Strong plume fluxes at Mars observed by MAVEN: An important planetary ion escape channel


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Abstract We present observations by the Mars Atmosphere and Volatile Evolution (MAVEN) mission of a substantial plume-like distribution of escaping ions from the Martian atmosphere, organized by the upstream solar wind convection electric field. From a case study of MAVEN particle-and-field data during one spacecraft orbit, we identified three escaping planetary ion populations: plume fluxes mainly along the upstream electric field over the north pole region of the Mars-Sun-Electric field (MSE) coordinate system, antisunward ion fluxes in the tail region, and much weaker upstream pickup ion fluxes. A statistical study of O$^+$ fluxes using 3 month MAVEN data shows that the plume is a constant structure with strong fluxes widely distributed in the MSE northern hemisphere, which constitutes an important planetary ion escape channel. The escape rate through the plume is estimated to be ~30% of the tailward escape and ~23% of the total escape for > 25 eV O$^+$ ions.

1. Introduction

The solar wind plasma and interplanetary magnetic field (IMF) generate a motional electric field in the Mars rest frame. Many global numerical models, including hybrid, test particle, and multifluid MHD models [Luhmann and Schwingschuh, 1990; Brecht and Ledvina, 2006; Fang et al., 2008; Najib et al., 2011; Dong et al., 2014; Curry et al., 2015; and others], have noticed a plume-like escaping ion population moving approximately in the upstream electric field direction in addition to the tailward escape. Both Phobos and Mar Express (MEX) spacecraft detected energetic ion beams [Kallio et al., 1995; Carlsson et al., 2006, 2008; Dubinin et al., 2006, 2011], which were inferred to be related to the plume fluxes accelerated by the electric field [Kallio and Koskinen, 1999; Kallio et al., 2006, 2008; Boesswetter et al., 2007]. However, the plume as a constant structure and an important ion escape channel has never been conclusively confirmed by observations. Liemohn et al. [2014] performed a statistical study of energetic ion beams using 3 year MEX Ion Mass Analyzer (IMA) data and found only weak plume signature. They discussed the possible instrumental reasons for MEX not detecting significant plume features. The limited field of view (FOV) and mostly fixed orientation of IMA likely result in it being unable to observe most of the plume fluxes. Even though energetic plume fluxes were sporadically captured by MEX IMA, it is difficult to infer their spatial distributions and velocity directions with respect to the electric field due to the lack of simultaneous magnetic field measurements.

In this study we analyze global planetary ion distributions using in situ particle and magnetic field measurements by the Mars Atmosphere and Volatile Evolution (MAVEN) mission. The MAVEN Suprathermal and Thermal Ion Composition (STATIC) instrument (J. P. McFadden et al., The MAVEN Suprathermal and Thermal Ion Composition (STATIC) Instrument, submitted to Space Science Reviews, 2014) has the same FOV (360° x 90°) as MEX IMA, but its orientation changes frequently (up to several times per orbit), which provides STATIC a greater chance to observe ion fluxes from different directions. STATIC measures the energy-angular distributions of positive ions from 0.1 eV/e to 30 keV/e and is capable of resolving the major ion species (including H$^+$, He$^{++}$, O$^+$, O$_2^+$, and CO$_2^+$) near Mars. MAVEN also carries the Solar Wind Ion Analyzer (SWIA) [Halekas et al., 2013] to measure solar wind ions and the Magnetometer (MAG) [Connerney et al., 2015] that can directly measure the IMF when the spacecraft is beyond the bow shock. These measurements are crucial to calculating the upstream convection electric field, which organizes the spatial distribution and velocity directions of plume ions. Equipped with these instruments, MAVEN provides an opportunity to better understand the global distribution of escaping ions within the context of the Mars-solar wind interaction.
In this paper, we present a case study of MAVEN observations of different escaping ion populations during one spacecraft orbit, followed by a statistical study of the spatial distribution of plume fluxes and their contribution to total ion escape from Mars.

2. Escaping Planetary Ion Populations Observed During One MAVEN Orbit

Figure 1 shows MAVEN data from one spacecraft orbit on 18 December 2014. Figures 1a and 1b show the SWIA solar wind velocities and magnetic field from SWIA and MAG. Figures 1c and 1d show the energy and mass spectra for planetary ions from STATIC. Figure 1e shows the O+ velocity directions. Figures 1f and 1g show MAVEN orbit. In Figure 1c, the energy sweep changed between ~ 00:20 and ~ 00:40 because of different STATIC operational modes. In Figures 1f and 1g, the black crosses are the bow shock locations identified from the data. The two black curves in Figure 1g are the bow shock and MPB from Vignes et al. (2000).

Figure 1. MAVEN data from one spacecraft orbit on 18 December 2014. (a and b) Solar wind velocities and magnetic field from SWIA and MAG. (c and d) Energy and mass spectra for planetary ions from STATIC. (e) O+ velocity directions. (f and g) MAVEN orbit. In Figure 1c, the energy sweep changed between ~ 00:20 and ~ 00:40 because of different STATIC operational modes. In Figures 1f and 1g, the black crosses are the bow shock locations identified from the data. The two black curves in Figure 1g are the bow shock and MPB from Vignes et al. (2000).
electric field and tailward escape. The plume fluxes detected are strongest when the IMF is oriented so that the electric field is directed mainly from Mars to the spacecraft and drop significantly (e.g., ~03:15–03:25) when the IMF direction changes. This further confirms that the strong O\(^+\) fluxes detected above the bow shock are plume fluxes from lower altitude being accelerated along the electric field.

During ~02:30–03:00, weak but continuous ion fluxes dominated by O\(^+\) are detected at ~20–30 keV (i.e., 500–600 km/s) (see Figures 1c and 1d). Although the velocity directions shown in Figure 1e are quite variable during this time interval, overall, they are approximately perpendicular to the magnetic field and close to the solar wind direction. The dynamics of these energetic O\(^+\) ions are generally consistent with pickup ions with cycloid trajectories near the phase with the maximum velocity under the relatively stable solar wind and IMF conditions during this time interval as measured by SWIA and MAG [see also Rahmati et al., 2014, 2015]. Thus, these weak but energetic O\(^+\) fluxes are most likely pickup ions originating from the tenuous upstream neutral corona, the same ion population as those detected by the MAVEN Solar Energetic Particle instrument at higher energy under different solar wind and IMF conditions [Rahmati et al., 2014, 2015].

In Figure 2, the O\(^+\) number fluxes ≥10\(^4\) s\(^{-1}\) cm\(^{-2}\) (above the approximate background level) and velocities are mapped to x-z and y-z planes in the Mars-Sun-Electric field (MSE) frame, with x axis pointing to the Sun and z axis along the upstream solar wind motional electric field. The transformation from MSO to MSE is a rotation around the x axis with an angle determined by the IMF orientation assuming the upstream solar wind always in −x direction. We use the real-time IMF measurements by MAG when the spacecraft is above the bow shock. When the spacecraft is below the bow shock, we use the closest (in time) MAG data points above the bow shock as IMF proxies. This explains why, in Figure 2, data below the bow shock are contiguous in MSE, while data above the shock are not. The gray arrows in Figure 2 show O\(^+\) fluxes above 20 keV and are only shown if the velocity direction is at least 45° away from that of 25 eV–20 keV. This criterion is taken to ensure that the energetic part is a different population from the relatively low energy part. These high-energy O\(^+\) fluxes are the upstream pickup ions near the phase with the maximum velocity discussed in last paragraph.

Figure 2 shows clear plume features in the MSE northern hemisphere and tailward escape fluxes on the nightside, with a transition region in between (see also ~03:30–04:00 in Figure 1). There are also identifiable upstream pickup ions mostly on the dayside with much weaker fluxes than the plume and tailward escaping
ions. These low fluxes should not significantly affect the total ion escape rate but can help constrain neutral corona models [Cravens et al., 2002; Rahmati et al., 2014, 2015]. The strongest plume fluxes detected (>10^6 cm\(^{-2}\) s\(^{-1}\)) are comparable to the tailward escape, which implies the potential importance of the plume on atmospheric loss.

3. Statistical Study

To better understand escaping ion distributions on a global scale, we perform a statistical study in the MSE coordinate system for >25 eV O\(^+\) fluxes using 128 s resolution STATIC data. Here we choose the MAVEN data over a more than 3 month time period (from 11 November 2014 to 28 February 2015), when the spacecraft goes above the bow shock for each orbit and therefore upstream solar wind conditions are available. In order to take the limited instrument field of view into account, we further classify the O\(^+\) measurements into different subsets according to whether the solar wind/tailward direction (i.e., \(-x\) in MSE) and/or the upstream electric field direction (i.e., \(+z\) in MSE) are within the STATIC FOV, as shown in the supporting information of the paper.

In Figure 3, the mean O\(^+\) number fluxes and velocities are mapped to the MSE x-z plane. Figures 3a, 3c, and 3e show the results using all the data, which has the best spatial coverage. Figures 3b, 3d, and 3f show the results from the data with both the solar wind/tailward (\(-x\)) and the upstream electric field (\(+z\)) directions within the STATIC FOV, which is a relatively unbiased data set for comparing the plume and tailward fluxes. The transformation from MSO to MSE is the same as described before, taking advantage of SWIA and MAG measurements.

The ion fluxes in Figure 3 from the two different data sets illustrate a consistent escaping ion flow pattern near Mars. In the tail region, the ion fluxes are mostly in the tailward (\(-x\)) direction, while there are electric field (\(+z\)) aligned flux components above the magnetic pileup boundary (MPB) in both the northern (\(+z\)) and southern (\(-z\)) MSE hemispheres. This flow pattern is consistent with previous numerical studies [e.g., Fang et al., 2008] and the global heavy ion flux map from MAVEN data by Brain et al. [2015]. The \(+z\) fluxes in the northern MSE hemisphere are the plume. Those in the southern hemisphere are generally weaker and have smaller velocities, likely because they are from a more tenuous neutral source at higher altitudes and have been accelerated over a shorter distance than those in the northern hemisphere. Some of these pickup ions will escape through the plume, while the others may precipitate back to the Martian atmosphere [e.g., Fang et al., 2013; Hara et al., 2013] or eventually merge into the tailward escaping ion fluxes. The escape probabilities of these pickup ions depend on their locations and global electromagnetic field distributions [Fang et al., 2010]. A small number of bins in Figure 3 show average fluxes in the \(-z\) direction. These bins tend to be sparsely populated and may be influenced by observations recorded right after the IMF changed direction or inaccurate IMF proxies (see section 2). Plume fluxes are seen primarily in the northern MSE hemisphere above the MPB and gradually transition to tailward fluxes on the nightside without any significant boundary in between.

The plume fluxes in Figures 3b and 3d from the relatively unbiased data set are a few times stronger and have larger velocities than those in Figures 3a and 3c, which shows that the instrument’s limited FOV has a significant effect on the plume observations. When the electric field (\(+z\)) direction is out of the STATIC FOV, the instrument will miss a large portion of the \(+z\) fluxes. These data points will weaken the apparent plume features as observed in Figures 3a and 3c. In Figures 3b and 3d, the plume fluxes (up to \(~10^7 cm^{-2}s^{-1}\)) are comparable to the tailward escape, while their velocities are significantly higher than the tailward escape. Most of the plume velocities range from \(~150 km/s\) to \(~350 km/s\) (\(~1\)–\(~10\) keV for O\(^+\)), consistent with the energetic ion beams detected by Phobos and MEX [Kallio et al., 1995; Dubinin et al., 2006]. As shown in Figure 3d, the plume ion velocities tend to increase with altitude, consistent with an electric field acceleration process [see also Dubinin et al., 2006]. These characteristics of the plume fluxes from MAVEN data are generally consistent with model predictions [e.g., Fang et al., 2008; Curry et al., 2015a].

Figures 3e and 3f show the likelihood that MAVEN STATIC observed ion fluxes in the MSE \(+z\) direction. Observations represented in this map have flux magnitude \(\geq 10^6 cm^{-2}s^{-1}\) (above the approximate background level) and velocity \(\leq 45^\circ\) from the electric field (\(+z\)) direction. The observation frequencies in
Figure 3e are significantly smaller than those in Figure 3f, because STATIC is not always pointing in the right direction to detect $+z$ fluxes. Figure 3f shows that when STATIC has both solar wind ($-x$) and electric field ($+z$) directions within its FOV, it detects significant $+z$ fluxes in the expected plume region (northern hemisphere in MSE, above MPB) about 80% of the time. The observation frequencies drop on the nightside, where the ion fluxes gradually transition to tailward directions. The high observation frequencies of $+z$ fluxes in the...
expected plume region show that the plume is a constant structure in the MSE coordinate frame even with time-varying IMF, because they rotate with IMF almost instantaneously (see section 2).

4. Plume and Tailward Ion Escape

To estimate and compare the ion escape rates through the plume and tail region, we choose a plume cross section at $z = 1.8$ to $2.0 R_M$ (with a bin size of $0.2 R_M$) and a tail region cross section at $x = -1.6$ to $-1.4 R_M$ as marked in Figure 3a. This choice aims to both maximize the data spatial coverage and have comparable cross-section areas. For the plume cross section, it is also important to have it mainly above the MPB to include the sources at high altitude [Fang et al., 2008]. The net ion fluxes through these two planes are shown in Figures 4a and 4b, which are dominant by escaping fluxes with returning fluxes only in some small areas as labeled with the gray color. In Figure 4a, the data set with the tailward ($-x$ in MSE) direction in the STATIC FOV (see the supporting information) is used for both good data coverage and a relatively unbiased estimate, because only $-x$ fluxes contribute to the escape through the tail region cross section. For the same reason, the data set with the $+z$ electric field direction in the FOV is used for Figure 4b. To further improve the data coverage especially for the plume cross section, we increase the thickness of the cross sections to $x = -1.8$ to $-1.2 R_M$ for the tail region and $z = 1.6$ to $2.2 R_M$ for the plume. The results are shown in Figures 4c and 4d. Harada et al. [2015] performed a more detailed study of the tailward ion fluxes using MAVEN data, which shows a similar pattern of distribution to that in Figure 4c.

Using the different cross-section thicknesses as described above, the plume escape rate varies between 4.0 and $5.4 \times 10^{23} s^{-1}$ with a mean number flux of $3.5 \times 10^5$ cm$^{-2}$ s$^{-1}$. The tailward escape rate varies between $1.3$ and $1.8 \times 10^{24} s^{-1}$ with a mean number flux of $1.1$ and $1.2 \times 10^6$ cm$^{-2}$ s$^{-1}$. The corresponding total escape rate for >25 eV O$^+$ varies between $1.7$ and $2.3 \times 10^{24} s^{-1}$, generally consistent with Brain et al.'s [2015] estimate ($\sim 3 \times 10^{24} s^{-1}$ for all heavy ion species) at the same energy range based on MAVEN data. From both methods, we get consistent results for the plume contribution relative to the

Figure 4. Net O$^+$ fluxes through cross sections of the (a and c) tail region and (b and d) plume region. Gray colors label returning fluxes (up to $10^5$ cm$^{-2}$ s$^{-1}$).
total ion escape. For O\textsuperscript{+} at >25 eV, the plume escape is 30% of the tailward escape and 23% of the total ion escape, which is an important contribution to the total ion escape. As expected, at higher energies (>100 eV) these ratios become larger (~40% of the tailward escape and ~30% of the total escape).

5. Discussion

MAVEN observations show constant and strong MSE-organized plume features in pickup O\textsuperscript{+} distributions, which could not be fully characterized in observations by previous Mars missions. As discussed in section 1, there are instrumental reasons that MEX has difficulties detecting and identifying plume fluxes. The similar characteristics between the plume fluxes observed by MAVEN and the energetic ion beams seen in Phobos and MEX data [Kallio et al., 1995; Carlsson et al., 2006, 2008; Dubinin et al., 2006, 2011; Liemohn et al., 2014] discussed in section 3 suggest that these energetic ion beams are most likely a part of the plume.

There are some uncertainties in this study. First, the straggling background from solar wind signals in STATIC data (J. P. McFadden et al., submitted manuscript, 2014) is roughly removed by subtracting an empirical ratio (2% or 20% depending on data products with different mass channels) of the counts at <2.5 amu from larger mass channels. This method removed most of the straggling background but may also have removed some real planetary ion data in the same energy-angular channels as the solar wind. Second, the limited STATIC FOV cannot capture all ion fluxes. In addition, the time-varying blockage of the FOV by the spacecraft (J. P. McFadden et al., submitted manuscript, 2014) will also affect ion flux measurements [see also Futaana et al., 2010]. The STATIC data calibrations are preliminary. Overall, there may be 20%–50% uncertainties in the ion fluxes reported in this paper. We leave to a future study to examine how these uncertainties affect our ion escape estimates. On the other hand, the simplified IMF proxies (see section 2) are sometimes inaccurate for the data points below the bow shock, which may explain some −z fluxes in the plume cross sections (see gray boxes in Figures 4b and 4d) and possibly results in underestimates of the plume escape. The fraction of the plume escape to the total escape may vary between different ion species and under different solar wind and solar radiation conditions. In particular, transient space weather storms at Mars are likely to alter the plume characteristics [Jakosky et al., 2015; Curry et al., 2015b].

As discussed in section 3, the transition between the plume and tailward escape is continuous according to the near-Mars observations. It is possible that the two channels will eventually separate at higher altitude as suggested by the multifluid MHD and hybrid models [Najib et al., 2011; Dong et al., 2014; Jarvinen et al., 2015]. However, with current data coverage, the estimates of ion escape through the two channels depend on the choice of cross sections. Previous ion escape rate estimates are usually based on the fluxes through a tail region cross section at x ~ −2 to −3 R\textsubscript{M} [e.g., Barabash et al., 2007; Lundin et al., 2008], which are likely to miss a major portion of the plume according to the spatial distribution and magnitudes of plume fluxes as shown in Figure 3. Thus, it is important to have a surface to cover the plume region when estimating the total ion escape rate as in Brain et al. [2015]. In Nilsson et al. [2011], the ions escaping in the directions perpendicular to x axis are included in the escape rate. However, since plume fluxes are often out of MEX IMA FOV [Liemohn et al., 2014], the escape rate by Nilsson et al. [2011] may still be underestimated. The current spatial coverage of MAVEN is limited for us to make direct comparisons with previous MEX studies, which will be carried out in future study when more MAVEN data are available.

6. Conclusions

We identified three escaping planetary ion populations in MAVEN observations: strong plume fluxes over the MSE north polar region moving mainly in the upstream electric field direction, strong antisunward ion fluxes in the tail region, and weak but energetic upstream pickup ion fluxes observed mostly on the dayside. Our statistical study illustrates a substantial plume with strong ion fluxes widely distributed in the MSE northern hemisphere above the MPB, which gradually transition to tailward fluxes on the nightside without any significant boundary.
The instrument FOV has a strong influence on the planetary ion plume observations and their interpretation in terms of atmosphere escape. When MAVEN STATIC is pointing in the right direction, it detects significant plume fluxes ~80% of the time in the model-predicted plume region, which shows that the plume is a constant structure in the MSE coordinate system.

We estimate the plume escape for O$^+$ at >25 eV ($4.0\times10^{23}$ s$^{-1}$) to be 30% of the tailward escape (1.3–1.8 x 10$^{24}$ s$^{-1}$) and 23% of the total escape (1.7–2.3 x 10$^{24}$ s$^{-1}$). These ratios get larger at higher energies. This study provides the first observational support for the significance of the plume as both a key feature and an important ion escape channel for the Martian atmosphere.

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