutoff or maximum allowed energy identified the H^+ pickup ions. This is valid because the ratio of the H^+ gyroradius to the scale height of H is much less than 1. On the other hand, this ratio is considerably greater than 1 for N^+ and N_2^+. Considering the Cytherian example above, these heavy ions cannot be identified by their cutoff energies because finite gyroradius corrections are large. Their peak fluxes should appear well below their maximum possible energies. The flux distributions of these ions observed just outside the magnetic tail of Titan by the PSI (point 4 of Figure 4 in Hartle et al., 1982) implied that they played a significant role in slowing down the magnetospheric plasma through mass loading. However, a quantitative understanding of this process awaits precise measurements of the complete velocity distributions.

CONCLUSIONS

Considering the similarities of the high-speed plasma interactions with the atmospheres and ionospheres of Titan and Venus, comparative analysis was applied to interpret the respective measurements made from Voyager 1 and PVO. The presence of ions flowing away from Titan, along its ionotail (Hartle et al, 1982), suggests the possibility of such flow in the ionotail of Venus. The Cytherian ionosphere was assumed to be the principal source of such ions. An analysis of ionospheric parameters measured from PVO was shown to be consistent with this picture. That is, an ionotail source results from the excess of the day to night O^+ flow necessary to maintain the nightside ionosphere and from O^+ flowing directly upward from the nightside ionosphere. This interpretation is supported by measurements made from SOHO, where "cool" ions, not "hot" pickup ions, were observed in Venus' wake at 1 AU. Taking comparative analysis one-step further, the evidence of an ionospheric source for Venus' ionotail reinforces an earlier suggestion (Hartle et al., 1982) that a similar process occurs at Titan. The interaction would be most similar to that at Venus when the Sun to Titan direction and the rotational velocity vector of Saturn's magnetosphere are similarly directed. Pickup O^+ ion flux energy distributions in the pickup source region of Venus were observed by OPA to peak below the maximum possible ion energy. It was shown that this is a consequence of the O^+ ion gyroradius being larger than the scale height of the O source. The signatures of these finite ion gyroradius effects are expected to be retained as the ions move into the wakes of Titan and Venus.

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