Atmospheric origin of cold ion escape from Mars

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[1] Cold ionospheric ions dominate the plasma escape from Mars. The flow pattern versus altitude, latitude and local time suggests a fairly symmetric transport of ionospheric plasma from the dayside into the nightside/tail region of Mars. An interesting aspect of the plasma escape from Mars is the large abundance of molecular ions, implying that the outflow source region extends down to the lower ionosphere where molecular ions dominate. We also find a fair amount of ionized molecular hydrogen, $H_2^+$, in the ion outflow, the $H_2^+$ outflow corresponding to some 1/10 of the $H^+$ outflow. Because the cold ionospheric ion outflow is dominated by $H^+$, $H_2^+$, $O^+$ and $O_2^+$, the average CO$_2^+$ outflow corresponding to about 10% of the heavy ion outflow, we have made a stoichiometric analysis of the ion escape. Adding the total outflow of hydrogen and oxygen respectively, we get $H/O = 0.6–1.3$. Altogether this suggests that the ultimate origin of the bulk ion escape from Mars is a minor constituent in the Martian atmosphere - water.


1. Introduction

[2] Water is central for the evolution of life, and for making a planet habitable. Water is abundant in Universe, but not necessarily stable, is readily dissociated by EUV/UV solar fluxes, and can be removed from a planet by thermal and non-thermal escape [Zhang et al., 1993; Fox, 1993; Jakosky et al., 1994; Chassefiere et al., 2007]. The present difference in water inventory of the terrestrial planets remains an intriguing issue. While Mercury’s proximity to the Sun, and its relatively low gravity explains the lack of water there, it is not obvious why Venus and Mars evolved so differently compared to the Earth. The magnetically shielded planet Earth has maintained a hydrosphere, while Venus has lost its hydrosphere. Mars, bears signatures of a wet past [e.g., McKay and Stoker, 1989; Kerr, 2000; Baker, 2001], but eventually transformed into an arid planet, let alone with some water ice deposits, particularly in the polar regions.

[3] The loss of water and the present difference in water inventory between the Earth-like planets is most likely the results of different evolutionary paths. Past cataclysmic meteoric bombardments in the early time of the solar system is one candidate. Yet another is mass-loss induced by the evolution of solar flux. The early Sun was characterized by extreme coronal activity, with intense UV, EUV and X-ray fluxes [Ribas et al., 2005], massive coronal mass-loss and intense solar wind fluxes [Wood et al., 2002], which together lead to severe atmospheric forcing of the terrestrial planets. The effect of the solar evolution may be tested, since variations in thermal and non-thermal escape from the Earth (and Mars) is correlated with solar activity [Yau and Andre, 1997]. For instance, the mass loss from Mars may be scaled backward in time by models and simulations [e.g., Zhang et al., 1993; Fox, 1993; Jakosky et al., 1994; Lammer et al., 2003a; Lundin et al., 2007; Terada et al., 2009].

2. Experimental Results

[4] We use data from the Imaging ion Mass Analyzer (IMA) of the ASPERA-3 experiment on Mars Express (MEX) for time periods when IMA operated in a post-acceleration mode capable of measuring cold ions with mass per unit charge (m/q) 1 to 44 (H$^+$ to CO$_2^+$). The data-taking period, October–November 2008 and February–March 2009, was characterized by low solar activity. We focus on energies less than $\sim$50 eV, an energy interval with only two-dimensional coverage, but instead provides energy and mass distributions every 12 second. Six mass per unit charges (m/q) - 1, 2, 4, 16, 32, 44 - corresponding to H$^+$, H$^+_2$/He$^+$, He$^+$, O$^+$, O$^+_2$, and CO$_2^+$ are analyzed in more detail. Figure 1, shows a MEX traversal of the terminator ionosphere, the six top plots illustrating the energy distribution of six ion species, from CO$_2^+$ to H$^+$. The bottom plot give the total escape flux of ionized oxygen and hydrogen. Because the spacecraft potential affects the ion energy, the ambient ion energy is an issue. The spacecraft potential may be determined from the electron data, but for the sake of simplicity we use here an “average” spacecraft potential of $\sim$9V, a value found to be reasonable from the analysis of hundreds of pericenter traversals. Figure 1 shows that the low-energy heavy ion fluxes (CO$_2^+$, O$^+$ and O$^+_2$) peak in the ionosphere near pericenter. On the other hand, low energy light ions (He$^+$, H$^+_2$ and H$^+$) in this example appear in the altitude range 600–2000 km. The ion data put in context with the orbit projection in Figure 1 (in cylindrical coordinates) display the cometary escape feature reported by Lundin et al. (2008), i.e., cold dayside ionospheric ions becoming gradually energized towards the nightside (08.30–08.40 UT).

[5] Figure 2 displays energy and mass spectra in the transition region separating slowly drifting dayside ionospheric ions and energized ions. The energy spectra (Figure 2a) of H$^+$, O$^+$ O$^+_2$ and m/q = 2 (H$^+_2$) display an interesting aspect of the Martian ion outflow, energization increasing with
increasing mass. Clear mass peaks for H\(^+\), O\(^+\), and O\(^2+\) are evident in the m/q diagram (Figure 2b). An m/q = 2 (H\(_2^+\)) peak is also present, although here close to the noise level. CO\(_2^+\) ions may be inferred at 22 eV (dashed curve), but the signal is contaminated by O\(^2+\) ions. Of particular interest in Figure 2b is the peak at m/q = 2 (H\(_2^+\)). Because the peak may be an artefact, due to crosstalk between IMA mass-channels, we have carefully checked the m/q=2 peak in data from another (lower post-acceleration voltage) mode (p/a 4). In the IMA p/a 4 mode all ion masses are shifted upward on the mass-image plane, H\(^+\) displaced out of range.

Figure 2. (a) Energy spectra for outflowing low-energy H\(^+\), H\(_2^+\), O\(^+\), and O\(^2+\). (b) Mass per unit charge spectra for Low-energy ions, demonstrating the mass resolution of the IMA instrument in post acceleration mode 7. The data is sampled during \(\approx\)3 minutes starting 08.40 UT (Figure 1) at an altitude range H = 1480–1250 km.
of CO$_2$. The abundance variability of O$^+$ versus O$^{2+}$ may be quite strong and individual samples may provide O$^+$/O$^{2+}$ number density ratios varying by an order of magnitude. However, the average O$^+$/O$^{2+}$ number density ratio stays within a factor of two.

To determine the species of the m/q=2 ions we have made a scatter plot analysis of simultaneously measured number densities of H$^+$ versus the number densities of m/q = 2 ions (Figure 4). The statistical average ratio between H$^+$ and m/q = 2 is ≈57, the bold dashed line in the scatter plot marking this ratio. The median value is 38, and the 25% and 75% percentiles are 13 and 75 respectively. Notice that the overall scatter of data points falls well below the minimum hydrogen/deuterium ratio (≈1000 on Mars according to Krasnopolsky and Feldman [2001]). This excludes D$^+$ from being the source for the m/q = 2 mass peak. The other candidate, He$^{++}$, originating from the solar wind, is even less likely since the m/q=2 ions are cold and well correlated with outflowing O$^{2+}$.

On basis of these observations we conclude that the cold ion outflow from Mars constitutes H$^+$, H$_2^+$, O$^+$, and O$_2^+$, with a small admixture of He$^{++}$, and CO$_2^+$. Data from this study gives the following CO$_2^+$ contribution to the heavy ion outflow: Average 10%; Median 8%; 25 and 75 percentiles, 5% and 15% respectively. The CO$_2^+$ contribution to the ion escape is in good agreement with that reported by Carlsson et al. [2006].

A summary of the average ion fluxes for different species and an estimate of the corresponding ion outflow are given in Table 1. The data set comprises 768 flux values for each ion species. To determine the net outflow in the Martian rest frame, the spacecraft velocity is taken into account for. Column 3 in Table 1 gives the sum of all oxygen ions. Adding also the hydrogen ions we derive the average H/O flux ratio 0.64 (column 7), and the H/O ratio for simultaneous H and O fluxes when both fluxes exceed 10$^6$ (m$^{-1}$ s$^{-1}$) (column 8). From this we conclude that the outflow ratio between hydrogen and oxygen ions is close to one. In view of the much lower carbon ion escape from Mars (column 6), the oxygen ion escape must originate from water. Notice that the escape rates in Table 1 are based on an average flux of ions through a tail cross-section area of 4·10$^{13}$ m$^2$.

3. Discussions

From a detailed analysis of IMA ion data we have identified H$^+$ and H$_2^+$ in the cold ion outflow from Mars. The outflow of H$^+$ is neither new, nor surprising, considering past findings from Phobos-2 [e.g., Lundin et al., 1990]. However, significant fluxes of H$_2^+$ are a new observation.
The total contribution of ionized hydrogen to the outflow is substantial, raising questions about the ultimate origin of outflowing oxygen ions (O$^+$ and O$_2^+$). The O$^+$ and O$_2^+$ ions we observe escaping from the ionosphere are mainly produced by reactions in the ionosphere, O$_2$, e.g., from dissociative ionization of CO$_2$. However, atomic oxygen stems from dissociation of water in the lower atmosphere, while most of the hydrogen produced in that dissociation may escape thermally. Notice that atomic oxygen may escape by other means such as sputtering [Fox, 2003; Jakosky et al., 1994]. Altogether it means that a stoichiometric ratio between oxygen ion and hydrogen ion escape is not expected. Nevertheless, the total oxygen ion escape should be a measure of the water escape if there is no oxidation of the soil.

[11] The fact that CO$_2^+$ represents a minor fraction of the ion outflow from Mars [e.g., Carlsson et al., 2006] raises some interesting questions about the atmospheric escape from a CO$_2$ dominated planetary atmosphere. If the ultimate source of escaping O$^+$ and O$_2^+$ is CO$_2$, and there is a minute outflow of CO$^+$ and CO$_2^+$, the result would be carbon (CO, C) enrichment. The limited mass resolution of the OMA instrument allows for some uncertainty, because some CO$^+$ may be embedded in the O$_2$ mass peak. However, measurements and models of the ionospheric ion composition [e.g., Hanson et al., 1977; McElroy et al., 1977] lend little support for a significant CO$^+$ source compared to O$_2$ in the Martian upper ionosphere. The carbon problem therefore remains, unless the oxygen ion escape originates primarily from dissociated water.

[12] The composition of the ion escape reflects the source altitude in the ionosphere. Roughly speaking, molecular ions originate from low altitudes while atomic ions originate from high altitudes. A large fraction of molecular ion outflow from Mars suggests that the ionospheric ion escape starts at altitudes as low as 300 km [see, e.g., Lundin et al., 2007, Figure 13]. Ionospheric ion-composition profiles based on data [Hanson et al., 1977] and models [e.g., McElroy et al., 1977; Fox, 2003] may serve as useful guides to the ion outflow.

[13] The extraction height of outflowing H$_2^+$ is related to the concentration of H$_2$ in the upper atmosphere of Mars [Krasnopolsky and Feldman, 2001; Fox, 2003], but the ionic profile of H$_2^+$ is yet to be determined. According to Fox [2003] an increased H$_2$ abundance is expected to raise the altitude of the exobase, thus affecting the composition of the outflow as well. Our data shows that the number densities of O$_2$ and H$_2$ in the outflow is well correlated, with a correlation coefficient $R^2 = 0.79$. This suggests that both molecules are extracted and energized at low altitudes. The general trend of simultaneously increasing H$^+$ and H$_2^+$ number densities (Figure 4) is similar, but the scatter is very large, regression analysis lending no support for correlation.

[14] An important aspect of H$_2^+$ is its association with water on Mars. The fact that it is ionized and part of the plasma escape may be new, but not surprising considering how substantial the molecular ion escape is. The ratio between the total hydrogen and oxygen ion outflow suggests that a significant fraction of ionized hydrogen and oxygen escape originates from water. However, since a large fraction of the oxygen atoms from dissociated water is expected to be responsible for surface oxidation on Mars [e.g., Lammer et al., 2003b; Zahnle et al., 2008], there is certainly room for a much higher hydrogen loss than inferred here. In fact observations by Mariner 6, 7 and 9 by Anderson [1974] implies 30 times higher hydrogen outflow than our H$^+$ outflow. Nevertheless, the ion outflow analysis made here gives an average hydrogen/oxygen outflow ratio close to unity, suggesting that a significant fraction of the dissociated water on Mars disappear from the planet by ion escape.

4. Conclusions

[15] The high fluxes of ionospheric H$^+$ and H$_2^+$, the latter a new finding in the ASPERA-3 data, suggests that at times a substantial fraction of the total hydrogen loss from Mars is due to ion escape. We note that the H/O escape flux ratio from Venus is $\approx 2$ [Barabash et al., 2007], implying that the water escape from Venus is primarily due to ion escape. We also find that molecular ions (H$_2^+$, O$_2^+$) provide significant contributions to the ion escape. This is different from Venus, where atomic H$^+$, He$^+$, and O$^+$ dominate the escape. Notice that CO$_2$ is the major constituent in the Martian atmosphere, four orders of magnitude more abundant than H$_2$O. Yet, the CO$_2$ contribution to the total heavy ion escape is about 10%, while 90% of the heavy ion escape is O$^+$ and O$_2^+$. An H/O outflow ratio close to one, the CO$_2^+$ outflow representing a minor part of the ion escape, suggests that the bulk ion escape from Mars, O$^+$, O$_2^+$, H$^+$, and H$_2^+$ has to be maintained ultimately by hydrogen and oxygen produced by photolysis of H$_2$O$_2$, a minor constituent in the Martian lower atmosphere. Solar forcing is therefore particularly effective in removing water from a planetary atmosphere. The extreme forcing by the young Sun [Wood et al., 2002; Ribas et al., 2005], may have caused equally extreme hydrogen and oxygen ion escape [Lundin et al., 2007; Terada et al., 2009], and a drastic loss of water at Mars.

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References


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