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H^+/O^+ Escape Rate Ratio in the Venus Magnetotail and its Dependence on the Solar Cycle

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Key Points:
- The escape rate of O^+ is almost stable over the solar cycle, while H^+ escape rate decreases by a factor of 3.6 from solar minimum to maximum
- The H^+/O^+ escape rate ratio decreases from 2.6 at solar minimum to 1.1 at solar maximum
- The historic escape rate has presumably been below the stoichiometric ratio of water

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Abstract A fundamental question for the atmospheric evolution of Venus is *how much water-related material escapes from Venus to space*. In this study, we calculate the nonthermal escape of H^+ and O^+ ions through the Venusian magnetotail and its dependence on the solar cycle. We separate 8 years of data obtained from the ion mass analyzer on Venus Express into solar minimum and maximum. The average escape of H^+ decreased from $7.6 \cdot 10^{24}$ (solar minimum) to $2.1 \cdot 10^{24}$ s^{-1} (solar maximum), while a smaller decrease was found for O^+: $2.9 \cdot 10^{24}$ to $2.0 \cdot 10^{24}$ s^{-1}. As a result, the H^+/O^+ flux ratio decreases from 2.6 to 1.1. This implies that the escape of hydrogen and oxygen could have been below the stoichiometric ratio of water for Venus in its early history under the more active Sun.

Plain Language Summary An open issue for the atmospheric evolution of Venus is how the presumably large water content was lost. In this study, we use 8 years of data collected by the ion mass analyzer instrument onboard Venus Express. We investigate the escape of hydrogen H^+ and oxygen O^+ ions, the components of water, from the Venusian atmosphere to space. If water is escaping from Venus entirely as ions, the hydrogen-to-oxygen ratio should be close to 2. We find that the ratio of H^+/O^+ ion escape is 2.6 for the solar minimum period, while the escape is close to 1-to-1 for solar maximum, when the Sun is more active. Thus, Venus is currently on average losing water as ions from its atmosphere. However, in the early history of the solar system, when the Sun was in an even more active state, the escape ratio was probably below the water ratio. This implies that the oxygen did not enrich the atmosphere and surface, and instead hydrogen remained in the Venusian system over its history.

1. Introduction

Today, the Venusian atmosphere is very arid, mostly containing carbon dioxide. However, observations of the deuterium-to-hydrogen ratio and surface properties indicate that Venus had water in its atmosphere billions of years ago, which must have been lost through its history (Donahue et al., 1997; Ingersoll, 1969; Taylor et al., 2018, and references therein). In addition, in the current state the surface temperature and water content of the lower atmosphere is considered to be stable (Taylor & Grinspoon, 2009). This suggests that the atmosphere is presently in an equilibrium state: That is, sources of water may be either outgassing from the surface or comet impacts (Grinspoon, 1993), while losses of water are mainly through either diffusion to the surface or escape to space.

Albarède (2009) suggests that water in the Venusian atmosphere was dragged into the mantle by early plate tectonics, which should have created a water-rich mantle similar to what is observed at Earth. However, currently no measurements have shown if this is the case. On the other hand, Gillmann and Tackley (2014) suggest that the high surface pressure at the surface does not allow for a large outgassing process, whereas the diffusion of volatiles into the surface material is also limited. They thus conclude that the diffusion of oxygen into the surface materials of Venus cannot account for the loss of water content in the Venusian atmosphere.

Thermal escape to space, including hydrodynamic escape where heating of the atmosphere expands it and allows the upper atmospheric particles to escape, is considered to be an important process for the early atmosphere of Venus, but not to a large extent today (Kasting & Pollack, 1983). Wordsworth and Pierrehumbert (2013) suggest that the current CO_2-rich atmosphere emits an equal amount of energy to the absorbed solar extreme ultraviolet (EUV) radiation energy through CO_2 emission in the upper atmosphere. However, in the younger solar system, the solar EUV radiation could have been as much as

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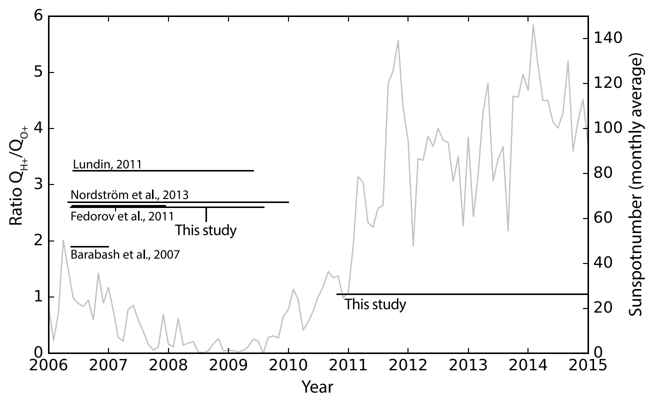

Figure 1. The ratio of H^+ and O^+ escaping fluxes from previous studies, together with the time period used for each respective study. The result of this study is also depicted (see section 3 for details). The gray curve is the monthly average sunspot number (http://www.sidc.be/SILSO/).

100–1,000 times stronger than today (Ribas et al., 2005). This would have heated the atmosphere considerably, allowing for a significant hydrodynamic escape of hydrogen and leading to oxygen escape via a drag force (Gillmann & Tackley, 2014; Wordworth & Pierrehumbert, 2013).

If most of the water had escaped to space via hydrodynamic escape during an early phase, the subsequent long evolutionary escape of water to space would be very low and not have a significant effect on the loss of water. However, the deuterium-to-hydrogen ratio in the atmosphere indicates a fractionated long-term escape, where the lighter hydrogen escaped at a larger rate than the heavier deuterium (Donahue et al., 1997). In addition, current measurements and models suggest a large nonthermal escape of atmospheric particles to space (see reviews by Lammer et al., 2006; Futaana et al., 2017). The nonthermal processes are thought to be important at Venus, where the conductive ionosphere interacts directly with the solar wind due to the lack of an intrinsic magnetic dipole field. Ions produced by solar EUV radiation in the exosphere are exposed to the solar wind and are thus "picked up" by the motional electric field and can escape the planet (Luhmann et al., 2004). Additionally, ions produced inside the ionosphere are accelerated by the polar wind electric field, created by the separation of the lighter electrons and the heavier ions, and can escape (Hartle & Grebowsky, 1990). The "draped" pattern of the magnetic field in the magnetotail also accelerates ions downtail where they escape (Barabash, Fedorov, et al., 2007; Dubinin et al., 2011). Moreover, photochemical reactions can provide energies above escape velocity for hydrogen but are not enough for oxygen escape (McElroy et al., 1982).

The main escaping species are O and H, in both neutral and ionized states (Lammer et al., 2006). If water escaped to space during the long history of Venus, H and O are expected to escape in a ratio of 2, the stoichiometric ratio of water. If the ratio is larger than 2, as found for Mars (Lammer et al., 2003), we would expect other processes, like thermal escape, to be more important. Indeed, studies using theoretical models suggest that the current average escape rate ratio is close to 2 (Lammer et al., 2006).

In this study, we investigate the escape rate ratio of H^+ and O^+ through the Venusian magnetotail, which is one of the major escape channels for nonthermal processes. Here we define the escape rate as the total net loss of each ion (Q_s) through the magnetotail

$$Q_s = \int_A - F_{x,s} dA, \tag{1}$$

where $F_{x,s}$ is the net escaping ion flux in the magnetotail (x axis points from Venus to the Sun), A is the cross section of escaping flow in the perpendicular plane to x, and s represents the species (H^+ or O^+). The ratio is calculated as Q_{H+}/Q_{O+}. Note that the negative (positive) F_x is the outflowing (Venusward) flux and all the data are used.

The Q_{H+}/Q_{O+} ratio in the Venusian magnetotail has been calculated in several previous studies using data from different time periods recorded by the Analyzer of Space Plasmas and EneRgetic Atoms (ASPERA-4) package onboard the Venus Express (VEx) spacecraft (Figure 1). Using data from 33 orbits between May to December 2006, Barabash, Fedorov, et al. (2007) calculated Q_{H+}/Q_{O+} = 1.9. Later, Fedorov et al. (2011) updated the study using the time period from May 2006 to December 2007. They found escape rates of $Q_{H+} = 7.1 \cdot 10^{24}$ s^{-1} and $Q_{O+} = 2.7 \cdot 10^{24}$ s^{-1}, with an accuracy estimated to be a factor 2, which gives an escape rate ratio of 2.6. Using a slightly different method and a longer time period between 2006 and 2009, Lundin (2011) calculated the escape rates to be $Q_{H+} = 3.9 \cdot 10^{25}$ s^{-1} and $Q_{O+} = 1.2 \cdot 10^{25}$ s^{-1}, giving a ratio of 3.3. Nordström et al. (2013) investigated effects of using different methods from data between May 2006 and December 2009 and found an average escape rate of $Q_{H+} = (14 \pm 2.6) \cdot 10^{24}$ s^{-1} and $Q_{O+} = (5.2 \pm 1.0) \cdot 10^{24}$ s^{-1}, giving a ratio of 2.7. Overall, all ratios are close to or slightly higher than the stoichiometric ratio of water. However, all these studies were made using the solar minimum period (Figure 1). In our study, we extend these studies by using all available data from VEx during 2006–2014 to clarify the escape rate ratio dependence on the solar cycle.

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2. Instrumentation

We use data from the ion mass analyzer (IMA), a part of the ASPERA-4 experiment onboard VEx. VEx had a 24-hr highly elliptical orbit with a nominal pericenter at 250 km near the north pole, which provided ~3,000 orbits with measurements of the Venusian plasma environment over 8 years. IMA is a top-hat type electrostatic analyzer. Its field of view is divided into 16 azimuth sectors with a resolution of 22.5°. By using an electrostatic deflector system in front of the top-hat analyzer, IMA determines the elevation angle of the incoming ions, with an aperture of ±45°. The elevation angle is separated into 16 steps with a resolution of 5.6°. The total angular field of view is ~2π sr, while a part of the aperture is blocked by the spacecraft body. An electrostatic analyzer is used to measure the ion energy per charge from 10 to 36 keV/q, with 96 logarithmically separated energy steps ($\Delta E/E$ = 7%). A permanent magnet assembly gives information about the mass per charge with a moderate mass resolution, sufficiently separating H^+, He^{++}, and He^+ and heavy ions (O^+, $O_2{}^+$, and $CO_2{}^+$). The time resolution obtaining the full 3-D velocity distribution is 192 s. Barabash, Sauvaud, et al. (2007) describe the instrument in more detail.

3. Method and Results

We calculate the escape rates of H^+ and O^+ through the Venusian magnetotail from the IMA measurements for two time periods: solar minimum (April 2006 to August 2009) and solar maximum (October 2010 to November 2014). The mass separation was done as described in Fedorov et al. (2011), where the heaviest ions are assumed to be O^+. We then produce an average differential flux of proton and oxygen ions in the magnetotail. In theory, the average differential flux has six degrees of freedom (energy, two incoming directions, and the position of the spacecraft). In this study, we assume an axisymmetric magnetotail, reducing the degrees of freedom to five. It is known that the Venusian magnetotail is asymmetric with respect to the direction of the solar wind motional electric field, $E_{\mathrm{mot}} = -v_{\mathrm{sw}} \times B_{\mathrm{IMF}}$, where v_{sw} is the solar wind velocity and B_{IMF} is the interplanetary magnetic field (Jarvinen et al., 2013; McComas et al., 1986; Zhang et al., 2010). However, because the escape rates are not sensitive to the choice of frame (Nordström et al., 2013), we use a cylindrical frame to represent the real space. X is along the Venus-Sun line, and R is the distance from the X axis. In velocity space, we use a spherical coordinate system with its origin in the spacecraft and define two angles: the azimuth angle as $\theta = \tan^{-1}$ (Vy/Vx) and the elevation angle as $\varphi = \sin^{-1}$ (Vz/V), where Vy is in the opposite direction to Venus orbital motion, Vz is normal to the ecliptic plane, and V is the speed.

The magnetotail is divided into spatial bins with a size of $\Delta X = 0.2\ R_V$ and $\Delta R = 0.3\ R_V$, where R_V is the radius of Venus (6,052 km). The energy space is divided as to be linearly distributed in velocity with Δv = 5 km/s. The elevation and azimuth angles have bin sizes of $\Delta\theta = 1.8°$ and $\Delta\varphi = 3.6°$. Then, the measured differential flux is assigned to the corresponding spatial bin where the spacecraft was located at the start time of each measurement, and to the corresponding energy and angular bins. By taking the arithmetic average in each five-dimensional bin, we can extract the average differential flux $\bar{J}(X_i, R_j, \varphi_k, \theta_l, E_m)$. Note that the energy, incoming directions, and the differential flux here are corrected to the Venus-fixed frame considering the spacecraft motion. Figure 2 shows examples of the average differential flux. The method of creating the average differential fluxes removes a bias from the angular coverage of the instant measurements (due to the non-4π field of view and the blockage by the spacecraft), as well as short temporal variations of the environment. Figure 2 confirms that the calculated average distributions cover most of the angular space. We disregarded bins with insufficient statistical significance, here less than 10 data points. The average number of data points in each bin is ~100.

The total flux for each spatial bin is then calculated through the integration

$$F_x(X_i, R_j) = \int \bar{J}(X_i, R_j, \varphi_k, \theta_l, \mathrm{E}_m) \cos^2(\theta_l) \cos(\varphi_k) \Delta\varphi \Delta\theta \Delta E_m, \tag{2}$$

where ΔE_m is the width of the energy bins. Figure 3 shows the calculated outflow fluxes. To separate the planetary protons from the solar wind protons we assume that the protons with velocities <200 km/s are of planetary origin, following previous studies (Fedorov et al., 2011; Nordström et al., 2013).

The flux $F_x(X_i, R_j)$ is then used to calculate the net escape rate

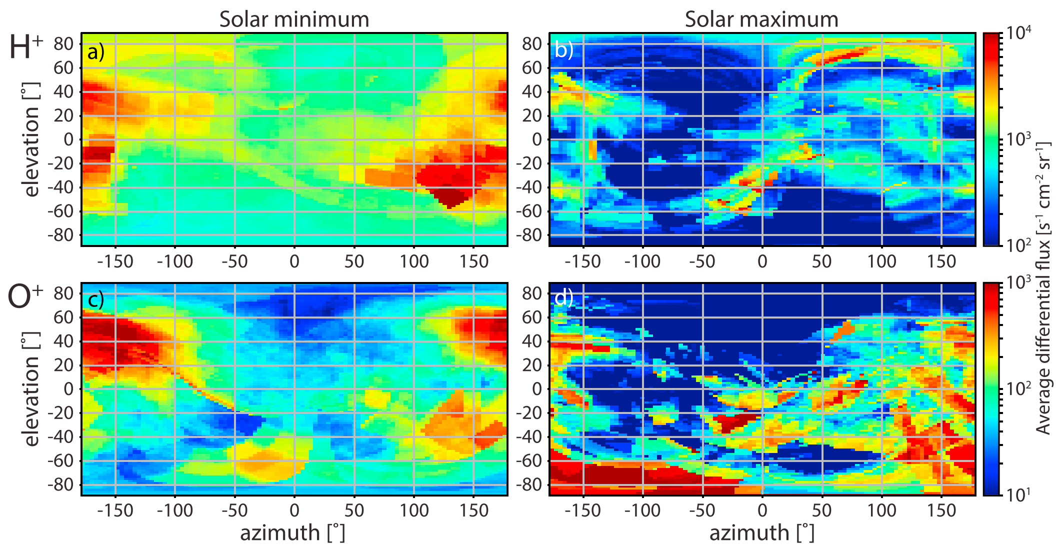

Figure 2. Average differential flux integrated over the whole energy range from the spatial bin at -1.9 Rv $< x < -1.7$ Rv, 0.6 Rv $< R <$ 0.9 Rv. The azimuth angles between −90° and 90° represent the fluxes toward Venus, while the azimuth angles between −180° to −90° and 90° to 180° represent the fluxes away from Venus. The color represents the differential flux for H^+ during (a) solar minimum and (b) solar maximum and differential flux for O^+ during (c) solar minimum and (d) solar maximum.

$$Q_s = \frac{1}{N_i}\sum_i\sum_j F_{i,j,x}\ 2\pi R_j \Delta R, \tag{3}$$

where N_i is the number of slices used in the X direction (5 in this case), R_j is the radius of the center of the bin used, and ΔR is the radial width of the spatial bin. We use the bins with the most frequent measurements to obtain the escape rates, namely, in the interval X = [−2.5, −1.5] Rv and R = [0, 1.2] Rv. The average escape rates for Q_{H+} and Q_{O+} during the solar minimum and maximum, with the corresponding escape rate ratios, are shown in Table 1. From solar minimum to solar maximum, a significant decrease in the H^+ escape rate is

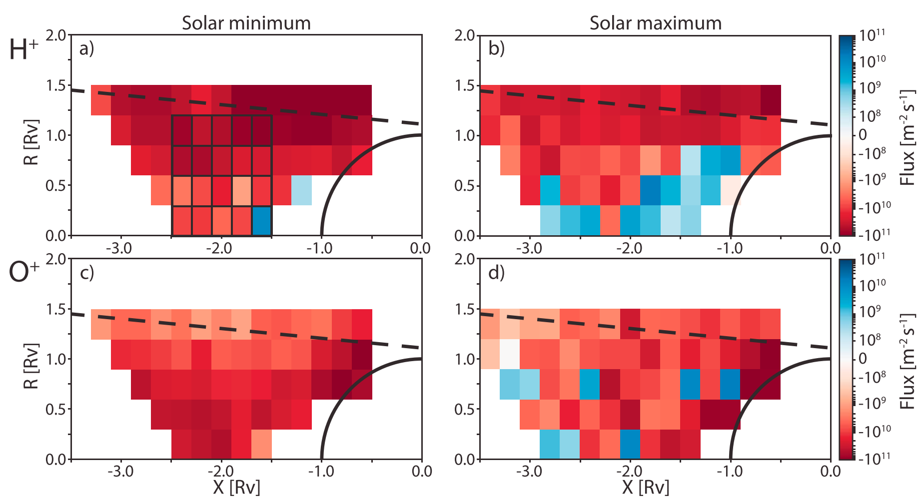

Figure 3. Maps of the ion fluxes in cylindrical coordinates for H^+ during (a) solar minimum and (b) solar maximum, and for O^+ during (c) solar minimum and (d) solar maximum. The color represents the flux (equation (2)). Negative fluxes (reddish bins) are antisunward net flow, and positive fluxes (bluish bins) are Venusward net flow. The black solid curves indicate the outer rim of Venus, and the dashed curves indicate the modeled induced magnetosphere boundary (Martinecz et al., 2008). The black boxes in (a) indicate the bins used for calculating the average escape rates (equation (3)).

Table 1
Average Escape Rates With the Standard Errors for H^+ and O^+ and Corresponding Escape Rate Ratio Calculated for Solar Minimum (2006–2009) and Solar Maximum (2010–2014)

	Solar minimum 2006–2009	Solar maximum 2010–2014
H^+ escape rate, Q_{H+} [s^{-1}]	$7.6 \pm 2.9 \cdot 10^{24}$	$2.1 \pm 1.2 \cdot 10^{24}$
O^+ escape rate, Q_{O+} [s^{-1}]	$2.9 \pm 1.1 \cdot 10^{24}$	$2.0 \pm 1.1 \cdot 10^{24}$
Escape rate ratio, Q_{H+}/Q_{O+}	2.6	1.1

seen, while the relatively small decrease of the O^+ escape rate leads to the ratio decrease from 2.6 to 1.1. The error given for each calculated value is the standard error, calculated using the bootstrap method.

4. Discussion

The escape rates of O^+ from Venus decrease slightly from solar minimum to solar maximum (Table 1). The decrease here may be due to a combination of several effects of the solar cycle variations. The increase of the EUV flux from solar minimum to solar maximum leads to a decrease of the O^+ escape rate (Kollmann et al., 2016). The average dynamic pressure decreases slightly from solar minimum to solar maximum (McComas et al., 2013), which also decreases the O^+ escaping flux (Edberg et al., 2011). However, the occurrence of high-dynamic pressure events is higher during solar maximum (Webb & Howard 1994), which leads to an increase in O^+ flux. These effects may counteract each other, while as a whole, they lead to only a slight decrease in the total O^+ escape rate.

The H^+ escape flux decreased by almost a factor 4 from solar minimum to solar maximum (Table 1). This decrease is mainly caused by the change in flow direction in the magnetotail. During solar maximum, a significant Venusward flow is present, mainly close to Venus and in the central magnetotail (Figures 2b and 3b). This is also consistent with the results of Kollmann et al. (2016), who report an increased Venusward flux of protons during high solar EUV fluxes. Such an increase in the Venusward flux is also seen in the O^+ flows, although it is not as significant as for protons (Figures 2d and 3d). Kollmann et al. (2016) suggest a link between increased Venusward flow and magnetic reconnection (Zhang et al., 2012), but responsible mechanisms are yet unknown. A dedicated investigation on the Venusward fluxes will be part of future studies. Nevertheless, the Venusward fluxes, together with a vortex-like flow found by Lundin et al. (2013), create complex flow patterns in the magnetotail, and it is important to consider these for the calculations of the total net escape rates.

The assumption of the threshold 200 km/s to separate the planetary and solar wind protons may influence the results of this study. We use the same threshold used in previous studies (Fedorov et al., 2011; Nordström et al., 2013) for consistency. On the other hand, the used threshold of 200 km/s may be an overestimation of the proton flux since most of the planetary proton flux seem to have a speed of $<$140 km/s. If the threshold was put at 140 km/s, Q_{H+} (and thus Q_{H+}/Q_{O+}) decreases both for solar minimum and maximum, but the trend over the solar cycle would remain.

The results in Table 1 show that Q_{H+}/Q_{O+} is close to the stoichiometric ratio of water over the investigated time period. Indeed, during the solar minimum condition, the ratio is slightly above 2, but during the solar maximum condition, the escape rate ratio is closer to 1. This indicates that hydrogen would remain in the Venusian system in some form, assuming that the magnetotail is the major escape channel. Moreover, we assumed here that the heavy ions are O^+. If the escaping heavy ions include molecules such as O_2^+ and CO_2^+, more oxygen atoms would escape than shown here. For example, if 50% of the heavy ions are O_2^+ or CO_2^+ (as is the case for Mars escaping flux; Carlsson et al., 2006), the escape rates increases to $4.4 \cdot 10^{24}$ s^{-1} for solar minimum and $3.0 \cdot 10^{24}$ s^{-1} for solar maximum. This leads to escape rate ratios of 1.7 and 0.7, respectively. Consequently, even more hydrogen than oxygen would remain in the Venus system.

The nonthermal escape through the Venusian magnetotail is not the only escape channel. We may include escape rates from other sources to deduce the total escape rate ratio. Lammer et al. (2006) summarize the most significant escape sources as photochemical reactions, pickup ions, electric field force in ionospheric holes, detached plasma clouds, and sputtering. Such sources were studied using theoretical models with inputs mainly from measurements by the Pioneer Venus Orbiter. These indicate that a lower limit on neutral escape rate is 50% of the H^+ escape and 25% of the O^+ escape. If these escape rates are added to the results of this study we get escape rate ratios of 3.2 for solar minimum and 1.3 for solar maximum. However, the total ion escape includes the pickup ion process, the main escape channel of which is in the magnetosheath, outside of the area used in this study. As summarized by Lammer et al. (2006) the pickup ion escape rate is of the same order as the escape of ions through the magnetotail. Including this in the results of this study, the total escape rates for oxygen and hydrogen are higher, but the escape rate ratios do not change significantly. Lammer et al. (2006) also indicate that the escape rates from the models are highly variable. Thus, depending on the other escape channels, the average escape rate ratio might change slightly but is expected to stay around 2.

The results of the escape rate ratio may be used to extrapolate backward in time in order to discuss the history of the atmospheric evolution of Venus, while a quantitative assessment is a challenging task for the future. For example, extraordinary conditions such as 100–1,000 times higher EUV flux (Ribas et al., 2005) and 100 times higher dynamic pressure (Wood, 2006) at 3.9 Ga should be considered. These conditions are not realized in today's solar conditions. However, provided that the magnetotail is the main escape channel and that the dependency of the Q_{H+}/Q_{O+} ratio on the solar cycle variations are kept at the current state, we may infer from this study that the long-term escape rates from Venus have been dominated by the oxygen ions. This resulted in the conclusion that the hydrogen, dissociated from the water molecules, remained to a higher degree than oxygen in the atmosphere, surface, and interior of Venus. In other words, Venus could be more reduced than oxidized. Otherwise, other escaping mechanisms, preferably applicable to hydrogen, would have operated.

5. Conclusions

We used 8 years of data obtained by the ASPERA-4 experiment on the VEx spacecraft and derived the ratio of escaping flux between H^+ and O^+ in the Venus magnetotail. The ratio was found to be 2.6 for solar minimum, while it decreased to 1.1 for solar maximum. The decrease is mainly caused by the significant increase in the return flow of protons toward the planet in the Venusian magnetotail at solar maximum conditions, which decreases the escape rate from $7.6 \cdot 10^{24}$ s^{-1} at solar minimum to $2.1 \cdot 10^{24}$ s^{-1} at solar maximum. The oxygen outflow flux was almost the same over the solar cycle, from $2.9 \cdot 10^{24}$ s^{-1} at solar minimum to $2.0 \cdot 10^{24}$ s^{-1} at solar maximum. The main reason for the decrease in the net escape flux is the structure of the magnetotail: A strong return flow toward Venus was found during the solar maximum condition. Considering that the Sun and solar wind conditions in the last 3.9 Ga resemble the solar maximum more than the solar minimum condition and that the dependency of the Q_{H+}/Q_{O+} on the solar cycle variations are kept at the current state, the historical escape rate ratio could clearly be below 2 (the stoichiometric ratio of water). Consequently, the oxygen atoms dissociated from water molecules have escaped to space more efficiently than the hydrogen atoms. Therefore, a high oxidation of Venus is unlikely. Otherwise, other escaping mechanisms, preferably applicable to hydrogen, would have operated.

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