Planetary and Space Science 58 (2010) 1784–1791

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Interplanetary coronal mass ejection influence on high energy pick-up ions at Venus

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ARTICLE INFO

Article history:
Received 7 March 2010
Received in revised form
16 June 2010
Accepted 13 July 2010
Available online 10 August 2010

Keywords:
Venus
Ion escape
Space weather
ICME

ABSTRACT

We have used the ion mass analyzer (IMA) and magnetometer (MAG) on Venus Express (VEX) to study escaping O^+ during interplanetary coronal mass ejections (ICMEs). Data from 389 VEX orbits during 2006 and 2007 revealed 265 samples of high energy pick-up ion features in 197 separate orbits. Magnetometer data during the same time period showed 17 ICMEs. The interplanetary conditions associated with the ICMEs clearly accelerate the pick-up ions to higher energies at lower altitudes compared to undisturbed solar wind. However, there is no clear dependence of the pick-up ion flux on ICMEs which may be attributed to the fact that this study used data from a period of low solar activity, when ICMEs are slow and weak relative to solar maximum. Alternatively, atmospheric escape rates may not be significantly changed during ICME events.

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1. Introduction

There may have been an ocean's worth of water on Venus early in its history, as evidenced by a D/H ratio 100 times that on Earth (Donahue et al., 1982; McElroy et al., 1982). We must question what happened to the ocean, because Venus's atmosphere currently contains little water vapor, only 200–300 ppm (Hoffman et al., 1980; Johnson and Fegley, 2000). Water vapor can be photodissociated by solar UV when it reaches a high enough altitude in the atmosphere. After dissociation, it is possible to lose the hydrogen to space via hydrodynamic escape (Kasting and Pollack, 1983), but getting rid of the heavier oxygen is more difficult. A portion of the oxygen may have been taken up by oxidation of the crust (e.g. Fegley, 1997), but this process cannot account for the amount of oxygen that is missing from the atmosphere (Lewis and Kreimendahl, 1980). Oxygen can be lost if it is ionized and stripped away by the solar wind.

The lack of a magnetic field at Venus allows direct scavenging of ionized atmospheric constituents by the solar wind (e.g., Barabash et al., 2007a; Terada et al., 2002; Luhmann et al., 2006, 2007). Oxygen ion escape has been observed on both Pioneer Venus Orbiter (PVO) and Venus Express (VEX), respectively, described in Luhmann et al. (2006) and Barabash et al. (2007a).

Estimates of the average escape rates of oxygen on Venus range from 10^{24} to 10^{26} s^{-1} (cf. Jarvinen et al., 2009). Atmospheric loss during the first billion years after planetary formation would have primarily been due to large impacts, but if subsequent escape (over the next 3.5 billion years) occurred at rates similar to the present day, the total escape of oxygen would be 10^{41} to 10^{43} total oxygen atoms. An Earth-like ocean contains 10^{45} water molecules or the equivalent number of oxygen atoms. Thus the currently observed average escape rates of O^+ are insufficient to account for an ocean's worth of oxygen loss. In addition, the current escape rate also includes oxygen from dissociated CO_2, so to account for the total oxygen loss from water you would need an even higher current escape rate. However, conditions in the solar system have also changed over time, including the Sun and its outputs which may have affected the total escape of oxygen. In particular, stellar analogs suggest the early Sun had both higher EUV fluxes and was more active (Newkirk, 1980; Zahnle and Walker, 1982; Lammer and Bauer, 2003). This paper describes a further contribution to the study of solar activity effects on the escaping oxygen ions at Venus, as observed on VEX.

Understanding the solar wind induced escape at Venus is also important for understanding Mars. Since Mars is also unmagnetized it interacts with the solar wind similar to Venus on the large scale but is more complicated because of its small size and remnant crustal magnetic fields. Escape of atmosphere on Mars is interesting because there is evidence that there was once surface water in liquid form (e.g. Head et al., 1999; Squyres et al., 2004)

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0032-0633/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.pss.2010.07.019

which would have required a thicker atmosphere to cause a greenhouse effect sufficient to warm the surface above the freezing point of water.

The solar wind induced escape of high energy O^+ from Mars has been investigated by Dubinin et al. (2006) who found a linear dependence of ion energy on altitude which was attributed to acceleration in an electric field. Dubinin et al. (2006) also noticed that ions in one orbit gained energy more rapidly with altitude than for other orbits. Using data from the Mars Global Surveyor spacecraft we confirmed that this particular case where the ions gained energy closer to the planet occurred during a solar wind disturbance. This study builds on the results of Dubinin et al. (2006) with a survey of more MEX ion data and a similar energy altitude analysis at Venus.

2. The Venus solar wind interaction

The interaction of Venus with the solar wind is illustrated in Fig. 1. Since Venus does not have a dynamo magnetic field, but has an ionosphere, it acts like a conducting sphere in this solar wind plasma (e.g. Luhmann, 1986). Around solar maximum, when PVO was at Venus sampling the ionosphere in-situ, the solar wind and interplanetary magnetic fields did not generally penetrate the ionospheric obstacle. The field lines drape around and slip over the ionospheric obstacle, frozen in the largely deflected solar wind. There is a collisionless bow shock that heats and deflects the solar wind, followed by a region where the solar wind is compressed and deflected around the ionospheric obstacle. The interplanetary magnetic fields pile up near the planet. The inner portion of this pile up region is known as the magnetic barrier or the magnetic pile-up region. The magnetic barrier interfaces with the main ionosphere at the ionopause current layer that forms between them. A comet-like tail of draped interplanetary fields is found in the solar wind wake downstream of the planet. This feature is called an induced magnetotail because it does not consist of fields of planetary origin like Earth's magnetotail. Zhang et al. (2007) refers to the regions near Venus and its wake in which magnetic pressure dominates the other pressure contributions, which includes both the magnetic barrier and the magnetotail, as the induced magnetosphere.

Proposed mechanisms for solar wind removal of O^+ ions include "ionospheric ion outflow" possibly connected to polarization electric fields (e.g., Barabash et al., 2007a) or "bulk ionospheric escape" related to macroscopic or fluid-like instabilities at the ionopause (e.g., Terada et al., 2002) but many features of ion escape seen in PVO have been reproduced in models solely based on the pick-up ion process (e.g. Luhmann et al., 2006, 2007). The pick-up process is a result of the action of the solar wind convection electric field, $E = -V_B \times B$, where V_B is the bulk velocity of the solar wind plasma and B is the frozen in interplanetary magnetic field. This electric field will be greatest when the velocity and magnetic field are perpendicular, and will go to zero as V_B and B become parallel. When there is just a small angle between V_B and B there will be a small electric field, and thus a small amount of acceleration, which can produce low energy ions. According to Luhmann et al. (2006), the population of ions that is ultimately picked up may be brought into the convection electric field acceleration region by other forces such as those from pressure gradients, or they may be produced by the ionization of neutrals that were already in the region where the electric field can be effective. But pick-up should work, unimpeded, on ions located everywhere above the exobase.

Pick-up ions will be lost mainly when they are produced on the side of the planet where the orientation of the convection electric field causes them to gyrate away from the planet. Pick-up ions produced on the opposite hemisphere are more likely to impact the exobase (Wallis et al., 1972), because the planet radius (6052 km) is comparable to the O^+ gyroradius. For average solar wind conditions with a velocity of 400 km and an interplanetary magnetic field (IMF) of 7 nT the oxygen ion gyroradius would be 9100 km. Therefore, one would expect to see an asymmetry in the pick-up ion population when it is organized by the convection electric field, as shown by numerical simulations of Fang et al. (2010). It has also been suggested that the pick-up ions

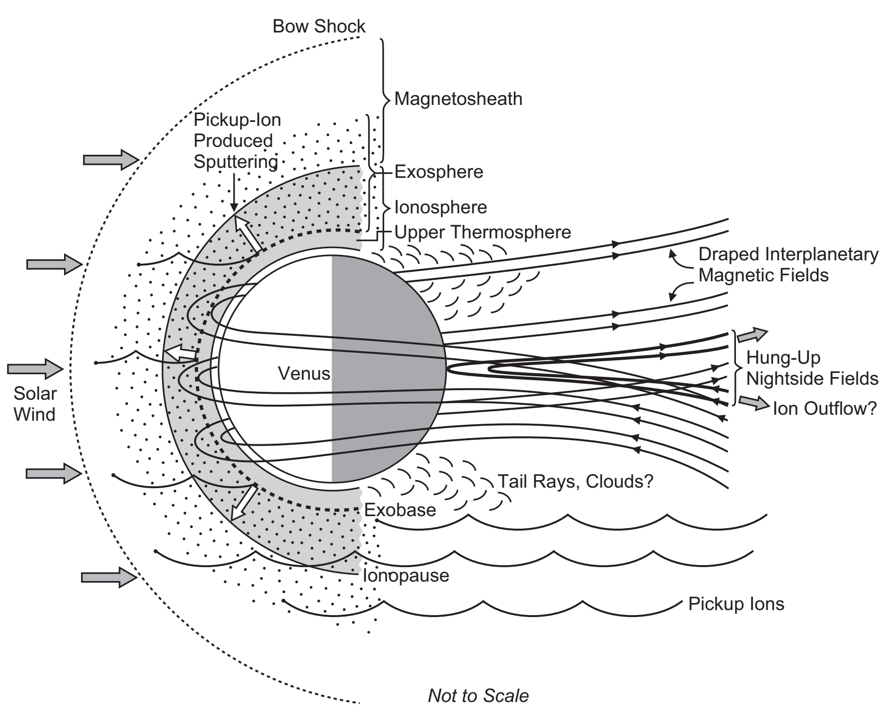

Fig. 1. The solar wind interaction with Venus and related atmospheric escape processes. (Russell et al., 2007).

that impact the exobase may sputter or knock out additional atmospheric particles (Luhmann and Kozyra, 1991), but the contribution to atmospheric losses of this process will not be considered here.

The amount of ions that reimpact the atmosphere depends on the gyroradius of the ions, which in turn depends on the velocity and magnetic field of the solar wind. The magnetic field can be greatly enhanced during solar wind disturbances called interplanetary coronal mass ejections (ICMEs). The velocity of the events can either be slower or faster than the background solar wind.

ICMEs are the solar wind (interplanetary) signatures of large ejections of plasma and twisted magnetic field from the sun called coronal mass ejections (CMEs). The effect of ICMEs on lower energy ions at Venus has been investigated previously. Luhmann et al. (2007) used ion mode data from the PVO neutral mass spectrometer, which is sensitive to >36 eV and found that three ICME passages were associated with an O^+ flux increase by a factor of 100 (out of five identified ICMEs) . Luhmann et al. (2008) looked at four case studies of planetary ions observed by Venus Express during ICMEs passing VEX. In three of the cases the planetary ions were either unobservable or below the limit of detectability. In the fourth case the ions were enhanced about 10 times over the typical undisturbed solar wind cases where pick-up O^+ was observed. These results indicated that ICMEs or disturbed solar wind conditions may significantly increase the rate of pick-up ion escape (also suggested for one VEX case by Futaana et al., 2007). Our present study adds to these results by analyzing more data with a broader survey of pick-up O^+ features during ICMEs at Venus using data from the Venus Express spacecraft.

3. Venus express

Venus Express arrived at Venus in April, 2006 and started operations on July 4, 2006. The science mission is planned to last until the end of 2012. It has a 24 h elliptical polar orbit with an apoapsis of 66,000 km and a periapsis of 250 km. To study the interaction of the solar wind with Venus, the spacecraft has a suite of plasma instruments called ASPERA-4 (Analyzer of Space Plasmas and Energetic Atoms) and a magnetometer.

ASPERA-4 includes an electron spectrometer, two energetic neutral atom (ENA) sensors, and the ion mass analyzer (IMA) which was used in this study. The instrument design is based on ASPERA-3 on MEX (Barabash et al., 2006).

IMA makes measurements between 10 eV and 30 keV for the main ion components H^+, He^{++}, He^+, O^+ and the group of molecular ions 20–80 amu/q. The IMA instantaneous field of view is $4.6^\circ \times 360^\circ$, but electrostatic sweeping performs elevation ($\pm 45^\circ$) coverage. ASPERA pointing generally includes the direction of the sun as part of its sampling sequence.

The IMA sweeps through the energy range over 96 steps, with sampling time for each energy step is 125 ms. The "mass image" of 16 azimuthal sectors $\times$ 32 rings (mass) is read-out once per sampling time. After each complete energy sweep the instrument changes the elevation angle of the field of view, which is broken into 16 sections. The total 3D sweep (32 rings (mass) $\times$ 16 azimuthal sectors $\times$ 96 energy steps $\times$ 16 elevation angles) takes 192 s. More details of the ASPERA-4 instrument are given in (Barabash et al., 2007b).

The ion mass spectrometer data can be plotted in energy time spectrograms, such as in Fig. 2. These plots show the integrated ion counts over a specified mass range as a function of time and energy. This particular spectrogram was made over masses of 12–60 amu. The detections you see on the left are background solar wind, and then you can see a broadening of the energy range of the detections near the planet when you go through the bow shock. Gaps in detections of ions occur in the energy-time spectrograms when the instrument is looking away from the sun, because both the solar wind and planetary ions flow in the anti-solar direction.

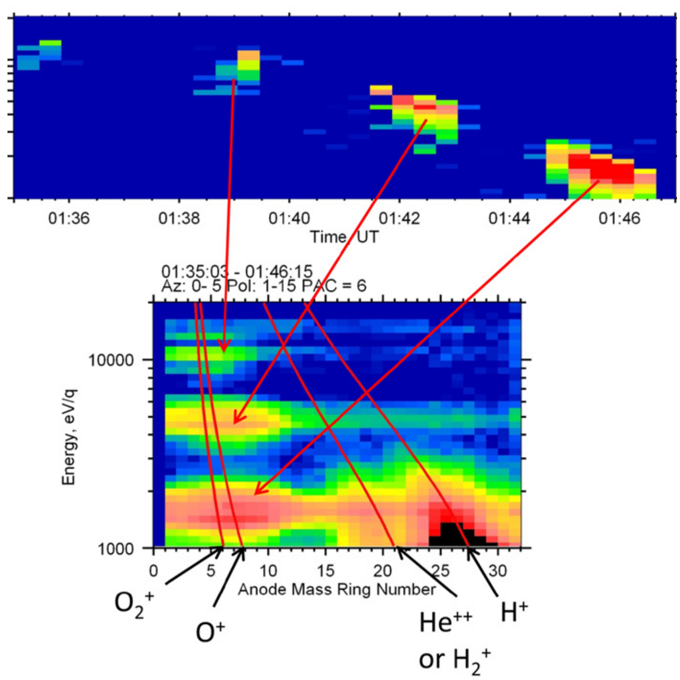

Fig. 3. Mass ring vs energy plot used to ensure that the ion beams were composed of high mass planetary ions. The mass ring vs energy plot shows the total counts during the time interval for ions at certain instrument mass rings and energies. The red lines on the mass ring plot correspond to H^+, He^+, O^+, and O_2^+. The corresponding energy-time spectrogram above shows an ion beam during this time period, with red arrows pointing to where each ion detection falls on the mass ring-energy plot.

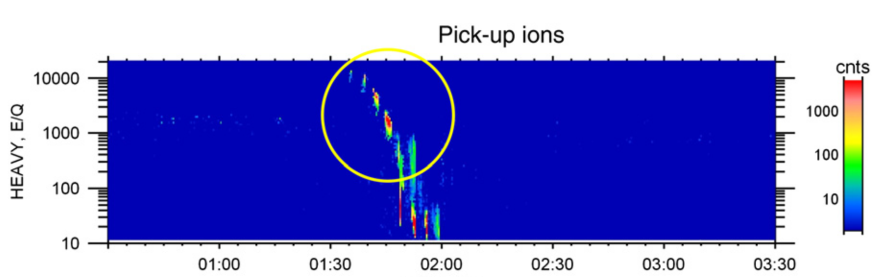

Fig. 2. Example VEX energy-time spectrogram for high mass ions showing pick-up ion "beam" detections circled in yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

An example of pick-up ions seen in an energy-time spectrogram is shown circled Fig. 2. These features have been referred to as "ion beams" (e.g. Carlsson et al., 2006). When the spacecraft intersects ions accelerating away from the planet it detects discrete ion features at sequences of increasing energies along the spacecraft orbit. Similar features have also been found around Mars by Phobos-2 and Mars Express (MEX) (Carlsson et al., 2006; Dubinin et al., 2006). Carlsson et al. (2006) showed the composition of the pick-up ion beams, at Mars, was primarily O^+ and O_2^+.

The magnetometer is a dual triaxial fluxgate magnetometer where one triad is used to correct the measurements for the spacecraft-generated magnetic fields (Zhang et al., 2006). It has a large dynamic range between ± 32.8 and ± 8388.6 nT, and sampling is at up to 128 vectors/s.

4. Venus express data analysis

In the present analysis, IMA data were plotted in energy time spectrograms, as in Fig. 2, for 389 orbits between 2006-05-20 and 2007-06-13. These spectrograms were then visually scanned for high energy ion beam features. Beam features were identified in 197 of the orbits. The criteria for identifying beams were that high mass ions were seen at energies above that of the solar wind background or below but with a quasi-linear increase in energy over time. These beams were then investigated to ensure that they were O^+ by plotting mass vs energy. The example in Fig. 3 shows ion mass and energy of ion detections with the counts integrated over a certain time interval when a beam was seen. The increased counts at higher mass can be O^+, O_2^+ or other high mass ions, but are likely mostly O^+ because it can escape easier because of its lower mass.

These features are also seen in the ion data at Mars, and are likely caused by a similar acceleration mechanism, so studies at Mars can lead to insight into what may be happening at Venus and vice versa. Analyzing similar pick-up ion features at Mars, Dubinin et al. (2006) found a linear dependence of pick-up ion energy on altitude which he attributed to acceleration in an electric field. The calculated magnitude of the required electric field was similar to that of the convection electric field, which is consistent with the assumption that these are pick-up ions. Dubinin et al. (2006) also observed that one of the beams had decreasing energy with altitude, which was also consistent with acceleration in the convection electric field, but in this case the ion started in the hemisphere in which the electric field was directed toward the planet. Dubinin et al. (2006) also noticed that beams in one of the orbits ions gained energy more rapidly with altitude than for other orbit than the rest which he thought was due to an enhanced solar wind period, which we confirmed using MGS data.

For our study, looking at the ion beams at Venus we were able to use magnetometer data to determine when the solar wind was

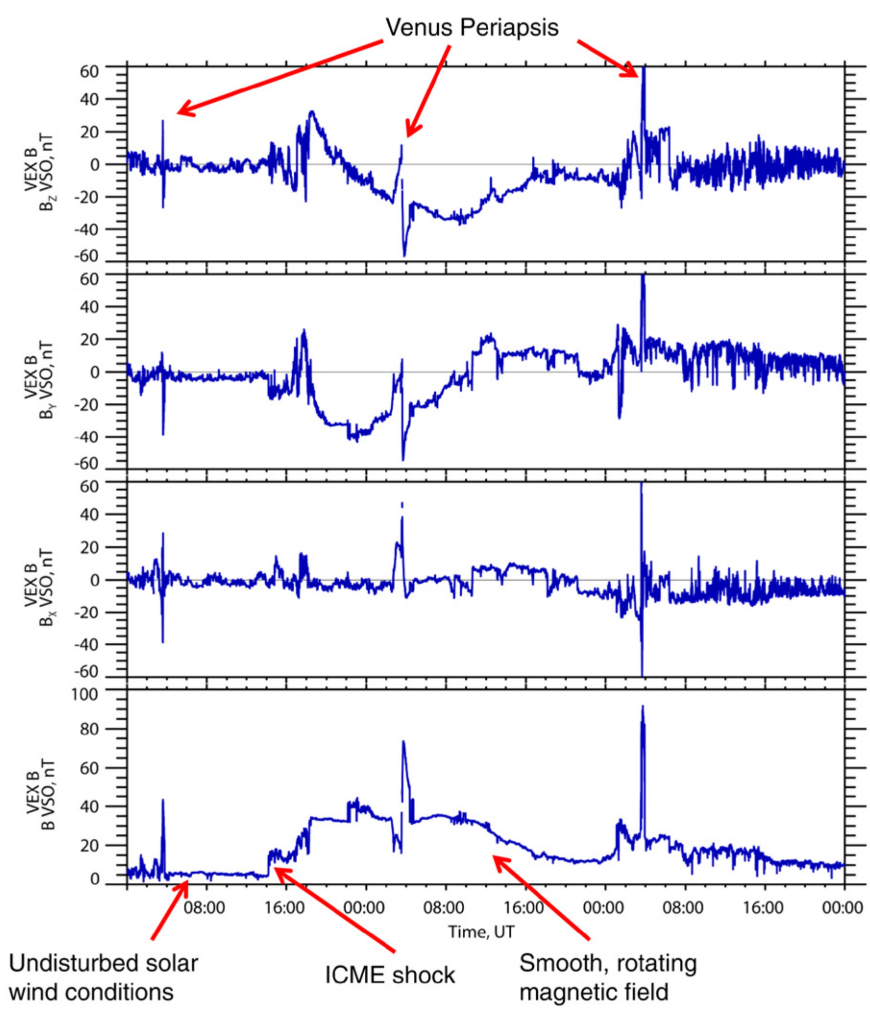

Fig. 4. Example ICME in VEX magnetometer, September 10–12, 2006. The periapsis pass near Venus causes a higher magnetic field because of the pile-up of field lines around the planet. The undisturbed solar wind, the ICME shock and the smoothly rotating field are identified.

disturbed for all of our ion beams. Example magnetometer data from September 10–12, 2006 is shown in Fig. 4, which shows higher magnetic field near Venus periapsis, because of the pile-up of the interplanetary magnetic field lines around the planet and what the undisturbed IMF looks like. This also shows what a ICME looks like. The data were visually scanned for these standard ICME signatures, including a leading shock jump and compressed solar wind followed by larger than average 'ejecta' magnetic field that is smooth and rotating (e.g. Luhmann et al., 2008). Most of the ICMEs were around 1–2 days in duration. In addition, IMA moment data, obtained by integrating over all angles and energies, show high densities and temperatures in the postshock sheath due to compression and shock heating. The velocity usually declines during passage of the ICME. The temperature can be abnormally low after the sheath. ICMEs are identified according to the characteristics from Jian et al. (2006) and Jian et al. (2008). The dates of the identified ICMEs are shown in Table 1.

Table 1
ICMEs identified during this study (June 2006–July 2007).

Start date/time	Stop date/time
2006-06-19/12:00	2006-06-21/5:00
2006-07-04/12:00	2006-07-06/1:30
2006-07-16/22:00	2006-07-19/18:00
2006-08-08/11:00	2006-08-09/22:00
2006-08-14/21:00	2006-08-15/23:00
2006-08-28/22:00	2006-09-01/8:00
2006-09-06/11:00	2006-09-08/4:00
2006-09-10/14:00	2006-09-12/16:00
2006-11-23/8:00	2006-11-25/2:00
2006-12-06/16:00	2006-12-09/04:00
2006-12-19/12:00	2006-12-21/20:00
2006-12-22/20:00	2006-12-24/12:00
2007-01-18/20:00	2006-01-19/16:00
2007-01-26/22:00	2007-01-28/20:00
2007-02-13/12:00	2007-02-15/2:00
2007-05-18/12:00	2007-05-19/20:00
2007-05-24/20:00	2007-05-26/2:00

5. Results

The energies of the detected ion beams are plotted in Fig. 5 as a function of altitude, showing a quasi-linear relationship. As Dubinin et al. (2006) pointed out for the counterpart Mars observations; this behavior likely corresponds to acceleration of the planetary ions due to the solar wind convection electric field. Dubinin et al. (2006) stated that the highest slope sequence of beam detections in their Mars cases was likely due to enhanced ion energization from the passage of a solar wind disturbance and our results confirm this assertion. In Fig. 5, the ICME cases are enclosed in diamonds. The ICME cases show higher slopes, meaning that the ions gain energy faster as the altitude increases. This is not surprising because the magnetic field in ICMEs is higher than under normal solar wind conditions, which results in a larger convection electric field. Assuming that the solar wind velocity is the same between the two cases the ions would reach their maximum pick-up energy ($2V_B$) at a smaller radius, and thus lower altitude.

We examined the count rates for each event integrated over the detection interval in the disturbed and the non-disturbed cases. Since we are interested in the relative differences between disturbed and non-disturbed cases, the absolute magnitude of flux in physical units was not necessary to plot. As shown in Fig. 5, the count rate does not clearly differ between the ICME cases and the others. The main organization of the count rate appears to be by altitude of the detections.

The orbital locations of each of the beam detections are shown in Fig. 6. The *x*-axis points toward the sun, the *y*-axis is along the planets orbit in the opposite direction to planetary motion and the *z*-axis points northward to complete the right handed set. In general, the shape of the orbit plots is due to the orbital sampling. The lack of detections in the $+Z_{VSO}$ hemisphere is due to the orbital sampling. The energy coded plots show that the ions are gaining energy as they move away from Venus. The count rate plots show that the highest count rates are close to the planet. Some of these ions close to the planet may still reimpact the atmosphere so the count rates measurements are not necessarily measuring the escape flux.

Previous analysis by Luhmann et al. (2006) on PVO data and Barabash et al. (2007a) on Venus Express data has shown that

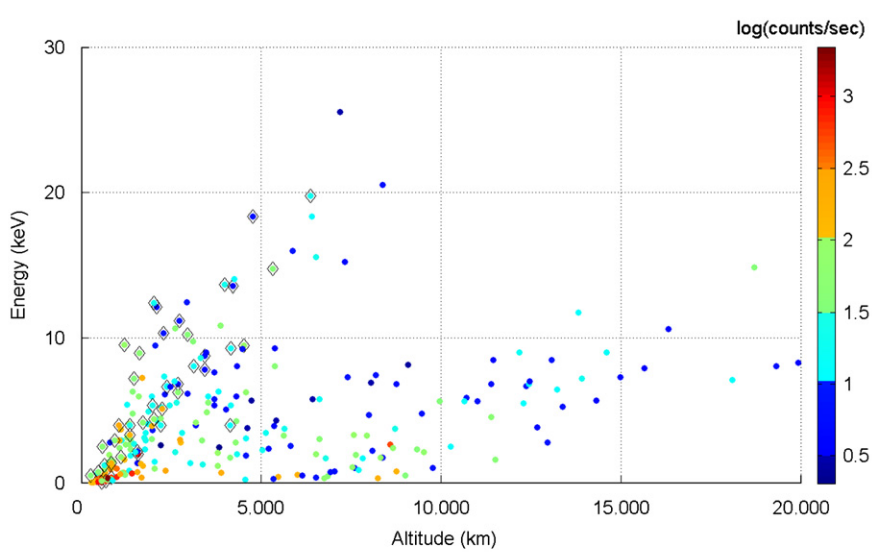

Fig. 5. Pick-up ion detections plotted with color corresponding to log(counts/sec). ICME cases have diamonds around them. The colors are not significantly different for ICME cases, so there is no clear correlation between count rate and ICMEs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

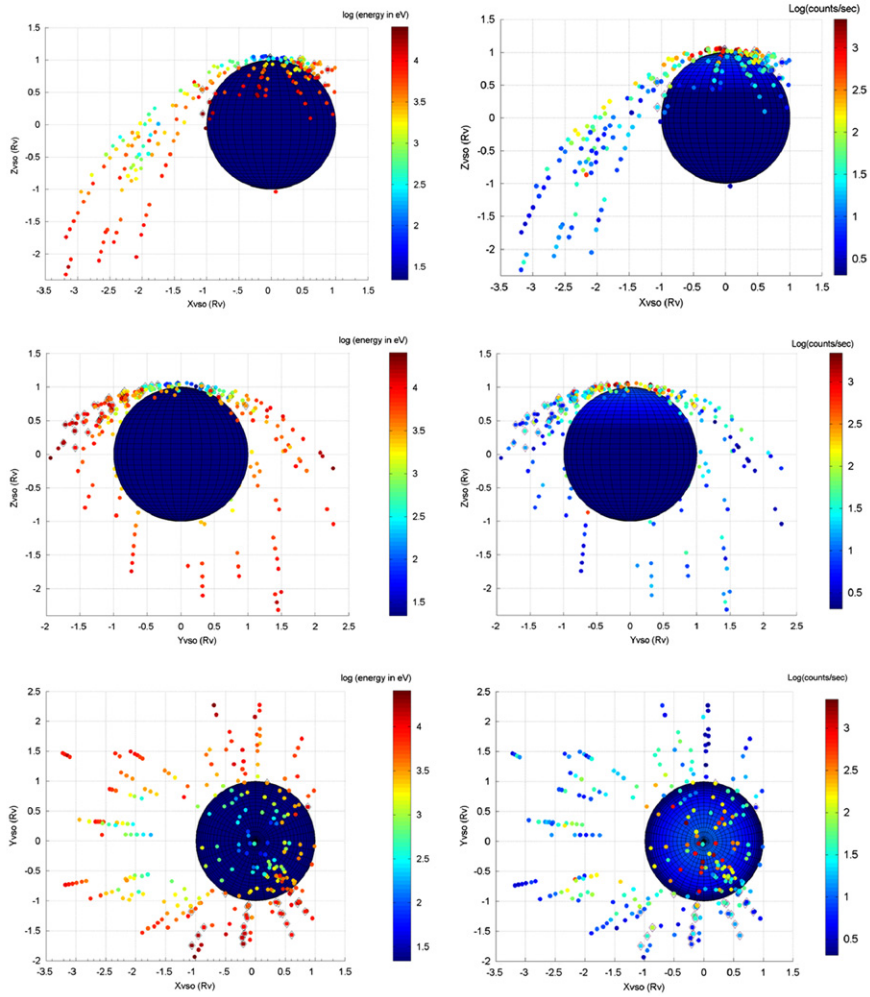

Fig. 6. Left: VEX VSO orbit plots color coded according to log (energy), Right: VEX VSO orbit plots color coded according to log(counts/sec) showing ICME cases in diamonds. Going from top to bottom the orbital views are from the side of the planet (X–Z plane), from the sun (Y–Z plane) and from the top (X–Y plane). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

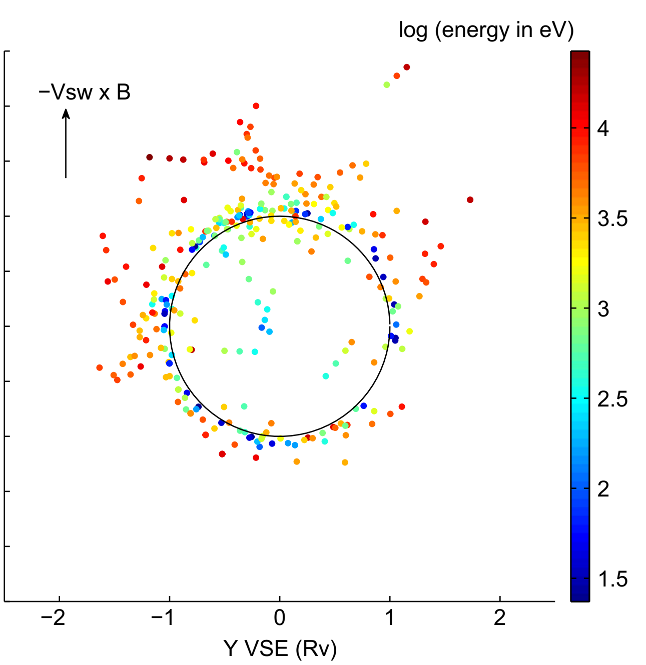

Fig. 7. Beam detections in VSE frame (where $+Z$ is in the direction of the $-V_B \times B$ convection electric field, $+X$ is toward the sun and $+Y$ completes the right hand frame).

high energy (>4 keV) planetary ions are organized by the convection electric field, consistent with a pick-up ion interpretation. This convection electric field control is established by rotating the orbital locations of the ion detections according to where the convection electric field was pointing during the detection. This rotated frame is called the VSE coordinate system in which $+X$ is toward the sun, and the convection electric field ($-V_B \times B$) in the +Z direction. The orientation of the IMF was determined from the magnetic field sampled closest to the beam detection outside of the bow shock. Cases where the IMF changed by $>40°$, were not considered, because the IMF measured outside the bow shock may not be reliable during the times that the beams were detected if it was rapidly changing. Fig. 7 shows the asymmetry expected for pick-up ions, and is consistent with the earlier results (e.g. Fang et al., 2010).

6. Discussion and conclusions

This analysis showed that, for the period analyzed, ICMEs clearly influence the energization of pick-up ion beams at Venus, their effects on the total escape rate is not clear. This may be due to the strength of the ICMEs encountered during this study. The period of the VEX measurements in relation to the solar activity (sunspot) cycle is shown in Fig. 8, while the dates of the identified ICMEs are shown in Table 1. All of the ICMEs for which the solar source has been identified have been slow (~250 km/s), as is typical for events occurring in the declining and minimum phase of the solar cycle (Fig. 8) compared to large events during solar maximum which can range from 800 up to ~2500 km/s (Cane and Richardson, 2003).

A possible cause for the fact that the ICME events did not result in larger pick-up ion fluxes might be that the observed particles for the ICMEs and for the undisturbed solar wind conditions came from different source regions. Also, an important parameter for evaluating the flux dependence, for total ion escape rate, may be the ion gyroradius which is proportional to V_B/B. When the magnetic field is higher the gyroradius is smaller so more ions may reimpact the atmosphere and not escape, but when the velocity is higher the opposite is true. Large values of V_B are therefore necessary for enhancing the ion gyroradius and thus the fraction of total pick-up ion escape. An increased solar wind velocity creates a larger gyroradius so more ions may be able to be picked up without reimpacting the atmosphere. We do not yet have a good sample of major solar events in the VEX observations.

As mentioned in the introduction, Venus also acts as a study test bed for Mars, because Mars also does not have a significant intrinsic magnetic field. Mars is smaller, and thus has a lower escape velocity of ~5 km/s which allows photochemical processes to make a significant contribution to oxygen escape (Nagy et al., 1981), which is not as important at Venus. Also, Mars has remnant crustal magnetic fields that modify its interaction with the solar wind (Fang et al., 2010). Understanding the simpler case at Venus will help us interpret the pieces of the puzzle at Mars. As a taste of the possible future comparisons we show comparable beam detections at Mars. Fig. 9 shows similar beam

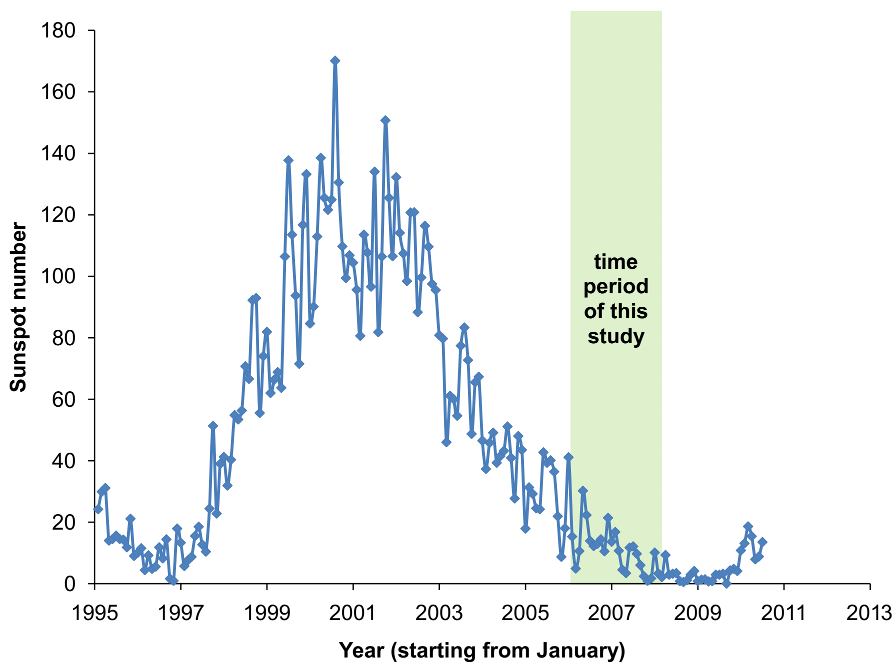

Fig. 8. Sunspot number graph with the time period of this study shaded in green (from NOAA/SEC Boulder, Colorado). The VEX observations available so far occurred during the declining-to-minimum phase of solar cycle 23. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

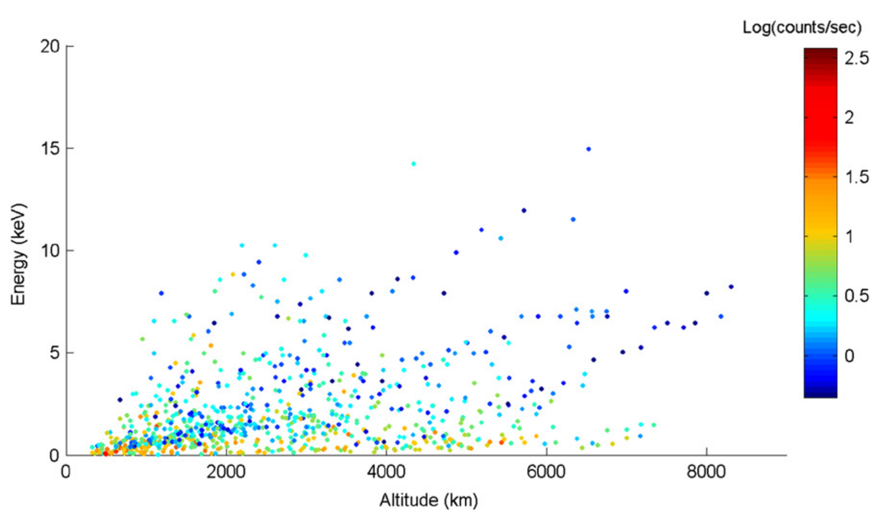

Fig. 9. Mars ion analysis. Each point corresponds to a pick-up oxygen "beam" detection by the Mars Express spacecraft plotted at the energy of the detection and the altitude that the spacecraft sampled it at. This plot shows that at Mars there is linear acceleration away from the planet due to the convection electric field. The color code is log(counts/sec). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

features that were seen with Mars Express data plotted in energy vs altitude and color coded for log(counts/s). Disturbed solar wind conditions are not easily identified because MEX does not have a magnetometer.

The main conclusion of this study is that ICMEs affect pick-up ions, but whether they change atmospheric escape rates as suggested by the earlier PVO based study is still to be determined. This will influence how we think about early Venus and early Mars, because the early active sun possibly produced more ICMES as well as higher EUV (Lammer and Bauer, 2003). Further characterization of the escape rate of oxygen with modeling and data analysis of ICMEs during the upcoming solar maximum will help us answer this question. In addition a new mission to Mars called MAVEN will investigate planetary pick-up ion escape further and will include a solar wind plasma analyzer and a magnetometer (Jakosky et al., 2008)

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