Effects of the solar wind and the solar EUV flux on O$^+$ escape rates from Venus

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ARTICLE INFO

Keywords:
Venus
Ion escape
Solar wind
Solar EUV flux

ABSTRACT

We investigate dependences of O$^+$ escape rates from Venus both on the solar wind and the solar extreme ultraviolet (EUV) flux by using the 8.5-year dataset (May 2006 to December 2014) of the Ion Mass Analyzer and the magnetometer aboard Venus Express. We examine the O$^+$ escape rates for 8 different conditions depending on the solar wind's dynamic pressure, the magnitude of the motional electric field, and the solar F10.7 index which is a good indicator for the solar EUV flux. We find that the O$^+$ escape rates are mainly controlled by the motional electric field and the solar EUV flux in the magnetosheath. We suggest that the ion pickup by the motional electric field is the main ion escape process in the magnetosheath. On the other hand, in the induced magnetosphere, the O$^+$ escape rates are controlled by not only the solar wind and the solar EUV flux but also return flows. We find that the return flows become dominant in the magnetotail in the solar maximum period, which results in reducing the net escape rates in the induced magnetosphere. As a result, net escape rates tend to become larger in the solar minimum period than those in the solar maximum period. Further analysis of the magnetic field shows that the return flows are preferably observed when the magnetic field component along the Venus-Sun line reverses multiple times in the magnetotail. We suggest that ionospheric irregular structures or IMF sector boundary crossings form the fine scale anti-parallel draping pattern of the interplanetary magnetic field (IMF), and this causes ion acceleration towards Venus due to the magnetic tension force or magnetic reconnections. Another possibility is precipitations of O$^+$ pickup ions on the nightside of Venus under the fine structure of IMF. Since the return flows significantly affect the O$^+$ escape rates from Venus, it is important to study not only long-term transition of ion outflow from Venus but also return flows to estimate the net ion loss from Venus over the long history of the solar system.

1. Introduction

Since Venus has no intrinsic magnetic field, the upper atmosphere of Venus is exposed to the solar wind. The direct interaction of the solar wind is known to cause loss of ions from the upper atmosphere of Venus (e.g., Luhmann, 1986; Futaana et al., 2017). The ion escape from Venus is one of the important scientific problems to address in order to understand the evolution of the Venusian atmosphere. To precisely extrapolate the atmospheric evolution of Venus backward, it is important to study the current ion escape rates from Venus.

One of the physical mechanisms to accelerate of the upper atmospheric ions of Venus is the motional electric field embedded in the solar wind. Once particles in the upper atmosphere are ionized by solar extreme ultraviolet (EUV) radiation, charge exchange, and/or electron impact, the ions are accelerated by the motional electric field and “picked up” by the solar wind (e.g., Coates and Johns, 2009). The pickup ions are preferably accelerated and escape the planet in the direction of the motional electric field (Barabash et al., 2007a; McEnulty et al., 2010; Masunaga et al., 2011,2013). The escape channel of pickup ions extends to the magnetosheath and sometimes above the bow shock (Wei et al., 2017).

The magnetotail is also one of the main ion escape channels at Venus. At the current sheet (CS) in this region, a contribution of the Hall term electric field ($j \times B$ force) becomes large and causes an ion acceleration with a hemispheric asymmetry (Dubinin et al., 2013; Rong et al., 2014). Tailward ion flows are often observed in the CS and lead
to the ions escape through the induced magnetosphere. The escape channels in the magnetotail change depending on the draping pattern of the interplanetary magnetic field (IMF) (Masunaga et al., 2011). On the other hand, it is known that Venusward flows (return flows) also exist in the magnetotail (Lundin, 2011; Kollmann et al., 2016). Their driving mechanism is yet unknown, but there are a few candidates such as gravitational force (Lundin, 2011), precipitations of pickup ions (Kollmann et al., 2016), and magnetic reconnections (Zhang et al., 2012).

Active solar wind structures, such as the interplanetary coronal mass ejections (ICMEs) and coronal interaction regions (CIRs), affect the ion escape. During such conditions, high speed, large density, and large magnetic field of the solar wind encounters Venus. Luhmann et al. (2007) showed that suprathermal ions (> 36 eV) escape 3–7 times more during these conditions than in the quiet periods within a year by assuming that an ICME hits Venus every month. Edberg et al. (2011) showed that O⁺ escape rates increased by a factor of 1.9 during the CIR and ICME periods.

Solar EUV fluxes, which vary with 11-year cycles, also play an important role in the ion escape from Venus. In one half of the 11-year cycle, the solar EUV flux becomes relatively high (low), so-called the solar maximum (minimum) period. It is known that the altitude of the ionopause is variable (~ 200–1000 km) in the solar maximum period while it becomes relatively constant and keeps lower altitude (~ 200–300 km) in the solar minimum period (Kliore and Luhmann, 1991). Using PVO observations, Brace et al. (1982a) estimated that escape rates of cold ions through plasma clouds in the solar maximum period were \( 7 \times 10^{26} \) s⁻¹, Brace et al. (1987) estimated the suprathermal O⁺ escape rates (8–16 eV) in the near tail region (> 2000 km) to be \( 5 \times 10^{25} \) s⁻¹ in the solar maximum period. Mihalov and Barnes (1982) showed that escape rates of energetic O⁺ ions (> 4 keV) in the distant tail region (8–12 R_V; R_V is a Venus radius) is \( \approx 10^{26} \) s⁻¹ in the solar maximum period. Recent Venus Express (VEX) observations showed that O⁺ escape rates (0.01–36 keV) in the solar minimum period was (3–6) \( 10^{24} \) s⁻¹ (Fedorov et al., 2011; Masunaga et al., 2013; Nordström et al., 2013; Kollmann et al., 2016; Wei et al., 2017). Furthermore, Kollmann et al. (2016) suggested that O⁺ escape rates through the induced magnetosphere reduces as the solar EUV flux increases due to the increase of the O⁺ return flows.

The ion escape rates shown above are measured by different instruments with different energy ranges, in different locations, and in different solar wind conditions and solar cycles. This makes it challenging to determine what controls the ion escape rates at Venus. Hence, comprehensive and systematic observations to compare the ion escape rates under different conditions are needed. VEX observed the plasma environment of Venus more than 8 years from May 2006 to December 2014. This period covers the solar minimum and maximum periods of the solar cycle 24, and VEX has collected different solar wind conditions over the period. Thus, we are able to investigate the dependences of the O⁺ escape rates on the solar EUV flux as well as the solar wind conditions. In this study, we study O⁺ escape rates in the magnetosheath and the induced magnetosphere and their dependence on the dynamic pressure and the motional electric field of the solar wind and on the solar EUV flux. We also study relations of the O⁺ escape rates with boundary locations and IMF morphology.

2. Instruments and data selection

In this study, we use ~8.5-year measurements (May 2006 to December 2014) of ion velocity distribution functions by Ion Mass Analyzer (IMA) and magnetic fields by the magnetometer (MAG) aboard VEX. VEX arrived at Venus in April 2006 and ended its scientific operation in December 2014. VEX orbited around Venus per ~24 h with an elliptical polar orbit. The typical orbit’s apoapsis and periapsis altitudes were ~66,000 km and ~250 km, respectively. IMA measures the ion velocity distribution function with an energy range of 0.01–36 keV/q with the energy resolution of 7%. It takes 12 sec to complete a scan over the 96 energy steps. The field of view (FOV) of IMA is 360° (azimuth) × 90° (elevation) with a resolution of 22.5° (azimuth) × 5.6° (elevation), while a part of the FOV is obscured by the spacecraft body. Since IMA has 16 elevation steps, it takes 192 sec in total to obtain a full 3D velocity distribution function. From the 3D velocity distribution function, ion moments for protons and O⁺ ions were calculated by Fedorov et al. (2011). For each ion moment data there is a quality index, ranging from 0 to 1, which gives a degree of the non-observed part of the ion velocity distribution in the IMA’s FOV. We, however, used all the data regardless of the index in this study. We also tried to limit our dataset only for those with the quality index over 0.5, but the results did not change significantly. MAG measures magnetic field vectors with a sampling frequency up to 128 Hz. We use 1 Hz sampled data in this study. The more detailed designs of the instruments are described in Barabash et al. (2007b) for IMA and Zhang et al. (2006) for MAG. Using these measurements, we calculate the solar wind dynamic pressure (\( P_{SW} = N_{SW} m_p V_{SW}^2 \); \( N_{SW} \) and \( V_{SW} \) are a proton density, a proton mass and a proton speed, respectively) and the motional electric field (\( E_{SW} = -V_{SW} \times B_{SW} \); \( V_{SW} \) and \( B_{SW} \) are the solar wind velocity and the magnetic field, respectively) in the solar wind region, as well as O⁺ flux (\( F_O = N_O V_O, N_O \) and \( V_O \) indicate a density and a velocity vector of O⁺ ions, respectively) in the Venus tail region. These solar wind parameters are averaged for 15 minutes before the inbound and after the outbound bow shock crossing for each orbit. By averaging these inbound and outbound values, we get an average solar wind parameter for a single orbit. Note that the ion velocities are corrected by the spacecraft velocity and that the spacecraft potential effect is assumed to be negligible. These measurements are organized in the Venus-Solar-Orbital (VSO) coordinate system where the X axis directs sunward, the Y axis directs to the opposite direction of the planet motion, and the Z axis completes the right-hand system. We convert O⁺ flux vectors into the Venus-Solar-Electric (VSE) coordinate system, where the X axis directs sunward, the motional electric field directs to the Z axis (by assuming that \( V_{SW} \) points anti-sunward), and the Y axis completes the right-hand system. For this conversion, we only selected the data where the change of the clock angle of the magnetic field between the inbound and outbound of the orbit is smaller than 90°. After this selection we obtained 1658 orbits of dataset out of the entire mission (more than 3000 orbits).

The solar wind conditions are classified into 4 cases depending on the solar wind dynamic pressure and the amplitude of the motional electric field: (1) \( P_{SW} \leq 1.3 \) nPa and \( |E_{SW}| \leq 2.0 \) mV/m, (2) \( P_{SW} > 1.3 \) nPa and \( |E_{SW}| \leq 2.0 \) mV/m, (3) \( P_{SW} \leq 1.3 \) nPa and \( |E_{SW}| > 2.0 \) mV/m, and (4) \( P_{SW} > 1.3 \) nPa and \( |E_{SW}| > 2.0 \) mV/m. Here, the dynamic pressure of 1.3 nPa and the motional electric field of 2.0 mV/m are the average values throughout our dataset. Regarding the solar EUV flux, we classify the dataset into 2 cases by using the F10.7 index which is a good indicator of the solar EUV flux. Fig. 1 shows the 27-day averaged solar F10.7 index from 1970 to 2017. From the change in the intensity, two periods of the solar cycle were defined: (1) the solar minimum period in which the F10.7 index is relatively low and (2) the solar maximum period in which the F10.7 index is relatively high. We defined the border as 31 Dec 2010 because the F10.7 index starts increasing abruptly after this date. Combining the solar cycle’s classification with the matrix defined by the dynamic pressure and the electric field amplitude, we finally obtain 8 conditions for the solar EUV flux as well as the solar wind. Table 1 shows a summary of the solar EUV and the solar wind conditions in each case.

3. Observations

3.1. Spatial distribution of O⁺ fluxes and O⁺ escape rates for different solar wind conditions and solar cycles

We statistically investigate the spatial distributions of O⁺ escape rates with 8 different conditions.
Fig. 1. 27-day averaged F10.7 flux from the beginning of 1970 to the end of 2017. The solar minimum and maximum periods where VEX orbits around Venus are shown by the blue and red hatches, respectively.

**Table 1**

| Case | Solar EUV period | $F_{\text{10.7}}$ (nPa) | $|E_{\text{EW}}|$ (mV/m) | Orbits |
|------|------------------|-----------------------------|----------------------------|--------|
| 1    | min              | ≤1.3                        | ≤2.0                       | 410    |
| 2    | min              | >1.3                        | ≤2.0                       | 233    |
| 3    | min              | ≤1.3                        | >2.0                       | 138    |
| 4    | min              | >1.3                        | >2.0                       | 211    |
| 5    | max              | ≤1.3                        | ≤2.0                       | 262    |
| 6    | max              | >1.3                        | ≤2.0                       | 79     |
| 7    | max              | ≤1.3                        | >2.0                       | 209    |
| 8    | max              | >1.3                        | >2.0                       | 116    |

Fig. 2 shows the spatial distributions of $O^+$ fluxes in the solar minimum period for the four different solar wind conditions described in the previous section. Fig. 2(a–c) show the number of measurements for the case 1. The same format is used for case 2, 3, and 4, which are shown in Fig. 2(e–h), Fig. 2(i–l), and Fig. 2(m–p), respectively. In these 4 cases, we commonly see that there is a spatial asymmetry in the $O^+$ fluxes in the direction of the motional electric field (the $Z_{\text{VSE}}$ direction). Anti-sunward $O^+$ fluxes tend to be increased in the +E hemisphere where the motional electric field points outward (positive $Z_{\text{VSE}}$) than those in the –E hemisphere where the motional electric field points inward (negative $Z_{\text{VSE}}$) (see, Fig. 2(a–b), (e–f), (i–j), and (m–n)). This feature is consistent with previous studies (Barabash et al., 2007a; McEnulty et al., 2010; Masunaga et al., 2011; 2013). For all the 4 cases, $O^+$ fluxes are strong in the induced magnetosphere compared with those in the magnetosheath, and most of the fluxes are tail-ward, although return fluxes exist to a small degree in the induced magnetosphere.

Fig. 3 shows spatial distributions of $O^+$ fluxes in the solar maximum period for the different solar wind conditions, with the same format as Fig. 2. Similar to the solar minimum period, there is an asymmetry of $O^+$ fluxes in the direction of the motional electric field in the solar maximum period for all the 4 solar wind conditions (see, Fig. 3(a–b), (e–f), (i–j), and (m–n)). However, the spatial distributions look different from those in the solar minimum period. Here, we can see that more Venusward $O^+$ fluxes appear in the induced magnetosphere compared to the solar minimum period (see, Fig. 3(c, g, k, and o)). The same tendency is reported in Kollmann et al. (2016). Nevertheless, there are no consistent patterns in the return fluxes between the four solar wind conditions.

We also investigate $O^+$ fluxes for the different regions under the 8 cases. Fig. 4(a) and (b) show average $O^+$ fluxes observed in the induced magnetosphere and the magnetosheath, respectively. The average $O^+$ fluxes are calculated in the VCY coordinate system by assuming rotational symmetry in each case. We calculated the average fluxes at 4 distances from Venus ($-1.5 \leq X_{\text{VSO}} \leq -1.0$, $-2.0 \leq X_{\text{VSO}} \leq -1.5$, $-2.5 \leq X_{\text{VSO}} \leq -2.0$, and $-3.0 \leq X_{\text{VSO}} \leq -2.5$, respectively). We also calculate a standard error of the average fluxes at each distance and add it as an error bar. In the induced magnetosphere (Fig. 4(a)), the $O^+$ fluxes are almost stable over the four different distances in the solar minimum period (cases 1–4). In the solar maximum period, however, the $O^+$ fluxes in the induced magnetosphere look different from those in the solar minimum period. The average $O^+$ fluxes are high near Venus but decrease rapidly to the similar level or lower of those observed in the solar minimum case in the distant tail. In some cases in the distant tail, average $O^+$ fluxes are directed Venusward (case 5, 6 and 8). In the magnetosheath, the average $O^+$ fluxes are one order of magnitude smaller than those in the induced magnetosphere and are...
relatively stable and direct tailward for all cases.

Then we calculate net $O^+$ escape rates from Venus. In each case, we can calculate $O^+$ escape rates at the four distances from Venus in each region by using the average $O^+$ fluxes in Fig. 4(a) and (b). Areas that the fluxes pass through in the induced magnetosphere and the magnetosheath are $\pi Y_{IM}^2$ and $\pi (Y_{BS}^2 - Y_{IM}^2)$ where $Y_{IM}$ and $Y_{BS}$ are the distance to the induced magnetosphere boundary and the bow shock from the X axis (the Venus-Sun line) in the nightside, respectively. Averaging the four escape rates in each region, we obtain the average net $O^+$ escape rates for the induced magnetosphere and the magnetosheath.

The average net escape rates from Venus are shown in Fig. 4(c). In the solar minimum period (case 1–3), the $O^+$ escape rate in the magnetosheath are $(1.5 \pm 0.1) \times 10^{23} \text{ s}^{-1}$, $(2.5 \pm 0.2) \times 10^{23} \text{ s}^{-1}$, $(3.2 \pm 0.4) \times 10^{23} \text{ s}^{-1}$, and $(2.6 \pm 0.3) \times 10^{23} \text{ s}^{-1}$, respectively. In the solar maximum period, the escape rates are $(3.9 \pm 0.7) \times 10^{23} \text{ s}^{-1}$, $(5.0 \pm 0.2) \times 10^{23} \text{ s}^{-1}$, $(6.6 \pm 0.7) \times 10^{23} \text{ s}^{-1}$, and $(4.8 \pm 1.0) \times 10^{23} \text{ s}^{-1}$, respectively. In each solar EUV period, escape rates tend to become large when the motional electric field is large.

In the induced magnetosphere, the escape rates in the solar minimum are $(2.2 \pm 0.1) \times 10^{24} \text{ s}^{-1}$, $(3.5 \pm 0.2) \times 10^{24} \text{ s}^{-1}$, $(4.7 \pm 0.2) \times 10^{24} \text{ s}^{-1}$, and $(4.2 \pm 0.2) \times 10^{24} \text{ s}^{-1}$ for case 1–4, respectively. In the solar maximum period, the escape rates are $(3.1 \pm 0.3) \times 10^{24} \text{ s}^{-1}$, $(1.1 \pm 0.3) \times 10^{24} \text{ s}^{-1}$, $(1.5 \pm 0.1) \times 10^{24} \text{ s}^{-1}$, and $(2.7 \pm 0.3) \times 10^{24} \text{ s}^{-1}$ for case 5–8, respectively. Being contrary to the magnetosheath, the escape rates within the induced magnetosphere tend to decrease when transited from the solar minimum to the solar maximum.

In total, including both magnetosheath and induced magnetosphere, the total escape rates are $(2.4 \pm 0.1) \times 10^{24} \text{ s}^{-1}$, $(3.7 \pm 0.2) \times 10^{24} \text{ s}^{-1}$, $(5.0 \pm 0.2) \times 10^{24} \text{ s}^{-1}$, and $(4.5 \pm 0.2) \times 10^{24} \text{ s}^{-1}$, in the solar minimum period (case 1–4), and they are $(3.5 \pm 0.4) \times 10^{24} \text{ s}^{-1}$, $(1.3 \pm 0.4) \times 10^{24} \text{ s}^{-1}$, $(2.1 \pm 0.2) \times 10^{24} \text{ s}^{-1}$, and $(3.2 \pm 0.4) \times 10^{24} \text{ s}^{-1}$ in the solar maximum period (case 5–8). Since the escape rates from the induced magnetosphere account for 69–94% of the total escape rates, $O^+$ ions mainly escape Venus from the induced magnetosphere over the entire mission of VEX. The largest escape rates are observed in case 3 which is in the solar minimum period. This tendency is consistent with Kollmann et al. (2016).

3.2. Responses of the ion composition boundary for different solar wind and solar EUV conditions

We also investigate the difference of the Venutian magnetosphere
boundary between the 8 cases. Fig. 5(a–d) shows altitudes of ICB, which is usually seen as the proxy of the induced magnetosphere boundary, observed by VEX within the solar zenith angle of 60°–90° in each solar wind condition and solar EUV period. We determined the boundary from ion spectra in each orbit (a sudden decrease of ion counts for >300 eV sheath protons). In Fig. 5(a–d), we can see that most of the observed ICB altitudes in the solar maximum period distribute in the higher altitude and become highly variable than the solar minimum period. This is consistent with the characteristics of the ionopause (Kliore and Luhmann, 1991). Fig. 5(e) shows average ICB altitudes calculated in each case. We can see that the average ICB altitudes in the solar maximum distribute at higher altitudes than the solar minimum. We can also see that the average ICB altitudes decrease when the dynamic pressure is large (see, the case 2, 4, 6, and 8).

3.3. Morphology of the magnetic field in the induced magnetosphere and its relation to the return flows

As shown above, O⁺ return flows appear significantly in the net fluxes of the induced magnetosphere in the solar maximum period. Here we investigate the morphology of the magnetic field in this region in terms of changes of the X component of the magnetic field (Bₓ reversal). The Bₓ reversal indicates a CS crossing and thus representing the IMF draping pattern around Venus (Masunaga et al., 2011). The number of Bₓ reversals are defined as the number of the change of the sign in the neighbouring data (1-s resolution). Based on the number of Bₓ reversals in the tail region (−3 ≤ Xᵥ≤ −1 and (Yᵥ² + Zᵥ²)⁰·⁵ ≤ 1), we used three categories of Bₓ reversal types: zero, single, and multiple. The zero reversal means no CS crossings. This means that VEX did not fly across the center of the CS but only one lobe. The single reversal corresponds to a single CS crossing, and thus the IMF drapes around Venus in a classical form (e.g., Fig. 6(a) in Masunaga et al., 2011). The multiple reversals correspond to either multiple CS crossings or wavy magnetic fields, and thus Venus magnetotail exhibited fine structures (e.g., Fig. 6(b) in Masunaga et al., 2011). Fig. 6(a) shows observation frequencies of the three Bₓ reversal types for the different solar wind conditions and the solar EUV period. We can see that observation frequencies of the multiple Bₓ reversals...
become on average ∼40% more dominant in the solar maximum period (case 5–8) compared to the solar minimum period (case 1–4). Their solar wind dependences are not clearly observed.

We also investigate the relationship between the O\(^{+}\) return flows and the B\(_x\) reversal types in the tail region. Fig. 6(b) shows observation frequencies of the return flows for each B\(_x\) reversal type per orbit in the tail region. Note that this does not mean that the B\(_x\) reversal and the return flow are always observed in the same time but both of them are observed in the same orbit. We can see that the return flows are preferably observed during the multiple B\(_x\) reversals in all solar wind and solar EUV conditions. In addition, in the solar maximum period, return flows are on average ∼20% more often observed under multiple B\(_x\) reversal type compared to the solar minimum period.

4. Discussion

We have statistically investigated spatial distributions of anti-sunward/sunward O\(^{+}\) fluxes in the Venus magnetotail and net O\(^{+}\) escape rates in the induced magnetosphere and the magnetosheath for 8 conditions depending on four solar wind conditions and two solar EUV periods. Our analysis showed that net escape rates from Venus are (2.4–5.0) \(10^{24}\) s\(^{-1}\) in the solar minimum period and (1.3–3.5) \(10^{24}\) s\(^{-1}\) in the solar maximum period. O\(^{+}\) ions mainly escape from the induced magnetosphere over the 8.5 years. The fraction of the escape rates of the induced magnetosphere range 69 – 94% of the total escape rates.

We also showed that O\(^{+}\) escape rates from Venus are highly controlled by both the solar wind and the solar EUV flux. In the magnetosheath, the escape rates tend to be larger in the solar maximum than those in the solar minimum under the same solar wind condition. Large escape rates in the magnetosheath are observed when the motional electric field is large (case 3, 4, 7, and 8). These tendencies suggest that the ion pickup by the motional electric field is the main escape process in the magnetosheath. Escape fluxes of the ion pickup are positively influenced by the magnitude of the motional electric field and photoionization rates (namely, the solar EUV flux).

In the induced magnetosphere, the O\(^{+}\) escape rates are controlled by not only the solar wind and the solar EUV flux but also the return flows. In the solar minimum return flows are not strong, and thus the net escape rates are controlled by solar wind. Since the escape rates increase from the weak solar wind condition (case 1) to the intense ones, both dynamic pressure and motional electric field positively affect the escape rates. In the solar maximum, return flows are frequently observed in the induced magnetosphere in any solar wind conditions. As a result, the net escape rates of the induced magnetosphere in the solar maximum tend to become smaller than those of the solar minimum.

The decreasing tendency of the net escape rates from the solar minimum to the solar maximum can be caused because either returning fluxes in the magnetotail become larger, or outgoing fluxes become smaller in the solar maximum compared to those in the solar minimum. Our study cannot distinguish these two effects because we average both Venusward and tailward fluxes. The two flow directions should be analyzed independently in each velocity distribution function to answer this question as a future work.

Further analysis on the magnetic field and the return flows shows that return flows are preferably observed when the fine structure of the magnetic field are observed in the magnetotail in both the solar minimum and maximum periods. We suggest that the fine structure of the CS in the magnetotail plays a key role in driving the return flows. We also suggest that return flows are more often observed in the solar maximum period because the fine structure is simply more often observed in the magnetotail in the solar maximum. This supports our observational result that show returning fluxes become dominant in the magnetotail in the solar maximum.

One possible candidate to cause the ion acceleration towards Venus is the magnetic tension force (Dubinin et al., 2013). Different from a single classical IMF draping at Venus (i.e., the single B\(_x\) reversal) as seen in Fig. 7(a), the IMF draping with fine structures exhibits multiple curls in the magnetic field line. These curls make the magnetic tension force pointing towards and away from Venus alternately as shown in Fig. 7(b). It is possible that this pattern produces return flows as well as antisunward flows in the Venus tail region. If the magnetic tension force drives the return flows, it would accelerate light ions more easily than heavier ions. This is consistent with the fact that proton return flows are more often observed than those of O\(^{+}\) ions in the Venus magnetotail (Kollmann et al., 2016; Persson et al., 2018). As mentioned before, however, we did not always observe the B\(_x\) reversals and return flows in the same time. In addition, since the magnetic field around Venus is generally unstable, it is questionable how to maintain the fine structure in the magnetotail so return flows are produced. Thus, we still need.
more dedicated analysis to study effects of the $j \times B$ force.

Another possible candidate is the magnetic reconnection (Zhang et al., 2012). The magnetic reconnection usually occurs at a CS of the classical single IMF draping pattern. On the other hand, the fine structure of IMF forms multiple CSs. If the reconnection rates are the same in each CS as that of the classical IMF draping pattern, more reconnections would occur in the tail region. Such multiple reconnections can produce multiple return flows as well as outflows in the tail region. Our observations show that return flows become dominant further than $X = -1.5$ R\textsubscript{V} at which Zhang et al. (2012) found an event of the magnetic reconnection. This suggests that the magnetic reconnection occurs at even further tail, at least at $X = -3$ R\textsubscript{V}. It is also possible that the B\textsubscript{X} reversals correspond to the flapping motion of the CS at Venus (Rong et al., 2015a,b). At Earth, the flapping motion of the magnetic field is also observed and it may be caused by fast plasma flows driven by the magnetic reconnection (Sergeev et al., 2006), and this analogy may apply for the Venus magnetotail. Thus, the multiple B\textsubscript{X} reversals may be caused as a result of the magnetic reconnection.

Another possibility is precipitations of pickup ions (Curry et al., 2015). Due to the spatially/temporally varying magnetic environment of Venus, a part of O\textsuperscript{+} pickup ions gyrate sunward. On the night side, this causes ion precipitations into the nightside ionosphere. Since the fine-scale structure of the draped IMF would disturb the trajectories of the pickup ions, it is possible that more inward flows are observed under this condition.

The cause of more frequent observations of the reversal of B\textsubscript{X} in the solar maximum period may be related to irregular structures on the ionospheric surface such as plasma clouds, tail rays, and holes (Brace...
et al. 1982a,1982b,1987). Such irregular structures could bend IMF locally, forming multiple curls in the magnetic field line, as visualized in Fig. 7(b). As shown in Fig. 5, the ICB altitudes are highly variable in the solar maximum compared to the solar minimum. This is consistent with PVO observations of the ionopause variations and may indicate that the irregular shapes appear frequently in the solar maximum which is consistent with a simulation study (Möstl et al., 2011). Note that although Masunaga et al. (2011) suggested that the fine-scale structures of IMF draping pattern are formed when the IMF cone angle is small, this tendency was not observed in our dataset. There was not a large difference in the cone angle distribution between the solar minimum and solar maximum periods. Another possible explanation to observe more multiple $B_x$ reversals in the solar maximum period is due to IMF sector boundary crossings (Edberg et al., 2011; Vech et al., 2016). An IMF sector boundary crossing is often associated with the ICMEs/CIRs that are in general more often observed in the solar maximum period. After the IMF sector boundary meets with the Venus induced magnetosphere on the dayside, the IMF reconnects with the draped magnetic field around Venus and cause ion outflow from multiple CSs in the magnetotail (Fig. 5 in Edberg et al., 2011). If VEX crosses such a magnetotail configuration, it would observe multiple $B_x$ reversals. Furthermore, Vech et al. (2016) statistically showed that average $O^+$ escape fluxes are reduced by $\sim 25\%$ after IMF sector boundary crossings. This may be consistent with our observations of the induced magnetosphere in which $O^+$ escape rates tend to be smaller in the solar maximum than those in the solar minimum. However, return flows are unlikely produced in this configuration because all the current sheets extend only tailward.

Fig. 6. (a) Observation frequencies of the number of $B_x$ reversals in the Venus tail region ($-3 \leq X_{VSO} \leq -1$ and $(Y_{VSO}^2 + Z_{VSO}^2)^{1/2} \leq 1$) for the 8 cases. Three types of $B_x$ reversals are shown in different colors: no reversals (Zero), a single reversal (Single), and multiple reversals (Multiple) per orbit. (b) Observation frequencies of $O^+$ return flows in the tail region per orbit under the three $B_x$ reversal types shown in (a).

Fig. 7. Schematic illustrations for (a) the classical IMF draping pattern and (b) the IMF draping with fine-structures deduced from the number of $B_x$ reversals observed by VEX.
Some of PVO observations showed that the $O^+$ escape rates are one order of magnitude larger than those in this study in the solar maximum period. Mihalov and Barnes (1982) showed that $O^+$ escape rate ($>4$ keV) is $\lesssim 10^{25}$ s$^{-1}$ in the distant tail region ($8-12 R_E$) in the solar maximum period. Brace et al. (1987) estimated $O^+$ escape rate (8 – 16 eV) in the near tail region ($\sim 2000$ km) near the solar maximum period and it was $5 \times 10^{25}$ s$^{-1}$. This difference may come from the difference of the energy range and/or the abnormal solar maximum period in this solar cycle, where the solar EUV flux is weaker than that in the period when PVO orbits around Venus. As seen in Fig. 1, an average F10.7 index in this solar maximum period where VEX was at Venus was $\sim 130$ while it was $\sim 190$ in the solar maximum period where PVO was at Venus. A comparison of the behavior of ion outflow and return flows between VEX and PVO datasets would help to understand the $O^+$ net escape rates, although what can be done is limited because the PVO plasma analyzer instrument was designed to observe the solar wind.

We conclude that the $O^+$ escape rates from Venus are controlled by both solar wind and solar EUV flux but return flows also significantly affect the escape rates especially in the solar maximum period. Since the return flows seem to be controlled by IMF draping patterns and ionospheric irregular structures, it is important to further investigate the relationship between the local magnetic field and ionospheric structures in a future study. It is also important to study the long-term transition of the solar wind, the solar EUV flux, and return flows to estimate the net ion loss from Venus over the long history of the solar system.

5. Conclusion

Using the $\sim 8.5$ years dataset obtained from the IMA and MAG instruments on Venus Express, we studied the $O^+$ escape rates from Venus under 8 cases defined by the solar wind dynamic pressure, the motional electric field, and the F10.7 index which is a good indicator of the solar EUV flux. We obtained the following results.

1. Net $O^+$ escape rates from Venus are $(2.4-5.0) \times 10^{24}$ s$^{-1}$ in the solar minimum period and $(1.3-3.5) \times 10^{24}$ s$^{-1}$ in the solar maximum period.
2. $O^+$ ions mainly escape from the induced magnetosphere over the 8.5 years. The escape rates from the magnetosheath only accounts for up to $\sim 30\%$ of the total net escape rates.
3. The net escape rates in the magnetosheath are strongly controlled by the motional electric field and the solar EUV flux.
4. In the induced magnetotail, return flows become dominant in the solar maximum period, which tend to reduce the net escape rates from the solar minimum period to the solar maximum period.
5. In the solar maximum period, ICB altitudes become highly variable and the magnetic field exhibits fine structures in the magnetotail compared to those in the solar minimum. In addition, return flows are preferably observed under the fine structures.

According to these results, we suggest that the ion pickup by the motional electric field is the main escape process in the Venus magnetosheath. We also suggest that the net $O^+$ escape rates in the induced magnetosphere at Venus are not only controlled by the solar wind and the solar EUV flux, but also by return flows. Ionospheric irregular structures or IMF sector boundary crossings may form fine-structures of the magnetic field in the magnetotail. The return flows could be caused by the magnetic tension force, magnetic reconnections and/or precipitations of $O^+$ pickup ions on the nightside. Since the return flows significantly affect the net $O^+$ escape rates at Venus, it is important to study long-term transition of return flows as well as the ion outflow to estimate the total ion loss from Venus over the history of the solar system.

Acknowledgments

This work was supported by the Swedish Research Council under contract 2015-04187. The authors would like to thank the European Space Agency (ESA) for leading the Venus Express mission to the successful mission. The ASPERA-4/IMA data are publicly available via ESA Planetary Science Archive. The ASPERA-4/IMA ion moment data and MAG data are available in AMDA (http://amda.cddp.e.earth/). The F10.7 index is available in OMNIweb (http://omniweb.gsfc.nasa.gov/html/ow_data.html).

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