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Space weather at Venus and its potential consequences for atmosphere evolution

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[1] Space weather storms at the Earth are dominated by the magnetosphere's response to coronal mass ejections, or CMEs, whose disturbances propagate through the solar wind to 1 AU, and to a lesser extent by the pressure ridges associated with the interactions of solar wind streams with different properties. The interplanetary signatures of these events include high solar wind dynamic pressures and high interplanetary magnetic fields, the same parameters that cause compression and/or magnetization of the ionosphere at weakly magnetized Venus. The nature of Venus' response to these events is also expected to include increased atmosphere erosion by the solar wind interaction, a matter of potential interest for historical extrapolations of atmosphere escape. We consider the possible evidence for enhanced escape during these disturbances in the data from the Pioneer Venus Orbiter (PVO). Available magnetometer and plasma analyzer results are used to identify periods of interest and the interplanetary characteristics of the disturbed periods. It is found that the suprathermal (>36 eV) ion measurements from the Pioneer Venus neutral mass spectrometer (ONMS) provide convincing evidence of the related enhanced escape of mostly O^+ suprathermal ions. The results provide the first direct demonstration that space weather has played an important role in Venus (and other weakly magnetized planet) atmosphere loss through time. It is important to pursue study of these effects with the new measurements from Venus Express and, in light of the approaching solar activity cycle rising phase, extremely timely.

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1. Introduction

[2] Renewed interest in the escape of terrestrial planet atmospheres has been sparked by the increasing evidence that Mars once had liquid water on its surface [e.g., *Haskin et al.*, 2005; *Squyres et al.*, 2004], requiring a milder climate and hence a more substantial inventory of volatiles. Planetary bodies have several avenues for the loss of their atmospheres, including early hydrodynamic escape enabled by a hydrogen-rich atmosphere and high early solar EUV flux, impact by other bodies (which in the case of comets is considered a source as well), and losses still operating today that are related to atmospheric photochemistry and the solar wind interaction. Venus, like Mars, presently has no substantial planetary dynamo-generated dipole field, and as a result its atmosphere interacts more directly with the solar wind than is the case for planets with significant magnetospheres [e.g., *Luhmann and Bauer*, 1992]. It has been inferred that the consequence of that direct interaction, in contrast to the indirect interactions occurring at Earth through the filter of Earth's magnetosphere, is the potential for significant escape of atmospheric constituents over time. The proof of this proposal remains to be confirmed, however, as all missions to Mars and Venus to date have only carried parts of the instrument complement necessary to quantitatively determine escape rates and their variations. Venus Express, which arrived at Venus in April, 2006, has the best opportunity yet to establish at least the current atmospheric ion escape rates that are an essential contributor to these loses. It also has the prospect of establishing the significance of pickup ion sputtering [*Luhmann and Kozyra*, 1991; *Barabash et al.*, 2007] and loss of neutrals by charge exchange processes [e.g., *Holmstrom and Kallio*, 2004].

[3] Earlier measurements of pickup ions on the Pioneer Venus Orbiter (PVO) by the NASA Ames Research Center Plasma Analyzer, while compromised by instrument limitations [e.g., see *Mihalov and Barnes*, 1982; *Moore et al.*, 1990; *Luhmann et al.*, 2006] established some important baselines and questions for Venus Express. A key issue is the range of magnitude of the pickup ion fluxes due to variations in both solar and interplanetary conditions. Earlier calculations of pickup ion production and loss, including the related exobase sputtering, for the Martian case [*Luhmann et al.*, 1992] suggested how the changing solar EUV flux over time, coupled with changing solar wind

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conditions, would modify the escape rates due to present-day processes. These calculations, though simplified by numerous assumptions, demonstrated the nonlinear nature of the problem. Higher solar EUV fluxes produce both a more extended neutral thermosphere and a denser exosphere, as well as increase the photoionization rate. Therefore the pickup ion reservoir enhancement is considerably more than the value of the solar EUV flux increase. At the same time, different solar wind properties modify the related pickup ion and sputtering escape rates by determining the additional charge exchange and solar wind electron impact contributions to the ion production rates, the altitude of solar wind electric field penetration into the atmosphere, and the pickup ion gyroradius (leading to changes in the number of pickup ions escaping into the wake versus impacting, and sputtering, the exobase region).

[4] Venus' situation is basically the same as for Mars, but greatly simplified by the absence of any appreciable remanent magnetic fields that introduce additional controls over ion escape rates, e.g., by partially shielding regions of the upper atmosphere, or by adding additional magnetospheric cusp-like escape mechanisms [e.g., *Seki et al.*, 2001; *Lundin et al.*, 2006]. While Venus' magnetic field and atmosphere history must have differed from those of Mars, Venus provides a much less complicated laboratory for studying the basics of solar wind-related atmosphere escape from an unmagnetized planetary body. With this general purpose in mind we revisited the PVO data set to determine what more can be learned about the variations of pickup ion escape rates with solar outputs. In particular, we investigated the effect of solar activity and solar wind structure-related extremes in incident dynamic pressure and magnetic field magnitude on the ion escape rates using a second escaping ion data set obtained with the PVO Neutral Mass Spectrometer (ONMS). While the responses to short-lived solar flare EUV enhancements are difficult to identify in PVO in-situ data, due to the limited probability of sampling the pickup ion fluxes at the right place and time, we could easily examine the responses to the relatively long-lived interplanetary disturbances associated with coronal mass ejections, or CMEs, the cause of major geomagnetic storm activity at the Earth. We also examined the effect of the solar wind enhancements due to the nonuniform stream structure of the solar wind. While the ONMS observations of escaping ions are neither continuous nor calibrated for details of spectral response, they provide unique evidence from PVO for solar wind controlled enhancements in the ion escape rates prior to any new results forthcoming from Venus Express.

2. PVONMS Pickup Ions

[5] *Brace et al.* [1995] summarize what is known about atmospheric ion dynamics and losses at Venus from the PVO data set. The four instruments on PVO that provided ion information from thermal to keV energies consisted of an ion mass spectrometer [*Taylor et al.*, 1980], a retarding potential analyzer [*Knudsen et al.*, 1980], a Langmuir Probe, through thermal electron density measurements [*Krehbiel et al.*, 1981], and the aforementioned plasma analyzer designed to detect solar wind ions [*Intriligator et al.*, 1981]. Of these, the plasma analyzer provided the clearest evidence of planetary ions moving at well above escape speeds down the wake in the form of high energy peaks in the ion energy per charge spectra [*Mihalov and Barnes*, 1982]. These peaks were consistent with the presence of O^+ comoving with the solar wind protons. The retarding potential analyzer showed nightward-flowing ionospheric ions moving at up to ~5 km/s at the highest altitudes near the terminator [*Knudsen et al.*, 1981], but ~11 km/s is required for near-Venus ions to escape. Further indications of suprathermal ions near the ionopause were detected by the thermal ion mass spectrometer, but that instrument was not calibrated for definitive interpretations of those signatures [e.g., see *Grebowsky et al.*, 1993]. Ion composition measurements in the nightside ionospheric holes observed during the high solar activity conditions of the PVO prime mission suggested the occurrence of modest Earth-like polar-wind outflows along the associated highly inclined magnetic fields [*Hartle and Grebowsky*, 1990], but these occurred only in limited areas of the nightside, and were not always observed. Finally, the Langmuir Probe found irregular or detached ionospheric plasma structures in the electron densities near the ionopause on many occasions, implying comet tail-like behavior [*Brace et al.*, 1982, 1987], or shear flow-related instabilities at the ionosphere-solar wind boundary [e.g., *Elphic and Ershkovich*, 1984], but again the evidence for associated ion escape was only suggestive. In addition, *Ong et al.* [1991] showed that many of these ionopause structures occurred at times of rotations of the interplanetary magnetic field orientation, raising the possibility that transient distortions of the ionospheric density at the ionopause are often present rather than a "bulk escape" process.

[6] The discovery that the PVO NMS could be used as an effective low-energy ion detector also providing directions of motion is described by *Kasprzak and Niemann* [1982]. Briefly, it was found that when the filaments for ionizing the entering neutrals were turned off, the PVO NMS responded to >36 eV ambient ions, and that the detected ions were mainly O^+, the principal ion species in Venus' upper atmosphere. *Kasprzak et al.* [1987, 1991] analyzed both the fluxes and inferred average directions of these suprathermal ions, the latter of which exhibited the antisolar streaming also seen in the PVO retarding potential analyzer data [*Knudsen et al.*, 1981; *Miller and Whitten*, 1991]. The important difference for our purposes is that the PVO NMS suprathermal ions have velocities well above the escape speed for O^+, which is about 10 eV for O^+ ions close to Venus. *Mihalov et al.* [1995] later compared low-energy ion fluxes detected in the Venus wake with the Plasma Analyzer with some of these PVO NMS ion observations, confirming their magnitudes.

[7] A key question is how the ions observed by the PVO NMS obtained their energies, and whether they should/could be considered pickup ions. The attractiveness of the pickup ion explanation is that it depends on a virtually limitless source of energy from the solar wind, which constantly carries the interplanetary magnetic field past Venus, exposing Venus' upper atmosphere to its related convection electric field $E = -VXB$, where V is the plasma velocity and B the draped interplanetary magnetic field. Any ion exposed to this electric field and the associated magnetic field will be accelerated to up to twice the ambient

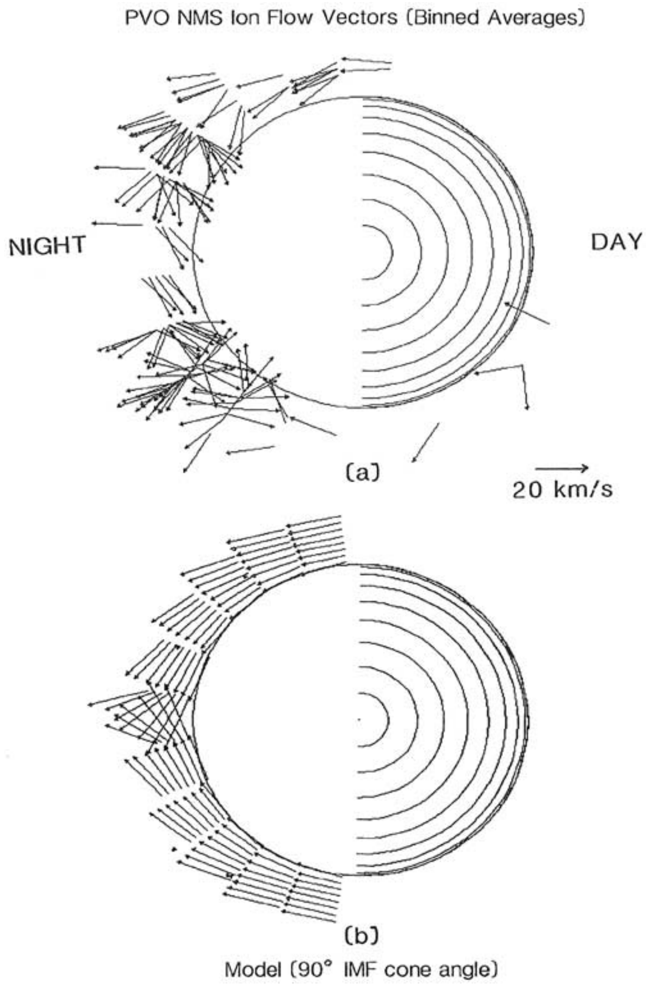

Figure 1. Figure from *Luhmann et al.* [1995] showing (a) the suprathermal ion velocities in the wake from the PVO NMS measurements of *Kasprzak et al.* [1991] compared to (b) a model based on the idea that these are low-altitude O^+ pickup ions.

velocity V, depending on the angle between V and B. Note that in general an ion exposed to this electric field may start from a nonzero velocity, and in this case it experiences a modified convection electric field where V is given by (V-v), where v is the particle's velocity. This is also a consideration when the ion experiences a changing plasma velocity and field environment along its trajectory, as it may pass with non-zero velocity from the site of its initial production and acceleration into a region of much higher or lower background V × B. However, such complications can be included in test particle treatments of ion pickup in background field and plasma flow models. These take the particles' history into account because they presume a global description of the field and plasma flow surrounding Venus and numerically solve the full Lorentz equation for the ion motion. Models of this kind can be used to illustrate that the only requirement for escape via pickup is the presence of a magnetic field and an ambient plasma velocity component perpendicular to local B of sufficient speed to accelerate the ion up to ∼11 km/s in an antisunward direction [e.g., see *Luhmann*, 1993]. That the field is interplanetary field that has diffused into the upper atmosphere and ionosphere is immaterial to the ion, which simply responds to its local field and background plasma flow environment from its creation through its subsequent path.

[8] In a study inspired by the PVO NMS ion observations of *Kasprzak et al.* [1991], *Luhmann et al.* [1995] carried out test particle calculations using a simplified description of the draped interplanetary fields around Venus to demonstrate that the observed suprathermal ion average velocity patterns and energies were consistent with an ion pickup process at work in the upper atmosphere. A comparison of the observed pickup ion average velocities with the results of those calculations is reproduced in Figure 1. The basis for this approach is the assumption that in the essentially collisionless region between the pressure balance ionopause (at ∼300 km subsolar, ∼1000 km at the flanks) and the exobase (at ∼200 km altitude), observed interplanetary field penetration and ion flows imply that a convection electric field is present. Any ions produced there or transported there from below can be picked up just as they are picked up in the magnetosheath, even in this planetary ion-dominated region of plasma flow.

[9] One may debate the notion that the PVO NMS suprathermal ions should be considered pickup ions, given the alternative viewpoint that pressure gradient forces alone or combined with JXB forces (where J is the current density) can produce a similar outcome in hydrodynamic [*Whitten et al.*, 1982, 1991; *Cravens et al.*, 1983] and mass-loaded MHD models of the Venus ionosphere-solar wind interaction [e.g., *Shinagawa*, 1996; *Tanaka*, 1998], respectively. However, the important point here is that the PVO NMS ions have velocities suggesting escape, and thus provide us with a PVO data base, in addition to the PVO Plasma Analyzer data, for empirically evaluating ion energization and escape rates. Moreover, because of the detector characteristics, the PVO NMS ion observations provide a means to investigate the low-altitude, low-energy end of the pickup process, in the major source region of the upper thermosphere/lower exosphere, and its dependence on external conditions.

3. Variability of Solar and Interplanetary Conditions

[10] Several earlier papers considered aspects of the possible effects of solar activity and solar wind variations on what was observed on PVO. For example, *Moore et al.* [1990] found a solar EUV cycle dependence of the average escaping O+ ion fluxes measured by the plasma analyzer. Similarly, *Brace et al.* [1990] showed that the density of the ionospheric wake detected with the Langmuir Probe varied with the changing average solar EUV flux but that orbit-to-orbit variations are mainly controlled by the solar wind pressure. The PVO NMS suprathermal ion data also suggest a variation with the average EUV flux [*Kasprzak et al.*, 1991], but considerable variability from some other controlling factor(s) is present. In more solar event-specific analyses, *Taylor et al.* [1985] examined the PVO (thermal) Ion Mass Spectrometer data during several periods of enhanced solar wind dynamic pressure detected by the PVO Plasma Analyzer. They found indications of enhanced solar wind interaction effects in the form of ionospheric

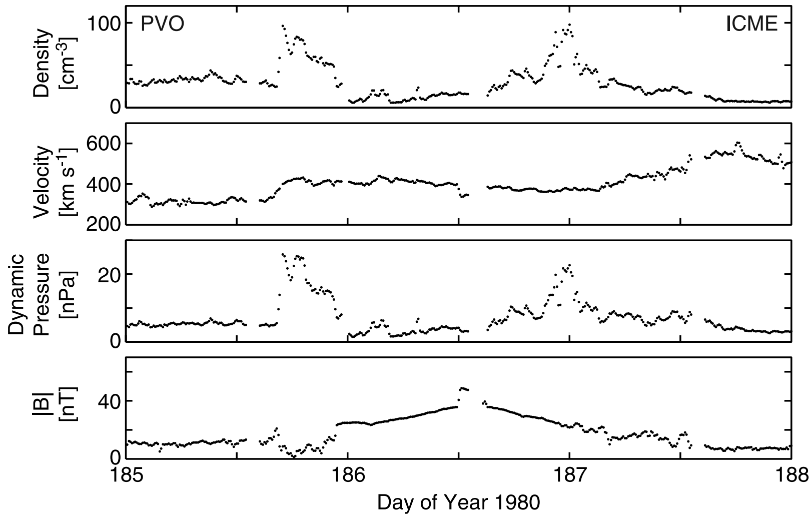

Figure 2. Example of an ICME detected on PVO, showing the key parameters contributing to a high solar wind pressure and magnetic field interaction. Enhancements in both the solar wind density and velocity at the beginning of the interplanetary disturbance produce most of the high solar wind dynamic pressure episodes found at Venus on PVO, although this event also has a trailing dynamic pressure increase due to a second region of high density (possibly from the driver expansion or a trailing filament). The two point styles represent 10 minute averages without data within a Venus bow shock shape mask removed (open points) and with the Venus interaction removed (solid points). Note that on this occasion Venus was encountered midway through the ICME passage, which took ~2 days.

compressions when apparently corotating stream structures passed Venus. *Kar et al.* [1986] showed evidence for increased atmosphere ionization during solar flares, when the solar EUV and soft x-ray fluxes are greatly enhanced for brief periods, in the measured profiles of electron density at ~200 km altitudes. *Dryer et al.* [1982] analyzed the PVO observations during passage of an interplanetary shock in May 1979, finding an ionospheric disturbance in the form of reduction of the ionopause altitude. All of these, especially the last three, can be considered investigations of "space weather" effects at Venus. Such effects are not unexpected, but for those interested in atmosphere escape they hint at the potential for active solar periods to have consequences for current escape rates and also for historical escape scenarios.

[11] The atmospheric effects of changing solar EUV and soft x-ray outputs are well-known from comparative Earth studies, and have been invoked by *Fox and Sung* [2001] and *Mendillo et al.* [2006] to explain terrestrial planet ionosphere alterations during both solar maximum and the more temporally abbreviated solar flare periods. The interplanetary plasma and field consequences of solar activity have also been studied at Earth and elsewhere in the heliosphere. *Luhmann et al.* [1993] examined the overall changes with the solar activity cycle of solar wind parameters measured on PVO, finding consistency with similar observations obtained upstream of Earth. But such statistical analyses average over the event nature of many of the changes of potential importance here. *Lindsay et al.* [1994, 1995] focused on the particular events known as interplanetary coronal mass ejections, or ICMEs, and solar wind stream interaction regions detected at 0.72 AU on PVO. These now well-known features are regularly studied in heliophysics for their connections with the Sun's magnetic and coronal activity cycles, as well as for their close association with geomagnetic storms at the Earth.

[12] The interplanetary plasma and field signatures of ICMEs often include a preceding shock followed by a magnetosheath-like region of compressed solar wind plasma and interplanetary field, and a driver or ejecta portion. The sheath-like regions of ICMEs are a primary cause of high solar wind dynamic pressures in the inner heliosphere when the Sun is active, each generally lasting a fraction of a day. In contrast, both the ejecta portion and the sheath portion often exhibit unusually high magnetic field strengths. In the ejecta portion the fields are often smooth and slowly rotating, while in the sheath they are often

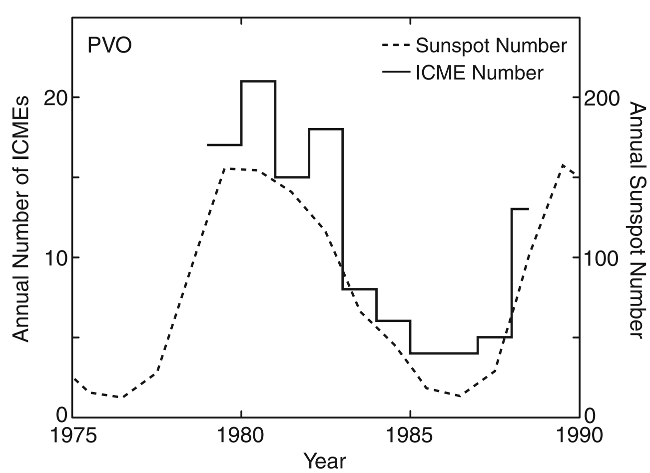

Figure 3. Annual statistics of ICMEs in the PVO interplanetary data identified by *Lindsay et al.* [1994] and annual sunspot number divided by 10.

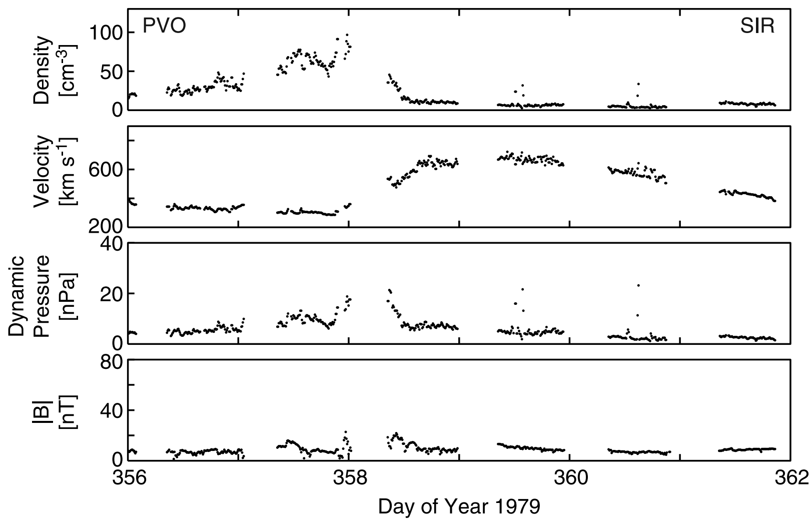

Figure 4. Examples of solar wind stream interaction regions, illustrating the associated dynamic pressure and magnetic field magnitude increases lasting a fraction of a day.

highly variable in orientation and strength. The intervals of combined sheath and ejecta fields can last up to several days. Figure 2 shows the key solar wind plasma parameters and magnetic field during an ICME passage detected on PVO by the plasma analyzer and the magnetometer.

[13] *Lindsay et al.* [1994], *Mulligan et al.* [1998], and *Jian et al.* [2006] studied the occurrence of ICME events in the PVO data sets. Lindsay et al. found the solar cycle dependence, also known from near-Earth solar wind studies, illustrated in Figure 3. The solar cycle variation in occurrence of ICMEs roughly follows the sunspot number, with a few ICMEs per month observed around activity maximum, and only one every few months around solar minimum. While each of these authors used slightly different selection criteria for ICMEs, they all used the general properties described above for the sheath and ejecta identification, and found comparable solar cycle rates and trends. It is notable that not all ICMEs are equally well-characterized. In particular, there are periods around solar maximum where several may occur in close succession, and merge to form a much more complex-looking structure. Therefore it is often useful to consider less active times on

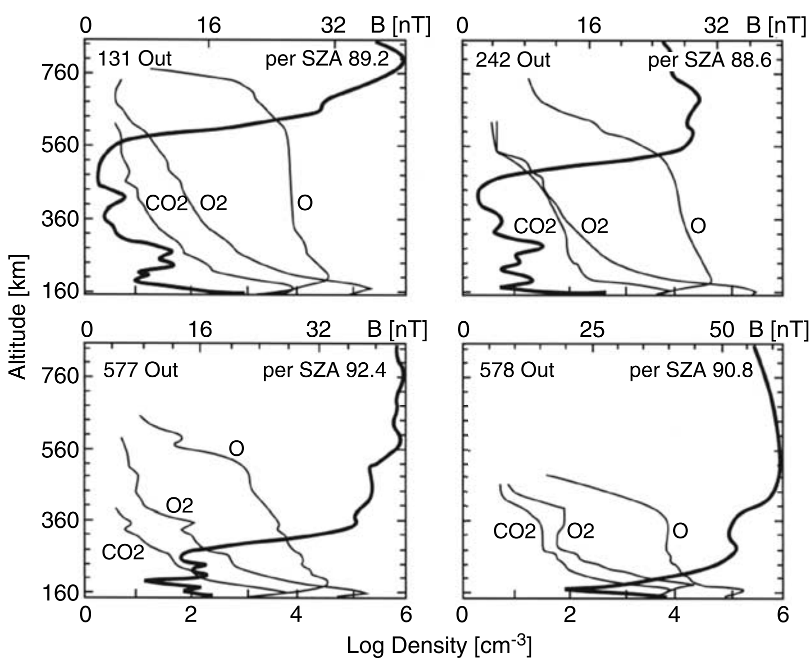

Figure 5. Figure from *Luhmann et al.* [1995] illustrating the occasional penetration (bottom panels) of draped interplanetary magnetic fields (heavy line) into the terminator ionosphere between the apparent ionopause and the exobase at ~200 km observed on PVO. "Per SZA" given in each panel is the solar zenith angle of periapsis.

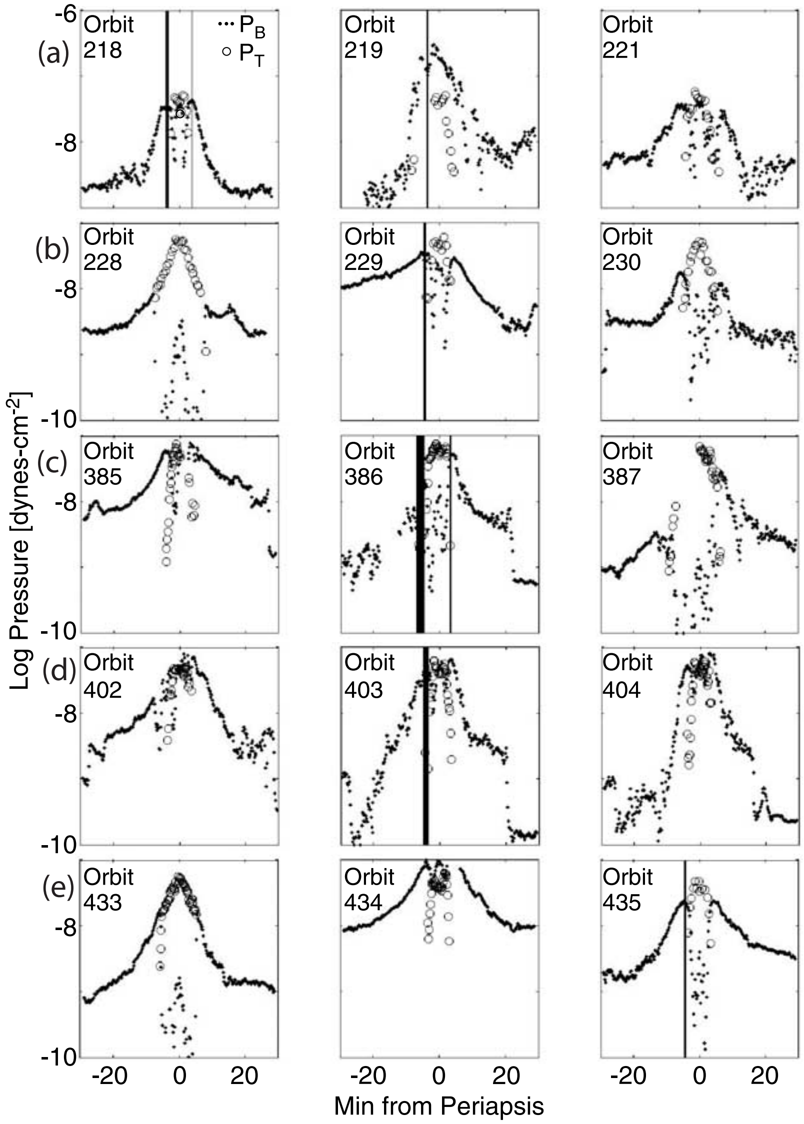

Figure 6. Near-periapsis time series of thermal pressures from the Langmuir Probe, and magnetic pressures from the magnetometer, measured on PVO during orbits in the range 1–600 that exhibited the highest suprathermal ion fluxes (>5 × 10^7/cm^{2}s) detected by the PV ONMS, together with similar plots for the adjacent orbits. In all cases a highly magnetized ionosphere, characteristic of high solar wind pressure interactions, was observed either on the orbit of the high suprathermal ion flux detection or on an adjacent orbit. (For comparison, Orbit 218 shows the appearance of a more typical solar maximum case with an unmagnetized ionosphere, showing only the low level fields of flux ropes in the ionosphere.) All of these orbits had their periapsis in the dayside ionosphere. The vertical lines indicate the times of the 12s average high ion flux detections, which are at SZAs >35 degrees, on either the inbound or outbound leg or both. (a) Orbits 218, 219, and 221; (b) Orbits 228–230; (c) Orbits 385–387; (d) Orbits 402–404; (e) Orbits 434–436.

the rising or declining phases of the solar cycle when analyzing ICMEs and their effects in observations.

[14] The stream interaction regions (SIRs), in contrast to ICMEs, have the appearance of spiral-shaped ridges of enhanced solar wind density and compressed magnetic field, and sometimes reappear every ~27 days as if they are corotating with the Sun. These were also studied by *Lindsay et al.* [1994], who found an inverse correlation with solar activity, although L. Jian et al. (personal communication, 2006) find less of a clear solar cycle dependence in their study of similar features. The stream interactions are expected to be present all of the time because of the general nonuniformity of the low-heliolatitude solar wind at its source. However, the stream interactions are easier to distinguish in the interplanetary observations, and are more clearly characterized, when ICMEs are absent. In fact during active solar times ICMEs and SIRs are probably merged together in many cases. Figures 4 and 5 shows an example of a well-isolated SIR in the PVO solar wind and interplanetary field observations. While SIRs, like ICMEs,

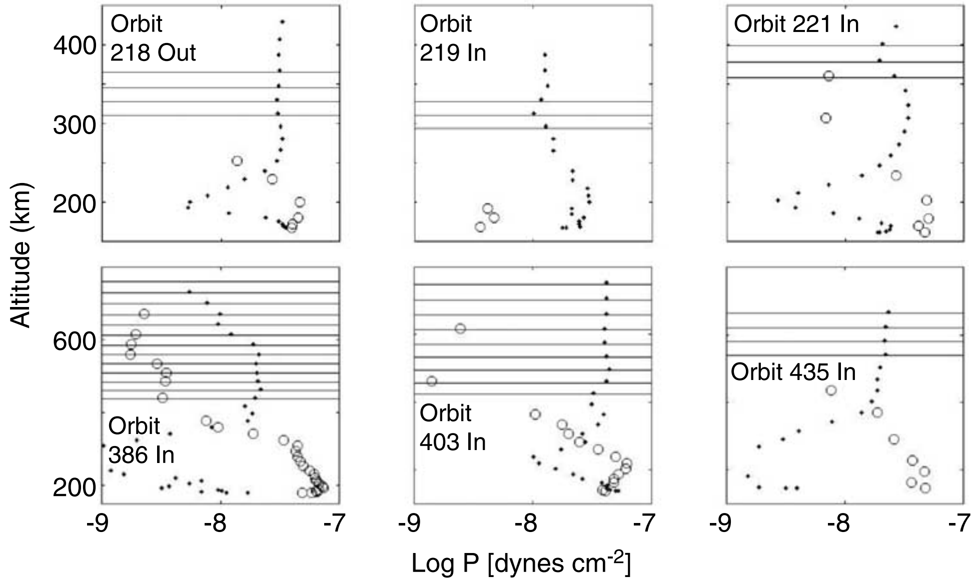

Figure 7. Altitude profiles corresponding to the high suprathermal ion flux detections shown in Figure 6. Sometimes the Langmuir Probe-derived thermal pressure suggests the presence of high-altitude thermal plasma at the time of the >36 eV ion detections by the PV ONMS (Orbits 386 and 403). The horizontal lines indicate times of the detections of high ion fluxes in the 12s averages and correspond to the vertical lines in Figure 6.

cause enhanced solar wind pressures and interplanetary field strengths at Venus, they are distinguished by their generally much shorter event duration and typical absence of an accompanying shock at Venus' heliocentric distance.

4. ICME and SIR Effects at Venus

[15] The control of the Venus solar wind interaction by the solar wind dynamic pressure is well-documented and moderately well understood (e.g., reviews by *Russell* [1991]). In particular, the main observed features of the high dynamic pressure interaction are the reduction of the ionopause altitude and the magnetization of the ionosphere [e.g., *Luhmann and Cravens*, 1991]. Both of these have the potential for increasing pickup ion production and losses. A low ionopause exposes more of the upper atmosphere to the solar wind, so that any ion produced above it by photoionization, charge exchange with solar wind protons or solar wind electron impact ionization can escape, while the magnetization of the upper atmosphere and ionosphere, considered to be produced by downward diffusion and convection of the draped interplanetary field, exposes even ions below the ionopause to a convection electric field, enabling their acceleration. It is moreover important to note that the presence of a large and relatively steady interplanetary magnetic field by itself can produce a magnetized ionosphere because the physics of the ionospheric magnetization process depends on the field strength at its boundary, and does not distinguish between a high field produced by magnetosheath field compression versus an intrinsically high interplanetary field.

[16] Figure 5 from *Luhmann et al.* [1995] shows some observations of the ionospheric magnetization during several PVO periapsis passes at Venus. These examples are especially notable because they are from cases where periapsis was near the terminator, thereby suggesting that the escaping ions observed by PVO NMS (see Figure 1) could have easily been picked up by a convection electric field in the collisionless region between the apparent ionopause, where the ionospheric density decreases in these altitude profiles, and the exobase at ~200 km. In the past these cases have simply been associated with large solar wind dynamic pressures, without regard for the source of the large dynamic pressure, or whether large ionopause field magnitude by itself could also be the underlying cause. In addition, nightside "disappearing ionospheres" [*Cravens et al.*, 1982] are observed under similar conditions. Both *Cravens et al.* [1982] and *Brace et al.* [1995] suggested that these could in fact be evidence for the escape of the usual pressure gradient-driven, antisolar-flowing ionospheric plasma rather than its typical subsidence to form the nightside ionosphere. They speculated that something in the high dynamic pressure interaction accelerates the normally ~5 km/s antisolar flowing ions at the terminator to escape speed, enhancing the solar wind-related ionosphere erosion effects.

5. Dependence of PVO NMS Ion Fluxes on Solar Wind Conditions

[17] Because the PVO Plasma Analyzer observations of pickup ions were limited by several detector attributes including energy response and directional response, these measurements cannot be readily used to study the dependence of ion escape on solar wind variations, and in particular for ICME and SIR conditions. We therefore analyzed the suprathermal ion data from the PVO NMS ion mode with this purpose in mind. While *Kasprzak et al.* [1991] studied the statistics of the escaping ion fluxes with a focus

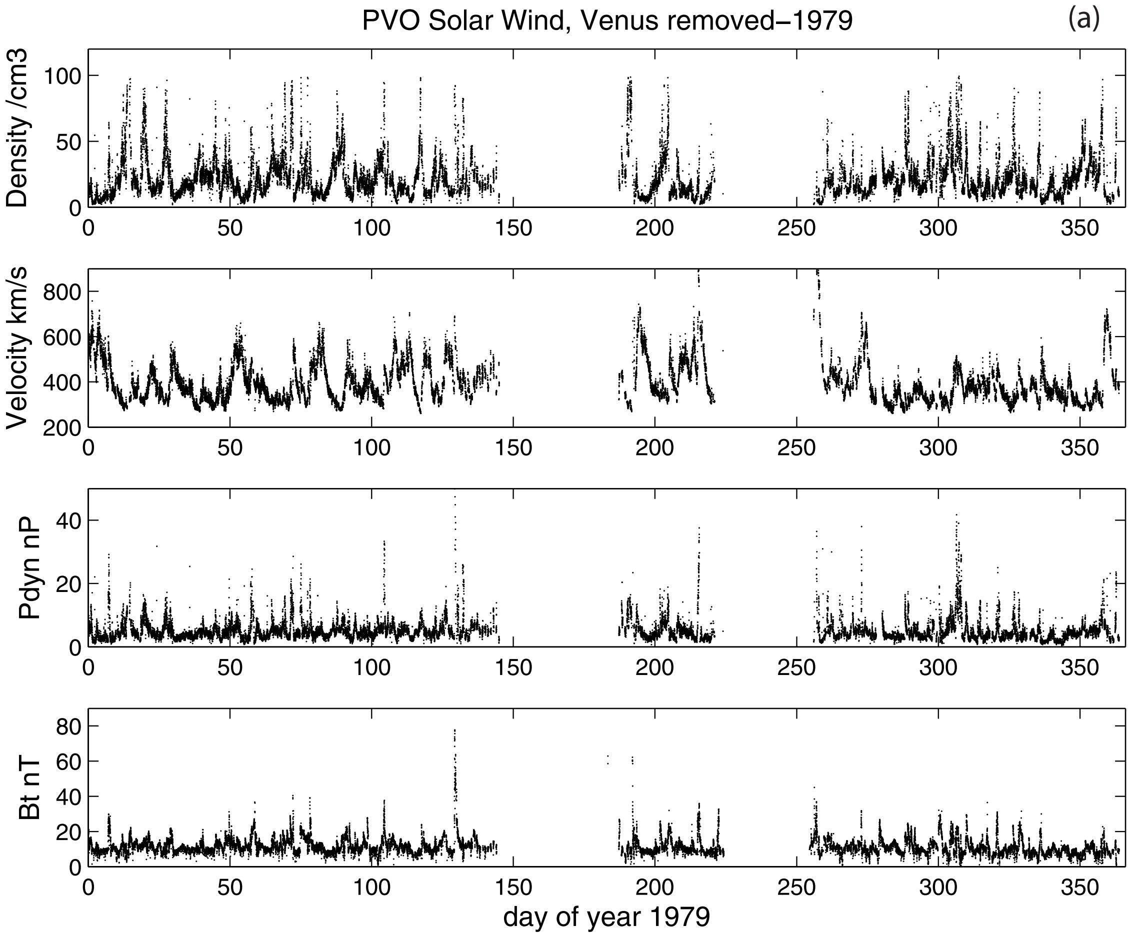

Figure 8. Overview of solar wind parameter behavior measured on PVO by the plasma analyzer for (a) 1979 and (b) 1980. Increases in solar wind dynamic pressure (Pdyn) and the magnetic field magnitude (Bt) may be associated with solar wind stream interaction regions or with ICMEs. The largest effects are typically from ICMEs.

on orbits 1300-3700, a period spanning solar minimum when few ICMEs occur, here the early period of PVO observations from orbits 1-600, including the high solar activity years 1979–80 when periapsis was still low, are examined. During this period the PVO NMS was generally operated in its neutral mode, but detected the suprathermal ions at altitudes where the neutral density fell below its detection limit of $\sim 10^5/\text{cm}^3$.

[18] The average 12s averaged >36 eV ion fluxes analyzed by *Kasprzak et al.* [1991] for the PVO observations spanning the 1985–6 solar minimum were $\sim 10^5/\text{cm}^2\text{s}$. During the earlier period of the primary mission when periapsis was low and solar activity was high, fluxes over $10^9/\text{cm}^2\text{s}$ were detected, although more typically the high fluxes were ~several $10^8/\text{cm}^2\text{s}$. This is comparable to the O^+ flux *Brace et al.* [1995] point out is needed to supply the observed solar maximum, quiet time nightside ionosphere, presumably by flow across the terminator of ions produced on the dayside. In the orbit range 1–600 there are 22 orbits when 12s averaged suprathermal ion fluxes of $>1 \times 10^7/\text{cm}^2\text{s}$ were detected, and 7 cases with $>5 \times 10^7/\text{cm}^2\text{s}$. All of these high suprathermal ion fluxes were detected on the dayside at solar zenith angles >35 deg, at altitudes of 300 km or greater. Examination of the highest flux cases shows that they always occur either on the orbit of, or on an orbit adjacent to, a period when a highly magnetized ionosphere was observed at periapsis. Figure 6 shows time series of the near-periapsis ionospheric thermal pressures derived from the Langmuir Probe measurements, together with the magnetic pressure from the magnetometer, for the cases in orbits 1-600 that had ion fluxes $>5 \times 10^7/\text{cm}^2\text{s}$. The times when the high suprathermal ion fluxes were detected are marked by vertical lines. Note that most detections occur on the inbound leg, on which the orbit intersects the ionopause at higher latitudes than the outbound leg. Altitude profiles for the orbit inbound legs with the ion detections indicated are shown in Figure 7. The corresponding upstream solar wind measurements with the plasma analyzer and magnetometer were not always possible because the orbit geometry in these cases sometimes prohibited it (for periapsis in the subsolar region, apoapsis is often within the Venus sheath and wake). Nevertheless, for the orbits where the interplanetary context could be sampled, the interpretation that the largest suprathermal ion fluxes occur during ICME and SIR passages generally holds.

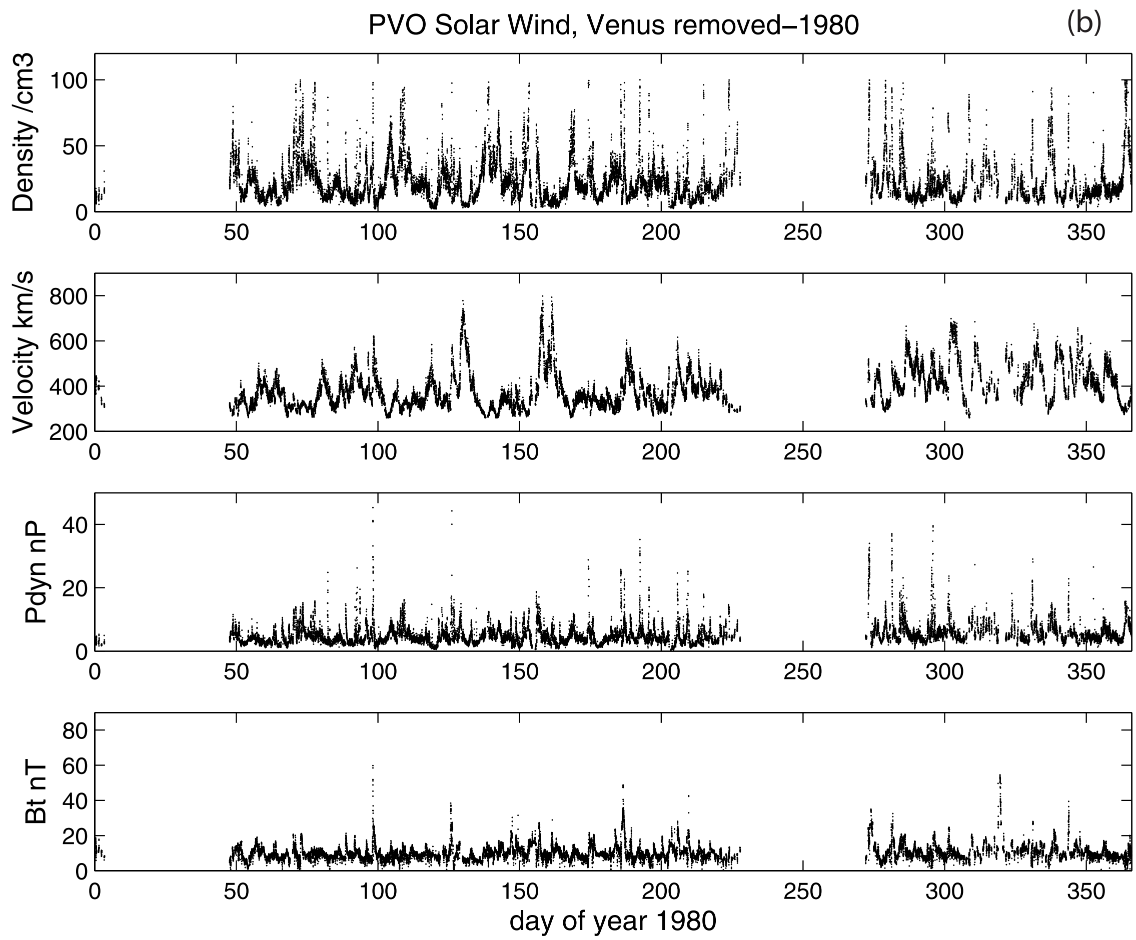

Figure 8. (continued)

[19] Figure 8 gives annual pictures of the solar wind and interplanetary field magnitude behavior for 1979 and 1980, which made up the bulk of the present study. These show that increases in both the dynamic pressure and the field occur regularly. The largest increases are generally associated with ICMEs. It is worth noting here that the highest (>$1 \times 10^9/\mathrm{cm}^2\mathrm{s}$) suprathermal ion fluxes recorded in the period covered by orbits 1-600 occurred on Orbit 153, day 126 of 1979, when the data set from many instruments appears to be unavailable, presumably due to operational anomalies occurring at the time. ICMEs are known to be preceded and accompanied by sometimes intense fluxes of solar energetic particles which can cause problems for spacecraft systems and operations.

[20] Statistical plots of the measured ion fluxes versus solar wind parameters such as dynamic pressure or interplanetary field magnitude exhibit considerable scatter. However, one particular plot type also strongly suggests the association between the largest escaping ion fluxes measured with the PVO NMS and the presence of ICME conditions. Figure 9 shows the >36 eV ion fluxes measured by the PVO NMS versus time for a period in the year 1997, when ICME rates were high enough to identify several major occurrences, and yet not so numerous as to cause confusion in individual event associations. We use a synthesis of the ICME lists of Lindsay (Ph.D. thesis, UCLA) and *Jian et al.* [2007] to mark the times when clear signatures were observed in the PVO plasma analyzer and magnetometer observations. It must be appreciated that the PVO NMS ion observations are not always possible. There are periods where the instrument is not pointed optimally and also when it is in another mode of operation. However, the coverage during this period is sufficiently constant to suggest that there is a relationship between the high escaping ion fluxes and the occurrence at Venus of the ICMEs identified by the vertical lines. The solar wind dynamic pressure and magnetic field magnitude also plotted in Figure 9 shows SIR-related increases, and suggestions of SIR effects on the escaping ion fluxes as well.

6. Implications for Pickup Ion Production and Related Escape Rates

[21] Pickup ion production rates depend on many factors. As noted earlier, the upper atmosphere densities and composition are the reservoir for planetary ion production, and then the ionizing EUV flux (photoproduction), solar wind electron flux (impact ionization production), and solar wind proton flux (charge exchange production of ions) determine how many ions are present at altitudes where

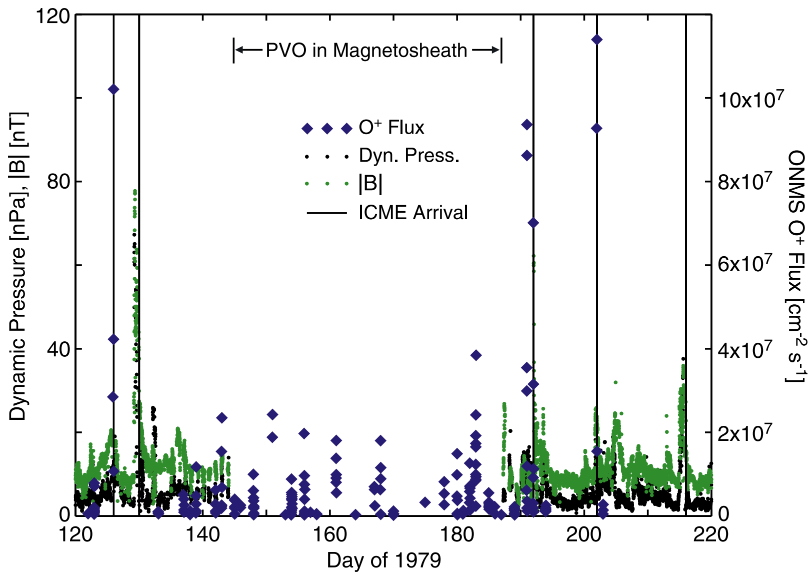

Figure 9. The suprathermal >36 eV O^+ flux measured by the PVO neutral mass spectrometer during 1979, compared to the magnetic field magnitude and solar wind dynamic pressure measured in the upstream solar wind. Enhancements of both dynamic pressure and interplanetary magnetic field are signatures of the passage of an interplanetary coronal mass ejection (ICME) or solar wind stream interaction region. Vertical lines indicate where ICMEs were identified in other studies (see text). On several of these occasions the PVO NMS measures significant increases in the O^+ flux. Note that the ONMS was not always configured to detect suprathermal ions, producing a number of observational gaps in that record, and that the gap in solar wind information centered on day 170 results from the PVO orbit remaining inside the bow shock during that period.

they can be affected by the penetrating magnetic field-related electric field. Planetary ions produced above the ionopause are always exposed to this pickup electric field that maps into the upper atmosphere from the solar wind along draped interplanetary (sheath) field lines. However, the densest reservoir of potential planetary pickup ions is at the altitudes between the exobase, where collisions with neutrals begin to restrict ion motion, and the ionopause. The ionopause altitude where solar wind dynamic pressure and ionospheric pressure balance (also controlled by EUV flux), determines how much of the planetary ion reservoir between the exobase and ionopause is exposed to a pickup electric field. The latter penetrates this pickup ion reservoir interior to the ionopause to varying degrees depending on solar wind conditions and upper atmosphere/ionosphere conditions, as described above.

[22] *Brace et al.* [1995] estimated that the nominal nightward integrated transport rate of ionospheric ions through the terminator plane, above the exobase, based on PVO ionospheric observations during typical solar maximum EUV conditions was $\sim 5 \times 10^{26}$ ions/s. They compared this to the nominal pickup ion escape rate inferred from the PVO plasma analyzer measurements in the Venus wake, of $\sim 5 \times 10^{24}$ ions/s [*McComas et al.*, 1986]. If we assume that during periods of ICME passage, when magnetized ionosphere conditions prevail, all of the nightward flux inferred from the ionospheric measurements escapes into the solar wind rather than subsiding to create the nightside ionosphere, we can estimate the total inferred loss for a typical solar maximum year. Assuming each ICME has conditions of either high solar wind dynamic pressure and/or high interplanetary field strengths leading to ionospheric magnetization lasting 1–2 days, and that 1–2 ICMEs per month encounter Venus, the ratio of ICME period pickup ion losses to quiet time losses during a year of high solar activity is

$$\left(12 - 24 \text{ days@}5 \times 10^{26}\right)/\left(350 \text{ days@}5 \times 10^{24}\right) = \sim 3 - 7\text{X}$$

This conservative estimate suggests that escape rates over decadal timescales are dominated by solar active times and especially by ICME event periods. The occurrence of SIRs throughout the solar cycle will further enhance this estimate of high dynamic pressure and high interplanetary magnetic field event effects.

[23] Pickup ion production and acceleration additionally have the potential for increasing related sputtering losses, an aspect that has not been considered here. The estimation of sputtering rates requires more sophisticated modeling that is beyond the scope of the present study. Direct loss of neutrals from the sputtering mechanism depends sensitively on the escape velocity, however, so is less important for Venus than for Mars [e.g., *Luhmann and Kozyra*, 1991]. The high solar wind densities that are a part of ICME sheaths and SIRs will also increase the rate of charge exchange-related pickup ion production, while the hot solar wind electrons in the post-shock sheaths of ICMEs will increase the impact ionization rate. All of these additional effects only serve to further boost the importance of ICME and SIR periods for overall losses of atmospheric constituents.

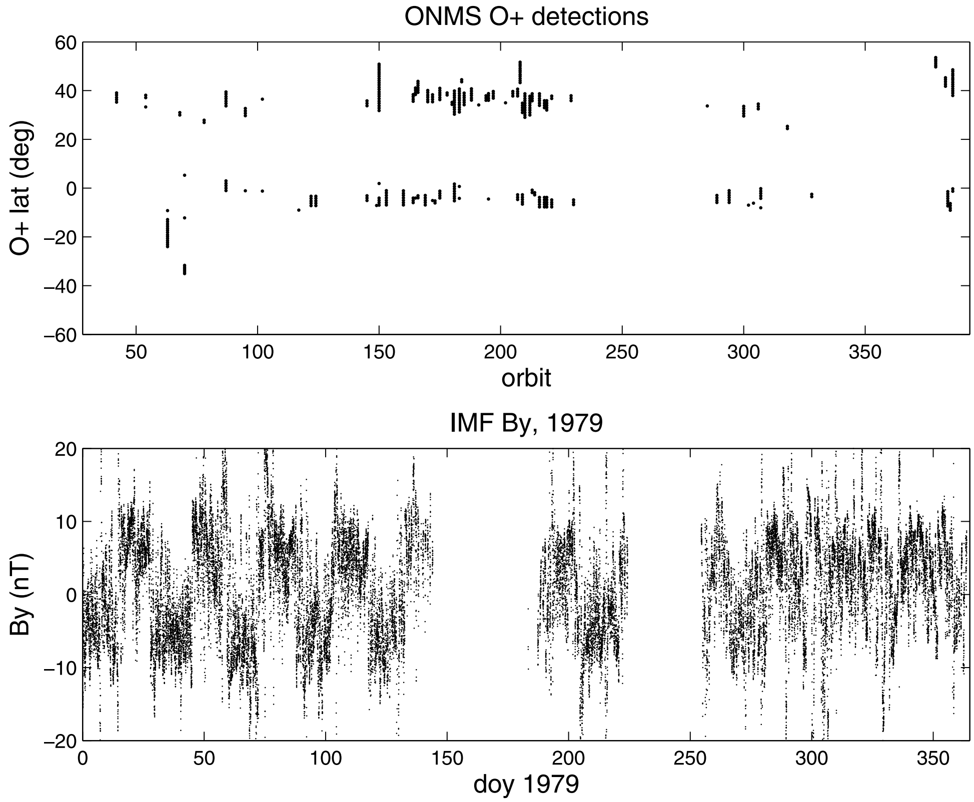

Figure 10. Illustration of the apparent lack of interplanetary field orientation control of the latitude of the high ion flux (>1 × 10^7/cm^{2}s) detections. The gap around day ∼145–185 occurs because the PVO orbit does not sample the upstream solar wind during these orbits, which have periapsis in the dayside and apoapsis in the wake. The bottom panel shows the east-west component of the interplanetary magnetic field measured by the PVO magnetometer, while the top panel shows the latitudes of the PV ONMS. If the interplanetary field orientation controlled the latitude of the pickup ion detections, north-south oscillations would be observed corresponding to the field oscillations.

[24] One important challenge to the above picture is whether the efficacy of the ion pickup mechanism can be supported by any other observations. *Kasprzak et al.* [1991] examined the near-solar-minimum, mostly lower flux ion detections, for evidence of interplanetary magnetic field control of their latitude of detection. A well known signature of the higher energy pickup O^+ detected by the plasma analyzer was the finite ion gyroradius-related north-south asymmetry, controlled by the interplanetary magnetic field east-west orientation [e.g., *Moore et al.*, 1990]. They found no evidence of organization by the interplanetary field. We examined the suprathermal ion high flux (>1 × 10^7/cm^{2}s) cases mentioned above and similarly found no signature of magnetic field orientation control, as seen in Figure 10. For the period of this study there was a well-ordered interplanetary field polarity pattern, especially in the first 75% of the interval. The lack of any sign of a corresponding oscillation in the pickup ion detection latitudes confirms the earlier result. One reason why this may not be fatal to the pickup ion mechanism interpretation is that a 36 eV ion in a ∼50–100 nT field, on the order of what is observed at the detection sites, is only 40–80 km instead of a planetary radius in scale. A better test than asymmetry in detection may thus be evidence that the detected ion distribution functions have a ring beam or shell shape, a well-known characteristic of pickup ions.

[25] The implications of the present investigation are significant for Venus Express, which is currently orbiting Venus. Venus Express is instrumented with both the Aspera-4 ion mass spectrometer, capable of measuring both solar wind conditions and planetary pickup ions (including their pitch angle distributions), and a magnetometer [*Barabash et al.*, 2007; *Zhang et al.*, 2007]. It arrived in Venus orbit at the present minimum of solar activity preceding the rise to the next cycle 24 maximum in ∼2010. The possibilities for quantitatively analyzing the impact of ICMEs and SIRs on Venus pickup ions are unprecedented. Together, the Aspera-4 and magnetometer experiments should be able to definitively establish whether these interplanetary structures enhance pickup ion production and escape, and to what degree. In particular, the results will tell us if a new focus of our thinking about pickup ion-related atmosphere escape should be the ICME phenomenon.

[26] The implications for the history of escape will be similarly affected by the Venus Express findings. The study of the evolution of the Sun and solar wind is severely limited by a lack of specific data, but studies of the irradiation history of both lunar rocks and meteorites indicate that the early Sun was more active than the current

Sun [*Sonett et al.*, 1991]. In addition, studies of Sun-like stars suggest that the early Sun may have been in a steady solar maximum-like state [e.g., *Ayres*, 1997], implying that in the first billion years of Venus' history, the solar maximum ICME occurrence rate may have applied throughout 100s of millions to ~a billion years, rather than only at solar maximum periods. Solar activity may arguably have been even greater as the Sun was still evolving from its initial post accretionary, higher-rotation state. The results also have implications for Mars and for weakly magnetized extrasolar planets similar to Venus and Mars, which would be exposed to ICME events and their atmospheric consequences. The results for extrasolar planets, as for Venus and Mars, depend on the planetary orbits and masses, and the activity level of the central star. Even in the absence of ICMEs, stellar winds are likely to include the SIR enhancements in dynamic pressures and magnetic fields found in the solar wind.

[27] It is also worth noting several related investigations regarding oxygen escape from Venus over time. *Chassefiere* [1996, 1997] updated the notion of oxygen loss via drag by a massive hydrogen outflow. In the latter work, they suggested that a terrestrial ocean's worth of oxygen could escape in as little as ~10 Myr if one considered the high rate of charge exchange between an early dense solar wind and the early hydrogen-dominated upper atmosphere. Most recently, *Kulikov et al.* [2006] considered the integrated picture of hydrodynamic escape and ion pickup losses in light of new stellar observation-based information on the early EUV output of the Sun and the early solar wind. Their approach to estimating early pickup ion losses, like that of *Luhmann et al.* [1992] for the case of Mars, starts with models of the early upper atmospheres for a sequence of higher solar EUV fluxes and includes several effects of the evolving solar wind conditions on the pickup calculations. They make some different assumptions regarding the details of the depth to which ion pickup can occur, and consider a process that is continuous rather than episodic in nature, but the conclusion regarding the potential long-term importance of the process is the same. They also point out the need to obtain better knowledge of early sun-like stars and their stellar winds to solve the Venus atmosphere evolution problem.

[28] The main conclusions here are that the PVO NMS ion observations suggest escape fluxes are significantly enhanced during ICME and SIR passages, and that there is basic understanding of the underlying physical reasons. It is important to examine Venus Express observations in light of the above considerations. So doing may well change our overall paradigm for thinking about solar wind erosion of unmagnetized planet atmospheres and its history, and precipitate further study of the activity and solar wind structure at early Sun-like stars as an essential element of planetary atmosphere evolution studies. In this context it is notable that *Crider et al.* [2005] recently examined the solar wind interaction with Mars, to the extent it could be deduced using MGS observations, during the October 2003 period of major ICME activity also experienced at Earth. They similarly speculated that increased atmosphere erosion at Mars was a likely consequence of the related enhanced solar wind interaction effects. Although Mars Express does not have a magnetometer, it has Aspera-3, the progenitor of Aspera-4 on Venus Express. Aspera-3 ion mass spectrometer measurements of escaping Martian ions should also show responses to the passages of ICMEs as solar activity increases the opportunities for observing their consequences.

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