

Atmospheric erosion of Venus during stormy space weather

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[1] We study atmospheric escape from Venus during solar minimum conditions when 147 corotating interaction regions (CIRs) and interplanetary coronal mass ejections (ICMEs) combined impact on the planet. This is the largest study to date of the effects of stormy space weather on Venus and we show for the first time statistically that the atmosphere of Venus is significantly affected by CIRs and ICMEs. When such events impact on Venus, as observed by the ACE and Venus Express satellites, the escape rate of Venus's ionosphere is measured to increase by a factor of 1.9, on average, compared to quiet solar wind times. However, the increase in escape flux during impacts can occasionally be significantly larger by orders of magnitude. Taking into account the occurrence rate of such events we find that roughly half (51%) of the outflow occurs during stormy space weather. Furthermore, we particularly discuss the importance of the increased solar wind dynamic pressure as well as the polarity change of the interplanetary magnetic field (IMF) in terms of causing the increase escape rate. The IMF polarity change across a CIR/ICME could cause dayside magnetic reconnection processes to occur in the induced magnetosphere of Venus, which would add to the erosion through associated particle acceleration.

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1. Introduction

[2] Venus is an unmagnetized planet with an appreciable atmosphere that is constantly being eroded through the interaction with the solar wind plasma flowing past it at supersonic speeds. This has been observed experimentally in both Pioneer Venus Orbiter (PVO) measurements [e.g., Luhmann *et al.*, 2006] and in Venus Express (VEX) measurements [e.g., Barabash *et al.*, 2007a]. The ionospheric erosion due to the interaction with ambient plasma flow is similar to that at other unmagnetized objects such as Mars [Lundin *et al.*, 1989; Barabash *et al.*, 2007b] and Saturn's largest moon Titan [Modolo *et al.*, 2007; Edberg *et al.*, 2010a]. The loss rates at all bodies have been estimated to be on the order of $10^{24} - 10^{25}$ particles s^{-1} .

[3] Edberg *et al.* [2010b] found that the atmospheric escape rate at Mars is not constant but rather increases by a factor of ~ 2.5 on average, when corotating interaction regions (CIRs)

and interplanetary coronal mass ejections (ICMEs) from the Sun impact the planet. In this study we investigate whether Venus's O^+ dominated ionosphere is affected similarly.

[4] McEnulty *et al.* [2010] studied 17 ICME events and demonstrated that the energy (but not the flux) of pickup ions around Venus increases whenever the planet is impacted by an ICME. Earlier, Luhmann *et al.* [2007] showed that atmospheric escape could increase by a factor of 100 during ICMEs, as measured by the PVO spacecraft. However, case studies of the influence of ICMEs have left ambiguous results, since in 3 out of 4 cases studied by Luhmann *et al.* [2008], the escape rate was not observed to increase. Futaana *et al.* [2008] showed that another single large ICME associated with simultaneous increase in solar energetic particle flux increased the atmospheric escape rate at both Venus and Mars, by a factor of $\sim 5-10$. It should be mentioned that McEnulty *et al.* [2010] and Luhmann *et al.* [2007] looked at the escape of high energy ions only while Futaana *et al.* [2008] included all ions. Dubinin *et al.* [2009] similarly showed that a single large CIR that impacted on Mars increased the scavenging of the ionosphere, with the escape rate again being estimated to increase by a factor of ~ 10 .

[5] There are several escape mechanisms at Venus that are likely to vary with solar wind conditions. Lundin *et al.* [2008], Nilsson *et al.* [2010], and Nilsson *et al.* [2011] showed that the ionospheric escape rate at Mars is dependent on the solar wind dynamic pressure and it is

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likely that Venus is affected similarly. This could be one responsible factor for the previously observed escape rate at Mars during CIRs and ICMEs, when the dynamic pressure increases.

[6] Pickup ions as discussed by *McEnulty et al.* [2010] and *Luhmann et al.* [2006] are driven by the convective electric field $\mathbf{E}_{\text{conv}} = -\mathbf{v}_{\text{sw}} \times \mathbf{B}$, where \mathbf{v}_{sw} is the solar wind bulk velocity and \mathbf{B} is the interplanetary magnetic field (IMF). Both parameters increase during CIR and ICME events and increase the energy of pickup ions [*McEnulty et al.*, 2010]. Particularly, oxygen ions assimilated into the plasma sheet flow downstream of Venus are accelerated by the \mathbf{E}_{conv} and can escape, as shown by *Slavin et al.* [1989] using PVO measurements and by *Barabash et al.* [2007a] using VEX measurements. These ions are accelerated away from the central axis of the tail sheet and are sensitive to both solar wind velocity and the IMF magnitude. In a recent study at Mars, *Hara et al.* [2011] similarly discussed how the enhanced magnetic field strength at low altitudes during ICME events accelerates the outflow and increases the atmospheric escape.

[7] The magnetic tension force $\mathbf{j} \times \mathbf{B}$, where \mathbf{j} is the electric current, pulls ionospheric “clouds” downstream [*Brace et al.*, 1982; *Ong et al.*, 1991]. Also, this force is possibly enhanced during solar wind events. Momentum transfer between the shocked solar wind in the sheath and the ionospheric particles has been discussed in terms of viscous-like forces [*Perez-de-Tejada*, 1982] and is yet another mechanism that might be temporarily enhanced. Thus it appears very unlikely that the impact of CIRs and ICMEs would have no effect on the escape rate of Venus's ionosphere, considering that there are several mechanisms that should be enhanced during such impacts.

[8] *Volwerk et al.* [2009] suggested the presence of substorm-like activity in Venus's magnetotail and presented a case study where magnetic reconnection occurred in the tail region of Venus. However, that study was later corrected as the identified reconnection case was initially misinterpreted [*Volwerk et al.*, 2009], and the existence of substorm-like processes are still in question in the Venusian system. At Mars, evidence of magnetic reconnection have been presented by *Eastwood et al.* [2008] and *Brain et al.* [2010], although those observations were believed to involve the crustal magnetic fields of Mars. *Halekas et al.* [2009] presented 28 events at Mars with field and particle signatures indicating that collisionless magnetic reconnection was occurring. They suggested that for Mars such processes could contribute significantly to the loss of ionospheric plasma. Those events were not preferentially found during IMF rotations, but not in correlation with the location of crustal magnetic fields either. They rather suggested that the draping alone, possibly enhanced by increased solar wind dynamic pressure, could result in the formation of current sheets capable of reconnection.

[9] *Halekas et al.* [2006] and *Halekas and Brain* [2010] presented rigorous studies of more than 10000 current sheets (but not necessarily reconnection events) in the Martian plasma environment from Mars Global Surveyor measurements. They showed that most current sheets were located in the nightside and polar regions, but some (~18%) were also seen on the dayside and suggested to be caused by

traveling solar wind discontinuities. If noncrustal magnetic reconnection has been found to occur at Mars, it is likely to occur at Venus too and would then contribute to the erosion of the ionosphere.

2. Instrumentation

[10] Venus Express (VEX) carries two instruments that we have used in this study; the magnetometer (MAG) and the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-4), which includes an ion mass analyzer (IMA) [*Barabash et al.*, 2007b]. IMA measures ions in the energy range 0.01 eV/q to 36 keV/q with an energy resolution of 7%. It covers the masses of H^+ , He^+ , He^{2+} , O^+ and heavier ions in the range 20–80 amu/q and has a field of view of $90^\circ \times 360^\circ$. For this study particle distribution moments (density and velocity for H^+ and O^+) are calculated every 192 s. The ion distribution measurements on VEX are often obscured by the spacecraft body, which means that the measured ion flux could be significantly underestimated. In this study we will therefore not attempt to estimate the absolute value of the outflow rate from Venus as that would require careful consideration of the biased sampling geometry and spacecraft attitude. We will rather use a large statistical data set and compare the fluxes during quiet solar wind times to those during stormy space weather. Any biased sampling will then be similar for the two cases.

[11] MAG consists of two triaxial fluxgate sensors and measures the vector magnetic field up to a maximum rate of 32 Hz [*Zhang et al.*, 2006], although usually at lower temporal resolutions. In this study we use 1 min average magnetic field measurements.

[12] VEX is in an elliptic 24 h orbit that precesses in local time. Apoapsis and periapsis are at a distance of 12 Venus radii ($1 R_V = 6052$ km) in the southern hemisphere and ~300 km in the northern hemisphere, respectively. The high altitude part of the northern hemisphere and the low altitude part of the southern hemisphere are not sampled, since the orbital coverage does not include these regions. In addition to VEX data, we use 1 h averaged measurements of the IMF, solar wind density and velocity from the Advanced Composition Explorer (ACE) spacecraft to identify large scale solar wind structures such as CIRs and ICMEs upstream of Earth, which will also have impacted on Venus as will be shown below.

3. Observations

3.1. Identification of CIRs and ICMEs

[13] As previously described by *Edberg et al.* [2010b], we automatically search the ACE data for CIR and ICME events and calculate their arrival time at Venus. In the interval 14 May 2006 to 15 Dec 2010, which is the interval when we have VEX/IMA data, we find 157 such events. As identification criteria we use the start of a sudden increase in IMF strength followed by a more or less gradual increase in solar wind proton velocity. The proton density also increases, but since there are many data gaps in the ACE data around high density events, we cannot reliably use this parameter for identification at ACE. Using these criteria we pick up the great majority of the CIRs and ICMEs that can

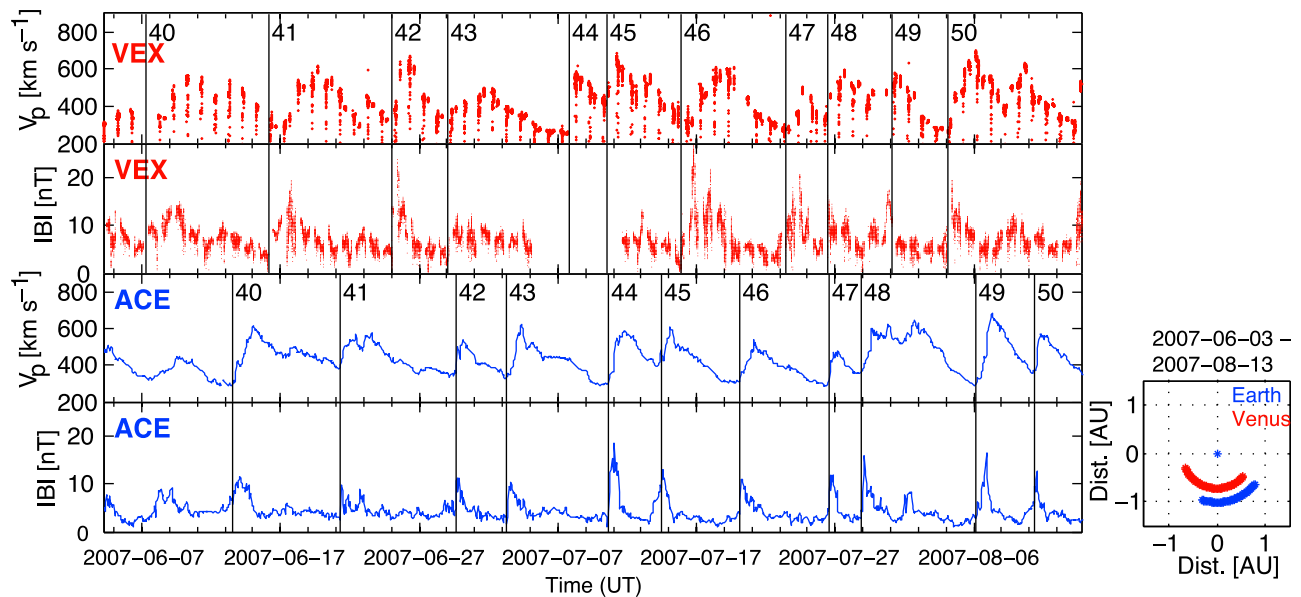


Figure 1. Time series of VEX proton velocity, VEX magnetic field strength, ACE proton velocity, and ACE magnetic field strength. The arrival times of events 40–50 are indicated by vertical black lines in both VEX and ACE data. The diagram on the right shows the orbits of Venus and Earth during the same interval.

also be observed by eye inspection of the data. We then use VEX IMA and MAG solar wind data to pinpoint the exact arrival time at Venus of each event by eye.

[14] Figure 1 shows an example of events 40–50. These events are observed in proton velocity and magnetic field measurements by VEX IMA and MAG (first and second panels) and by ACE (third and fourth panels), during almost three solar revolutions ~ 72 days, from June to August 2007. During this time period ACE and Venus were on similar heliospheric longitudes. ACE constantly measured in the solar wind while VEX measured both in the solar wind and in the induced magnetosphere due to its orbit around Venus. Note that for VEX, the IMA velocity measurements includes data from within the induced magnetosphere, which can be seen as frequent drops in velocity magnitude, while for the MAG measurements, data from this region have been removed. The 11 events observed at ACE, identified by an increase in velocity and magnetic field strength, have clear counterparts in VEX data, as indicated by the vertical lines in all panels of Figure 1. This nicely illustrates that we regularly have solar wind disturbances propagating outward in the solar system impacting on the planets.

[15] For a number of events (~ 20) we do not have access to both IMA and MAG data so that we can only use one of them to determine the arrival time. We estimate that the accuracy of our initial calculated arrival time is better than approximately 12 hours for most events, and using the by eye inspection to pinpoint the impact time we can determine the arrival time to within a couple of hours, provided that the events do not impact during a data gap. Out of the 157 initial events some are not observed in VEX data for a variety of reasons. In some cases events reached Venus during data gaps, or are ICMEs whose radial propagation did not hit Venus. Alternatively there are CIRs that are observed at large longitudinal separations from Venus such that the

prediction becomes too uncertain and finally some CIR events merged with ICMEs. We can also identify several clear events in VEX data that are not seen in ACE data. Some of these are ICMEs that do hit Venus but miss Earth, some are CIRs that are not affecting the solar wind reaching ACE due to the large difference in longitude, and some are events that have arrived at ACE during a data gap. The final number of identified events is therefore 147.

[16] CIRs, which are also known as stream interaction regions (SIRs) that are recurring with a period of one solar rotation, and ICMEs are both disturbances in the solar wind but have different characteristics. CIRs are quasi-steady features in the solar wind and corotate with the Sun. They are built up when slow streaming plasma from the Sun are caught up by faster streaming plasma. A rarefaction region is created in the trailing region and a compression region with increased total pressure in the leading region. ICMEs, the solar wind manifestation of coronal mass ejections on the Sun, are not corotating but rather transients propagating radially outward in interplanetary space. They can be characterized by strong and rotating magnetic fields, low plasma β , low ion temperature, high α /proton density ratio, counter streaming suprathermal electron strahl, declining velocity and unusual ion charge states [Jian *et al.*, 2008, and references therein]. We do not attempt to differentiate the effect of SIRs, or CIRs, which are more numerous, from ICMEs, which could be more extreme. During the period considered in this study, the Sun was at solar minimum and so the ICMEs were slow [Jian *et al.*, 2008].

[17] In order to show the average behavior of our selected events we have performed a superposed epoch analysis of the 147 CIRs/ICMEs, which is shown in Figure 2. Naturally, the start of the epoch time is chosen as the time of impact on Venus. A few days before the arrival the velocity (Figure 2c) decreases somewhat, while after impact it increases gradually

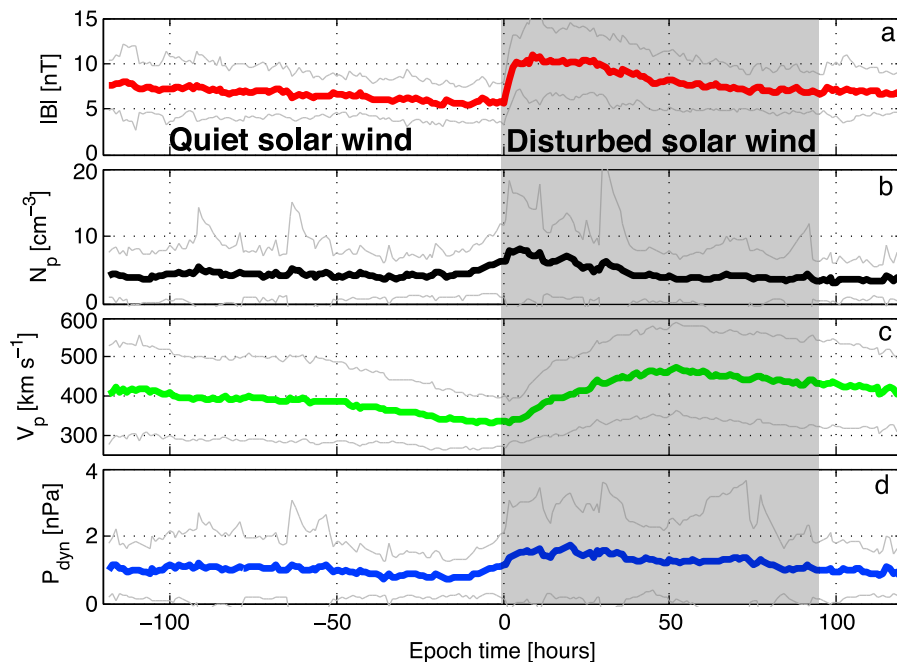


Figure 2. Superposed epoch analysis of VEX measurement in the solar wind during pressure pulses. Shown are (a) magnetic field strength, (b) proton density, (c) proton velocity, and (d) dynamic pressure. The grey lines indicate plus or minus one standard deviation from the mean value. The shaded region shows the 4 day period when the solar wind is considered to be disturbed by CIR and ICME events.

over several days, on average. For ICME events, the velocity increase can be more sudden. At impact time, the magnetic field strength makes a clear jump in magnitude and so does the proton density. The density jump is somewhat weaker, possibly due to that the included CIRs have not developed fully at the orbit of Venus. The dynamic pressure also increases at impact and stays higher than average for several days. Note that the velocity decreases slowly after the velocity peak and remains higher than the average solar wind speed of $\sim 400 \text{ km s}^{-1}$ for longer than approximately 4 days, while the duration of the magnetic field strength and plasma density increase are shorter (~ 2 days). *Jian et al.* [2008] discussed the duration of CIR and ICME events at Venus and stated that SIRs (or CIRs) have a median duration time of 32.5 h but could last as long as 122 h, while the ICME median duration is 23.2 h.

[18] At Mars, *Edberg et al.* [2010b] noted that the time it takes the selected events to completely pass by the planet, meaning that the total pressure during the event has receded to quiet solar wind values, is on average 36 hours. At Venus, which is closer to the sun, CIRs have not developed fully yet and therefore last longer. It is somewhat uncertain to identify when each individual event has passed by Venus, since the parameters used to identify them, especially the velocity, usually decrease gradually. We therefore use the crude approximation that all events last 4 days on average, which covers the time frame when the magnetic field strength and density remains high and also covers the interval when the velocity is higher than average. The disturbed interval is marked by a shaded region in Figure 2. The dynamic pressure also appears to decrease back to quiet solar wind times after approximately 4 days. Choosing a slightly longer duration time also means that we include some of the time

period when the induced magnetosphere recovers after the events have passed. This approximation introduces an error which will be discussed further below.

3.2. Escape Increase During CIRs/ICMEs

[19] As a next step we compare the ASPERA-4 measured antisunward fluxes of O^+ ions in the induced magnetosphere of Venus, when the 147 solar wind events impact on Venus and the solar wind is disturbed, with those fluxes at times when the solar wind is undisturbed. Figure 3 shows maps of these fluxes as well as the ratio between the fluxes in the two cases. We have binned all the flux measurements in $0.15 \times 0.15 R_V$ bins and calculated the mean flux in each bin. The bins that contain less than 4 measurements are discarded. We find that during the times of impact of CIRs/ICMEs the O^+ ion flux increases on average by a factor of ~ 1.9 as compared to quiet solar wind times. This flux increase means that increased atmospheric escape occurs when pressure pulses impact the planet. The fluxes that are being compared are calculated as averages over all bins in the $x - (y^2 + z^2)^{1/2}$ plane for $x > -1 R_V$ in Venus Solar Orbital (VSO) coordinates. We hence only focus on the tail fluxes. In the VSO coordinate system the x axis is directed toward the Sun, the z axis is parallel to the orbital angular momentum vector of Venus, and the y axis completes the right-handed system. The ions in the region $x > -1 R_V$ are more likely not to escape at all and also, the measurements are potentially affected by spacecraft charging and the velocity of the spacecraft in the dense ionosphere region, which could introduce an error. In order to exclude measurements in the magnetosheath, where proton contamination of the higher mass channels in the instrument is more common, we have set a constraint that the simultaneous

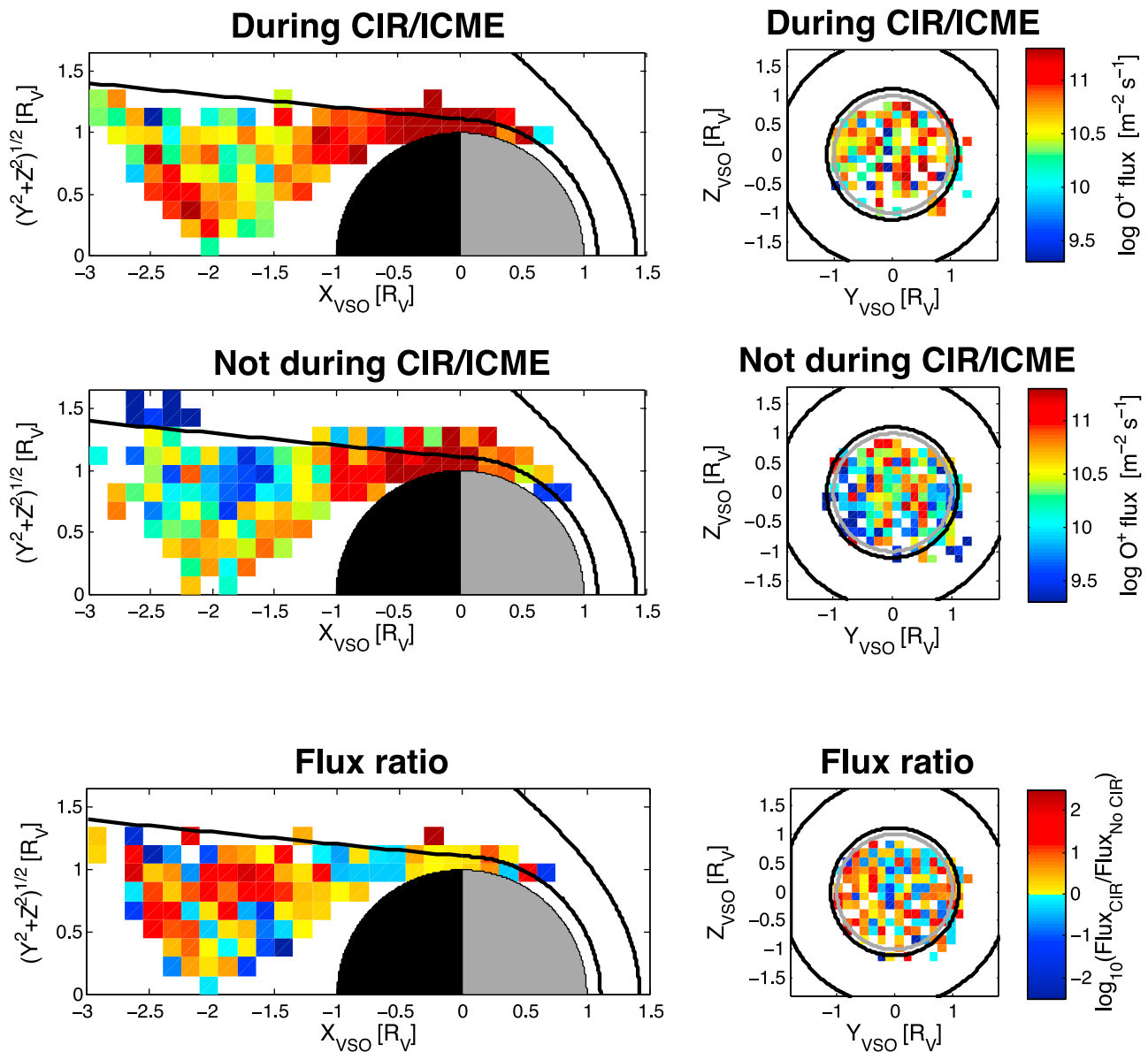


Figure 3. Antisunward fluxes of planetary O^+ ions as measured (top) during the impact of CIRs/ICMEs and (middle) during the time of quiet solar wind as well as (bottom) the flux ratio between disturbed solar wind times and quiet times in each bin. The data is shown (left) in cylindrical VSO coordinates as well as (right) in the VSO $y-z$ plane for $-3 R_V < x < -1 R_V$. Each bin is $0.15 \times 0.15 R_V$ large and contains at least 4 measurement points. The black lines indicate the average locations of the bow shock and the magnetic pileup boundary from *Martinez et al.* [2008] and the grey circles indicate the limb of the planet.

proton fluxes must be lower than $10^{11} \text{ m}^{-2}\text{s}^{-1}$. If including either or both of these constraints then the flux ratio between quiet and stormy solar wind times is about the same ($\sim 1.7-1.8$), indicating that these constraints are not vital for this study. If changing the bin size to 0.1 or 0.2 and setting the minimum number of data points in each bin to 3 and 5, in the respective cases, then the flux difference changes to 1.97 and 1.89, respectively, indicating that the results are not sensitive to the chosen bin size.

[20] Figure 3 (bottom) shows that, locally, the flux ratio can be much larger than 1.9, by orders of magnitude, which is in agreement with earlier case studies at Venus and Mars [*Luhmann et al.*, 2007; *Futaana et al.*, 2008; *Dubin et al.*,

2009; *Edberg et al.*, 2009]. Some bins do show a decrease in flux during disturbed times, but these are in minority, and could be caused by a poor viewing angle of the instrument. Still, this illustrates that the outflow of ionospheric plasma from Venus is not at a constant pace but rather fluctuates with time.

[21] If we assume that each event last 2.5, 3 or 5 days rather than 4 days, then the flux ratio changes from 1.9 to 1.65, 1.72 and 1.75, respectively. This indicates that we mix in undisturbed data with the disturbed data for longer assumed durations and similarly mix in disturbed data with undisturbed data for shorter intervals, making 4 days a good assumption.

[22] Although we do not study total escape rates, it is interesting to estimate how large a portion of the total escape

that occurs during stormy space weather. 147 events times 4 days over a period of 1676 days means that CIRs/ICMEs pass by Venus 35% of the time. If the loss rate is n during quiet times, then the total outflow during CIRs/ICMEs is $1.9n \times 0.35 = 0.67n$ while during non-CIR/ICME times it is $0.65n$. The relative outflow during CIRs/ICMEs is then $0.67/(0.67 + 0.65) = 0.51 \pm 0.19$. The error values are calculated assuming the above stated shorter/longer duration times with the corresponding measured flux increase factors; a duration of 2.5 days and flux factor of 1.65 gives that 32% of the outflow occurs during CIRs/ICMEs; a duration of 5 days and a flux increase factor of 1.75 gives the value 59%. In summary, roughly half of the total outflow of ionospheric plasma from Venus presently occurs during the impact time of CIRs and ICMEs, corresponding to 35% of the time.

3.3. The Effect of Increased Dynamic Pressure

[23] Across a CIR or an ICME, two parameters change that could be responsible for the observed increased escape rate and are particularly investigated. One is the solar wind dynamic pressure and the other is the change in the orientation of the IMF.

[24] An increased dynamic pressure implies that solar wind plasma can penetrate deeper into the ionosphere and more effectively erode plasma away, as is the case for Mars [Lundin *et al.*, 2008; Nilsson *et al.*, 2010, 2011]. It could also increase the wave activity in the induced magnetosphere, which could initiate wave-particle interaction leading to heating and acceleration of particles. In theory we could perform a quantitative study on the effect of the dynamic pressure by plotting the escape rate as a function of dynamic pressure. However, due to the uncertain absolute values of the solar wind dynamic pressure and planetary ion flux as well as the significant decrease in number of data points if subdividing the VEX data further into dynamic pressure intervals, this would not become accurate and we leave this exercise for a future study. Instead we test the effect of the dynamic pressure in another way by dividing the 147 events depending on whether the mean dynamic pressure during each event is higher or lower than the median of the mean pressures of all events. The median pressure is measured to be 1.3 nPa using VEX IMA moments from the solar wind. In Figure 4 (top) we show the O^+ flux during the high pressure events, while in Figure 4 (bottom) we show the flux during low pressure events. The average flux for the high pressure cases is found to be ~36% higher than that for the low pressure cases, indicating that the dynamic pressure is an important factor; when the dynamic pressure increases, Venus loses more plasma.

[25] There might also exist a threshold in escape rate at some level of the dynamic pressure meaning that above or below this threshold, the escape rate significantly changes. We have searched for this threshold by studying the escape rates for events within certain dynamic pressure intervals, but as the number of data points decreases when including less events it again proved too difficult to reliably identify such a threshold.

3.4. The Effect of IMF Rotations

[26] In Figures 5a–5d we show the average behavior of the x component of the draped IMF as measured by MAG from 4 days before to 6 days after the impact of the CIR/ICME

events. In order not to mix cases with different initial polarity of the draped fields we include in this plot only data when the upstream $B_y > 0$, leaving us with 56 events. (The results are quite reproducible for the 91 $B_y < 0$ cases, but with reversed polarity). The data is projected on the $y-z$ plane and binned in $0.2 \times 0.2 R_V$ bins. In the solar wind outside of the bow shock, and before the arrival of CIRs, B_x is mainly negative (Figure 5a). This is a natural consequence of choosing only cases when B_y is positive due to the Parker spiral configuration of the IMF. Inside the induced magnetosphere B_x is still negative in the $+y$ hemisphere but positive in the $-y$ hemisphere, as expected for the draping of the IMF around the planet, and very similar to the results presented by Zhang *et al.* [2010]. As the IMF is hung up around the obstacle and at the same time pulled in the downstream direction, the direction of the IMF changes around the obstacle. The IMF can also have significant z components, which is not depicted in Figure 5. During the impact of CIRs/ICMEs (Figure 5b), the averaged orientation of the draped magnetic field, both in the solar wind and in the induced magnetosphere, is changing and clearly becomes more mixed. Note that some of the mixture is simply due to the fact that we include measurements from several different events. Some time after impact (Figure 5c), the polarity of the field has changed from before such that the induced magnetosphere can start to restabilize with a new polarity (Figure 5d) where B_x is negative in the $-y$ hemisphere and positive in the $+y$ hemisphere. Hence the induced magnetosphere of Venus has reconfigured across a CIR/ICME and changed polarity.

[27] During this reversal process draped antiparallel magnetic fields will meet on the dayside of the induced magnetosphere in the magnetic barrier or in the region of penetrated fields in the dayside ionosphere, and magnetic reconnection could occur. For many individual events the IMF rotation might be somewhat smaller than 180° , and the IMF might not be exactly antiparallel across the discontinuity. However, that is not a critical criteria for reconnection to occur. Figures 5e–5h show an illustration of how this process would proceed during the passing of a CIR with an ideal 180° magnetic field rotation. A “steady” IMF with $B_y > 0$ is first present as indicated in Figure 5e and an induced magnetosphere with a certain polarity is formed around Venus. The IMF drapes around the obstacle and slowly diffuses through the system. A CIR impacts on Venus (Figure 5f) with an associated IMF rotation such that the magnetic field is oppositely directed across the CIR. As the oppositely directed IMF sector (blue lines) meet on the dayside of the previously induced magnetosphere (red lines) magnetic reconnection can occur (black X). The reconnection will lead to acceleration of plasma through magnetic tension forces such that dayside plasma is transported in the downstream direction (Figure 5g). Finally, the induced magnetosphere has completely changed polarity and restabilized itself with the new IMF orientation (Figure 5h).

4. Discussion

[28] Although it has been shown that the erosion of Mars's ionosphere is strongly dependent on the solar wind dynamic pressure it is not immediately clear that the erosion of Venus's ionosphere should be dependent on dynamic pressure. Venus has a much denser atmosphere and ionosphere than Mars and even though an increased pressure can

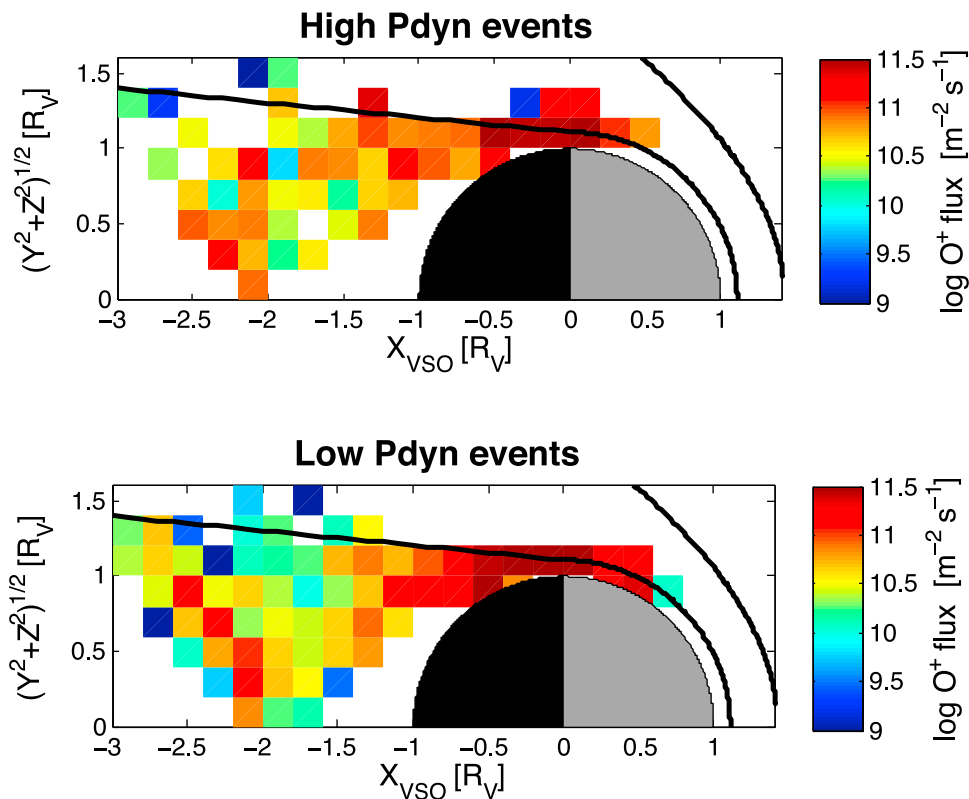


Figure 4. Measurements of antisuward O^+ fluxes from the times when the pressure pulses impact the planet (same data as in Figure 3 (top)) divided according to whether the mean dynamic pressure of each event is (top) larger or (bottom) smaller than the median pressure (1.3 nPa) of all events. A grid size of $0.2 \times 0.2 R_V$ is now used and there are a minimum of two data points in each bin, since the total number of data points in each panel is smaller than in Figure 3.

cause the IMF to penetrate deeper into the ionosphere, the planetary ions are collisionally coupled to the neutral thermosphere. Also the ions are more strongly gravitationally bound to the planet. However, in our data we find that during half of the CIR/ICME events, when the dynamic pressure is higher, the outflow rates are increased by 36% compared to the other half, the lower pressure events (see Figure 4). This tells us that Venus does behave in a similar way as Mars and loses more plasma when the dynamic pressure increases.

[29] Figure 3 reveals that the main flux increase is observed in the tail within $-2.5 < x < -1.0 R_V$ and $\sqrt{(y^2 + z^2)} > 0.5 R_V$, and can locally be increased by several orders of magnitude. Close to the x axis, in the wake of the planet, the flux increase is much smaller. Similarly, close to the planet just above the ionosphere the flux difference is generally less increased. Thus we conclude that the ionospheric plasma is able to detach from the ionosphere in a much more efficient way during CIR/ICME events and can be accelerated downstream, also close to the magnetic pileup boundary, as it leaves the

ionospheric regime. It appears as if the region in the tail where the outflow primarily occurs during undisturbed intervals moves from being mainly close to the x axis to include also regions at larger distances from this axis during disturbed times.

[30] An interesting mechanism that could occur during the impact of CIRs and ICMEs, which may add to the erosion, is magnetic reconnection. A polarity change of the IMF almost always occurs during the passage of a CIR/ICME, as the planet is usually located in a different solar wind sector before compared to after the event has passed. Hence the induced magnetosphere will need to reconfigure and globally change the polarity of the draped magnetic fields. We suggest that this process can increase the efficiency of the escape of ionospheric plasma. The reconfiguration could trigger magnetic reconnection events when oppositely directed draped magnetic fields meet on the dayside of the induced magnetosphere. Piled up IMF on the dayside slowly advect through the system and is caught up by oppositely directed IMF from across the CIR/ICME, where the velocity

Figure 5. Average B_x around Venus projected on the $y-z$ plane as measured (a) 1–4 days before impact of CIRs/ICMEs, (b) 1 day before to 1 day after impact, (c) 1–3 days after impact, and (d) 3–6 days after impact. The VSO coordinate system is used. Only cases where the solar wind $B_y > 0$ before impact are included. The grey circles indicate the limb of the planet while the black circles indicate the position of the bow shock and magnetic pileup boundary in the terminator plane. (e–h) Cartoon of the changing draping polarity across a CIR/ICME and the suggested associated dayside magnetic reconnection causing particle acceleration downstream through $\mathbf{j} \times \mathbf{B}$ forces.

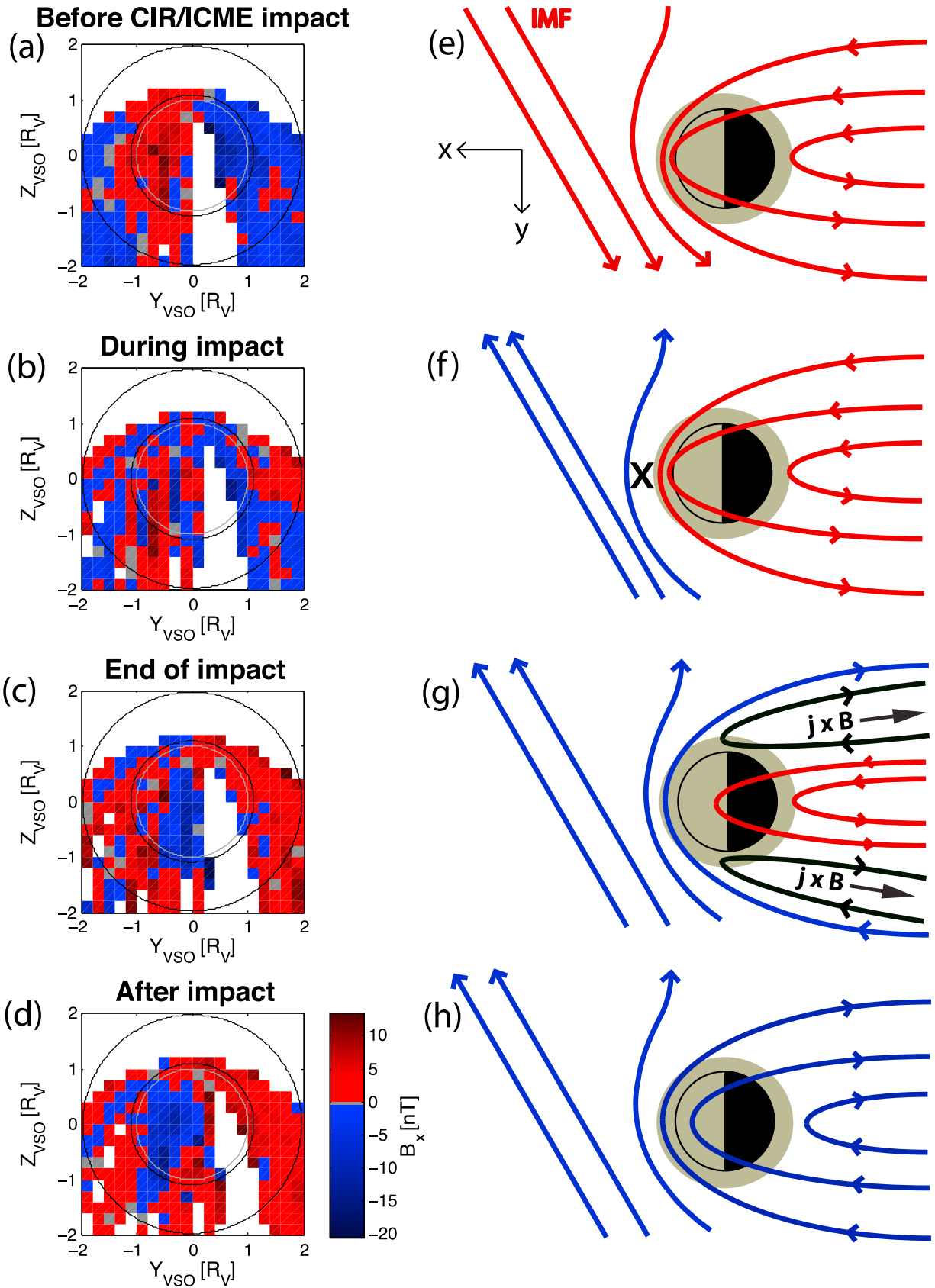


Figure 5

is greater. As they meet, they can consequently reconnect and accelerate plasma from the dayside to the nightside and farther downstream, through magnetic tension forces, as illustrated in Figure 5.

[31] One should also consider that the idea of magnetic reconnection at Venus following IMF rotations during the impact of CIRs and ICMEs are in ways similar to the observations of the comet-tail disconnection processes, as studied by *Niedner and Brandt* [1978]. They showed that a cometary ion tail was lost due to a reconnection event following the crossing of a solar wind sector boundary, across which the IMF changed orientation. It would be interesting to compare our predictions to 3D simulations of the solar wind interaction with Venus during the passing of a solar wind sector boundary. In order to do so one would need time-dependent boundary conditions, which change after some time (once the simulation has stabilized) to a new IMF orientation together with a pulse in the magnetic and dynamic pressure. Such comparison would also provide leverage on the reconnection rate and how much plasma is actually being lost through this mechanism.

[32] At this point, we cannot say that IMF induced dayside magnetic reconnection is a major source of plasma loss during CIR/ICME impacts, but only that it could be an additional process, which would contribute in addition to other escape mechanisms. Quantitative calculations would be needed to more accurately determine the effect of such processes, but that is beyond the scope of this paper. If reconnection-related escape occurs it will probably not occur over several days but rather on the timescales of minutes to hours during the initial impact and hence add little to the total escape, whereas an escape caused purely by increased pickup of ions and increased dynamic pressure scavenging would endure for longer, which is generally what we observe.

[33] Another possible scenario following from IMF rotations is that the draped magnetic field of the induced magnetosphere simply rotates globally, depending on the timescale of the IMF rotation, without any consequential reconnection processes. *Ong et al.* [1991] related detections of ionospheric “clouds” during solar maximum with the changing IMF direction, which should be considered as further evidence of enhanced erosion by IMF rotations. It should be noted that the reaction of the Venus system to IMF rotations could be somewhat different at solar maximum and solar minimum, since the ionosphere is more robust at solar maximum. It is also important to note that CIRs are not so solar cycle dependent while ICMEs are very much so [*Jian et al.*, 2008]. It would therefore be worthwhile to study the separate effects of CIRs and ICMEs over a full solar cycle.

5. Conclusions

[34] Mars and Venus are well known to constantly lose fractions of their ionospheres into space. For Mars, it has been shown that solar wind pressure pulses significantly increase the escape rate, which has motivated a similar study for Venus. We have therefore studied the influence of 147 CIR and ICME events on the induced magnetosphere of Venus in terms of escape rate of the ionosphere. We find a factor 1.9 increase in the observed average flux of escaping

ions from Venus during the impact of these events, for solar minimum conditions. This means that roughly half of the escaping plasma is lost during disturbed space weather. CIRs are less developed at the orbit of Venus than at Mars, where a factor 2.5 increase in the ion escape was found [*Edberg et al.*, 2010b]. The pressure pulses are generally less steep at Venus, hence the impact should be less violent. However, they last longer at Venus and can therefore erode ionospheric plasma over a longer time, resulting in a larger net loss at Venus than at Mars. ICMEs on the other hand are extreme events that are already fully developed at Venus, and should hence cause similar effects as at Mars.

[35] In addition to other loss mechanisms, such as pickup of ions and ions lost from the tailside plasma sheet through acceleration by convective electric field and magnetic tension forces, we have particularly suggested and studied two mechanisms. Firstly, the increased dynamic pressure during solar wind events seems to be one important factor in causing the enhanced outflow. The higher the dynamic pressure, the higher the outflow rate. Secondly, we suggest that magnetic reconnection processes could occur when antiparallel magnetic fields meet during the impact of CIRs and ICMEs, which cause acceleration of plasma leading to increased escape rates.

[36] The ionosphere of Venus changes from solar minimum to solar maximum and becomes more robust at maximum. We have only been able use data from a solar minimum period and we will have to wait until the next maximum to see how more extreme ICMEs influence the ionosphere and induced magnetosphere of Venus. It is possible that the Venus system responds in different ways to different events, and differently to CIRs and ICMEs, and also that the signatures are not the same globally around the planet, which would naturally be overlooked in single spacecraft measurements for individual events.

[37] We plan to continue to observe and analyze the response of ion escape to space weather around Venus as the new solar cycle activity increases.

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