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Article

Ablation of Venusian oxygen ions by unshocked solar wind

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ABSTRACT

As an Earth-like planet Venus probably had a primordial dipole field for several million years after formation of the planet. Since this dipole field eventually vanished the ionosphere of Venus has been exposed to the solar wind. The solar wind is shocked near Venus, and then scavenges the ionospheric particles through the magnetosheath and the magnetotail. The escape rate of oxygen ions (O^+) estimated from spacecraft observations over the past several decades has manifested its importance for the evolution of planetary habitability, considering the accumulated effect over the history of Venus. However, all the previous observations were made in the shocked solar wind and/or inside the wake, though some simulations showed that unshocked solar wind can also ablate O^+ ions. Here we report Venus Express observations of O^+ ions in the unshocked solar wind during the solar minimum. The observations suggest that these O^+ ions are accelerated by the unshocked solar wind through pickup processes. The estimated O^+ escape rate, 2.1×10^{24} ions/s, is comparable to those measured in the shocked solar wind and the wake. This escape rate could result in about 2 cm global water loss over 4.5 billion years. Our results suggest that the atmospheric loss at unmagnetized planets is significantly underestimated by previous observations, and thus we can emphasize the importance of an Earth-like dipole for planetary habitability.

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1. Introduction

Terrestrial planets with an atmosphere, Venus, Earth, and Mars, are losing volatiles presumably since their formation, and this issue has been extensively studied in recent several decades [1–8]. Nowadays, the dominant species subject to non-thermal escape are hydrogen ions (H^+) and oxygen ions (O^+ or O_2^+) on these planets [4,6,9–11]. The O^+ is of special interest because it can only originate from planetary atmosphere, while the H^+ escape could be compensated by solar wind protons (though no observational evidence has been published). The Pioneer Venus Orbiter mission (PVO) discovered the continuous ion escape from the Venusian ionosphere and helped to build a theoretical frame of non-thermal ion escape [7,12]. Recent observations made by the Analyser of Space Plasmas and Energetic Atoms (ASPERA-4) [13] onboard Venus Express (VEX) in the Venusian wake and magnetosheath region suggested that the escape rate ratio of H^+ to O^+ was between 1.9 [4] and 2.6 [8], which reaffirmed the close relation between O^+ escape and water loss. These results confirmed the importance of atmospheric escape for the evolution of planetary habitability.

To estimate the total escape rate of O^+ ions, one should first consider how far out freshly ionized planetary particles can propagate away from Venus. Considering their energy planetary O^+ ions should not only be expected in the magnetosheath and the induced magnetosphere, but outside of the bowshock. This phenomenon has been repeatedly observed at other unmagnetized solar system bodies, namely Mars [14] and several near-Sun comets [15], where O^+ ions were found to escape through both the shocked and unshocked solar wind. However, most of published PVO observations only included O^+ ions in shocked solar wind near Venus. Several observations of oxygen ion fluxes in the unshocked solar wind recorded during 14-year orbiting of (PVO) [16] and 1-h Galileo flyby [17] are found to be not identical to escaping O^+ ions. Since simulation results have already suggested that unshocked solar wind can also ablate O^+ ions [7], the possible reason for the absence

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of this expected observation may be instrumental limits of the Orbiter Plasma Analyzer (OPA) onboard PVO: the low energy range (<8 keV), a high count threshold (90 ions/s), the low time resolution (9 min) and the incapability of recognizing ion species [3,7]. The ASPERA-4 on VEX has a much better capability of detecting escaping O^+ ions, especially, it has energy range from 1 eV to 15 keV (electrons) and from 10 eV to 36 keV (ions) and can separate different ion species [13]. This energy range covers the typical energy of O^+ ions originating from the Venusian ionosphere or atmosphere and picked up by solar wind. We have examined ASPERA-4 data during the long solar minimum (2006.6–2010.12) and found that escaping O^+ ion indeed frequently appeared outside the bowshock near Venus.

2. Observation and discussion

We first show a typical event observed on November 14, 2009 that shows fluxes of escaping O^+ ions outside the bowshock near Venus. During this event, VEX moved from dawnside to duskside, and its trajectory was parallel to the *Y-Z* plane in the planet-centered Venus Solar Orbital (VSO) coordinate system, with *X* sunward and *Z* toward orbital north, and *Y* completing the orthogonal coordinate system. Fig. 1 shows the VEX observations when it approached the Venusian northern polar ionosphere from the dawnside. The magnetic field (Fig. 1a) measured by the magnetometer [18] and the energy spectrum of electrons (Fig. 1b) measured by ASPERA-4 demonstrate that VEX stayed in unshocked solar wind before 0414 UT, where the IMF was stable in both magnitude and orientation and the electrons remained unheated. At 0414 UT VEX crossed the bowshock and then observed the typical features of the magnetosheath, i.e., enhanced magnetic field and heated electrons. After 0433 UT, the strength of the magnetic field did increase further while both the energy and the fluxes of electrons decreased, suggesting that VEX entered the induced magnetosphere. The energy spectrum of ions (Fig. 1c) shows two populations: (1) solar wind protons with energy less than 0.7 keV outside the bowshock were heated in the magnetosheath; (2) O^+ ions were distributed in both sides of the bowshock. The O^+ ion observations can be confirmed through the Energy-Mass matrix shown in Fig. 1(d). There was no comet passage upstream of Venus at that time, thus these O^+ ions must have planetary origin. Of particular interest here are the O^+ ions outside the bowshock, whose energy varied with time (distance to Venus). Specifically, the energy was less than 3 keV at 0324 UT, compared to 13 keV at 0337 UT. Such a behavior is consistent with pickup ions whose minimum speed lower to zero and whose maximum speed is up to two times that of the solar wind.

We have carefully examined VEX observations during the long solar minimum (2006.6–2010.12), and discerned 286 instrument records (full 3D scan, 192 s resolution) containing O^+ ion observations outside of the bowshock, which are distributed over 73 VEX orbits (24 h period). In this study we only use 241 records due to data gaps in the magnetic field observations. The position of these O^+ ions in the VSO coordinate system clearly depends on the orientation of the interplanetary magnetic field (IMF), which is taken as the local magnetic field. As shown in Fig. 2(a), most of the ions appearing in the VSO $-Y$ ($+Y$) hemisphere region correspond to IMF $B_Z > 0$ (<0). This feature can be interpreted as that the O^+ ions preferentially appear in the positive **E** hemisphere, where E is the solar wind motional electric field ($-\mathbf{V}_{SW} \times \mathbf{B}$). This is a typical characteristic of pickup ions [7]. The speed of pickup ions varies between 0 and $2V_{SW}\sin\Theta$, where V_{SW} is the solar wind speed and Θ is the angle between the solar wind velocity vector $\mathbf{V}_{SW}$ and **B**. Fig. 2(b) shows that most of these O^+ ions have a speed which can be expected for pickup ions. These features suggest that those O^+ ions in this study are indeed pickup ions.

The essential question remains what these ions contribute to the total escape rate. Fig. 3(a) shows that the velocity vectors of the O^+ ions are overwhelmingly oriented outward, suggesting a tendency to escape from Venus. Since the location of pick up ions depend on the orientation of motional electric field **E**, we organize the data in the Venus Solar Electrical (VSE) coordinate system (+*X* is the same as the +*X* in VSO, but +*Z* is rotated to align with **E**). Fig. 3 (b) shows that these ions indeed prefer to appear in the positive E hemisphere, consistent with the results depicted in Fig. 2(b). Considering all escaping ions must cross the terminator plane ($X = 0$), the escape flux is defined as the net tailward flux (sum of tailward and sunward flux) perpendicular to the terminator plane, and in this study the averaged value of this flux is 1.7×10^5 ions/cm^2/s.

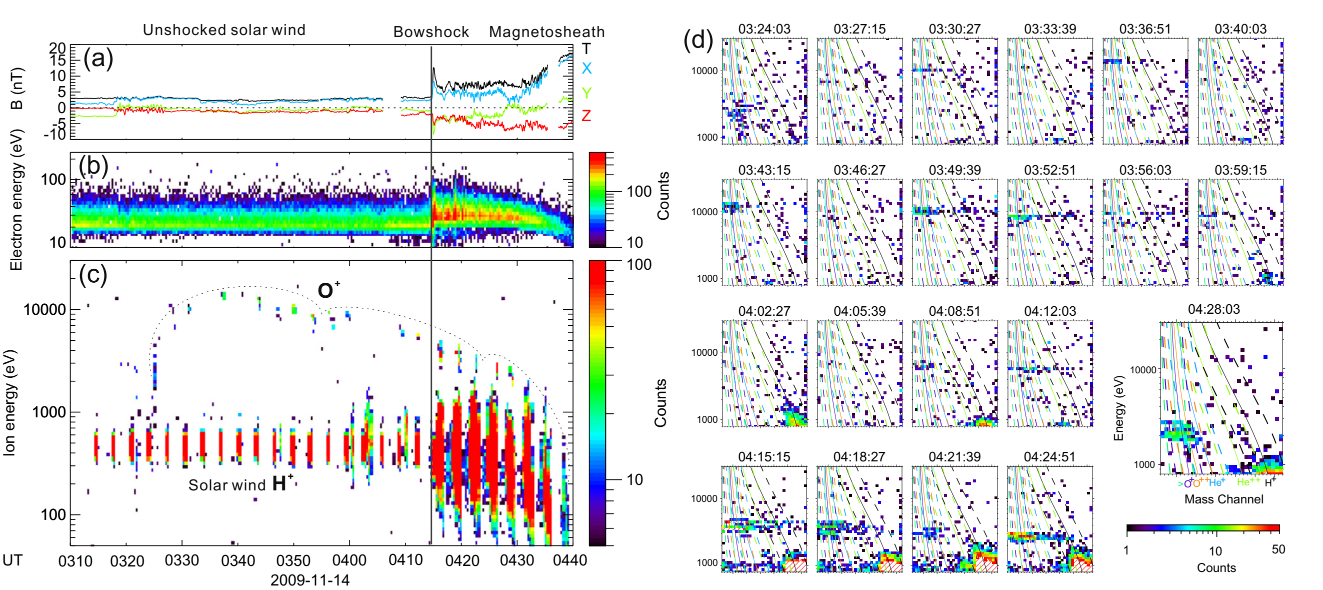

Fig. 1. VEX observations of O^+ near Venus on Nov. 14, 2009. (a) Magnetic field in VSO coordinate system; (b) Electron spectrum; (c) Ion spectrum; (d) Energy-Mass matrix of Ions. The dashed lines denote where different ion species are expected (labeled in the right-bottom panel).

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