Reduced Atmospheric Ion Escape Above Martian Crustal Magnetic Fields

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Abstract Martian crustal fields were considered as too weak to have a distinctive effect on global escape rates of Martian heavy ions. However, new observations by the Mars Atmosphere and Volatile Evolution mission reveal a more precise result and show a notably lower atmospheric ion escape region above the area of the strongest crustal fields. A comparison between the fluxes of high and low energy O⁺ ions suggests that the strongest crustal fields may trap low energy ions and reduce the solar wind pick-up efficiency while high energy ions form a flux depletion above the crustal field. Statistical results indicate a maximum reduction of the global escape flux by nearly 35% when the strongest crustal field region is oriented sunward. This is the first time that the protective effect of the crustal fields on heavy planetary ions has been observed and it might indicate a more effective protection of atmospheres by stronger magnetic fields like at Earth.

Plain Language Summary The disappearance of liquid water on Mars is frequently understood as a consequence of enhanced atmospheric escape due to a lack of Earth-like dipole magnetic fields to protect its atmosphere from erosion by the solar wind. However, this hypothesis does not have a lot of supporting evidence. The Mars Atmosphere and Volatile Evolution mission for the first time observes an area of lower outflow of high energy O⁺ ions above the region of the strongest crustal magnetic fields on the Martian southern hemisphere. Four years of statistical results show that up to 35% of O⁺ ions do not escape when the strongest crustal magnetic fields are facing toward the Sun. Our results suggest that the crustal magnetic field is crucial for ion escape processes and may significantly affect the evolution of the Martian atmosphere.

1. Introduction

For a planet with a sufficiently dense atmosphere, neutral particles are ionized by solar irradiation and the impact of energetic electrons. Ionized planetary particles form an ionosphere, located typically at altitudes above 120 km on Mars (e.g., Nagy et al., 2004; Bougher et al., 2015; Pätzold et al., 2016). These ions gain energy from several mechanisms and may attain enough speed to reach escape velocity (e.g., Chamberlain & Hunten, 1987). Since the motion of ions depends on the magnetic environment they are passing through, a strong dipole magnetic field like at Earth will form a magnetosphere that can trap outward planetary ions and send part of them back to the planet’s atmosphere (e.g., Seki et al., 2001; Yau & André, 1997). The disappearance of liquid water on Mars is frequently understood as a consequence of enhanced atmospheric escape (e.g., McElroy et al., 1977; Lundin et al., 2007; Jakosky et al., 2015a, 2015b). Mars may have lost its global magnetic field since its initial magnetic dynamo ceased billions of years ago (e.g., Langlais et al., 2010), as compared to present day Earth which preserves a strong dynamo field and deep oceans.

However, this concept has been doubted in recent years because the huge size of the Earth magnetosphere may increase the area of solar wind interaction and thus may collect more energy for the escape of planetary ions (Barabash, 2010; Strangeway et al., 2010). So far, both concepts lack direct supporting evidence, and we can also not set up an experimental magnetic field of sufficient size to test ideas. The fast-changing solar wind conditions and the atmospheric differences between the terrestrial planets make it difficult in a comparison between planets with a dipole magnetic field and nonmagnetic bodies to clarify the effect of the planetary
magnetic field alone (e.g., Moore & Horwitz, 2007; Wei et al., 2012). But Mars provides a great natural laboratory to compare the effect of magnetic field on ion escape processes. Martian crustal fields are mainly located in its southern hemisphere between longitude 120° and 240° and are about 100 times stronger than in other regions of the planet (Acuña et al., 2001). The strongest crustal field’s magnitude can affect the behavior of electrons at altitudes up to the magnetic pileup boundary MPB (e.g., Acuña et al., 1998; Brain et al., 2005; Matsunaga et al., 2017), which is the boundary between planetary ions and the solar wind. There have been in recent years several numerical simulations of the effect of the crustal fields on ion escape. The most recent one by Egan et al. (2019) claims that ion escape is enhanced by fields residing inside the MPB but inhibited by fields extending beyond the MPB. However, there are no detailed observations which could show whether Martian crustal fields can affect the motion of planetary ions at such an altitude. Moreover, the physical mechanisms of the effect of the crustal field on ion escape are also unknown and have been debated, since the orbits or the instruments of former Martian missions were not able to observe any effects by the Martian crustal fields on ion fluxes at low altitudes while they are well visible in the electron fluxes (e.g., Brain, 2006; Fränz et al., 2006). The Mars Atmosphere and Volatile Evolution (MAVEN) mission allows us for the first time to observe the magnetic fields and the flow of planetary ions simultaneously which provide a good chance to investigate these questions (Jakosky et al., 2015a, 2015b).

2. Data

Observations from the Supra Thermal And Thermal Ion Composition (STATIC) instrument onboard MAVEN provide ion data in the energy range from 0.1 eV to 30 keV with a 90° × 360° field of view and 4-s temporal resolution which corresponds to about 20-km spatial resolution (McFadden et al., 2015). STATIC can distinguish different ion species which dominate the Martian upper atmosphere such as H+, O+, O2+, and CO2+. Hydrogen ions exist in both the solar wind and the planetary atmosphere while the heavier ions are rare in the solar wind. We choose O+ as a marker of the crustal field effect on planetary ions since O+ is much lighter than O2+ and CO2+ and thus has a smaller gyro radius. In this work, we used 4 years (from Sep 2014 to Aug 2018, a total of 7505 orbits) of O+ moment data calculated from 32 energy steps, 8 mass steps, 4 deflector angles, and 16 azimuth angles with a 4-s time resolution. Here we divided the O+ ion distribution into two parts: the low energy part for all ions with energy below 30 eV and the high energy part with energy from 30 eV to 30 keV. O+ ions with energy above 2 eV can in principle escape from the planet, but observations below 30 eV are influenced by spacecraft charging such that it is difficult to determine absolute fluxes without carefully correcting the observations. Above 30 eV there is no such limitation, and the energy of 30 eV is also the lower limit of Solar Wind Ions Analyzer, another electrostatic analyzer onboard MAVEN designed to measure solar wind protons (Halekas et al., 2015). A cross validation of protons data between STATIC and Solar Wind Ions Analyzer guarantees the reliability of ions data measured by STATIC above 30 eV. The low energy distribution has been corrected for the influence of the spacecraft potential and spacecraft speed (Dubinin et al., 2017). MAVEN also provides a magnetometer to measure the local magnetic field with the same time resolution (Connerney et al., 2015).

3. Results

The statistical results by using 4 years of STATIC data show that there is a clear depletion in the outward flux of high energy O+ ions above the region of the strongest crustal fields at altitudes between 300 and 600 km (Figure 1). The outward fluxes above the strongest crustal field region are at least 10 times smaller than above weak or no crustal field regions. Dayside is here defined by the Martian local time of MAVEN in situ observations from 6 a.m. to 6 p.m. Outward fluxes are defined by the angle between flux vector and the radially outward direction to be less than 90°. Inward fluxes have angles larger than 90°. This definition gives a method to estimate the outflow of heavy ions across the dayside hemispheric shell at given altitudes.

Results show that a region of visibly low outward flux forms for energized O+ ions above the strongest crustal field region. The magnitude of the Martian crustal magnetic fields quickly attenuates with increasing altitude which results in a corresponding shrinkage of the size of the flux depletion. This low flux region could be identified for each single year of observation which benefits from the short global scanning time of MAVEN spacecraft with a 4.5-hr processing orbit. But when we consider the small aerographical size of regions with strong horizontal crustal magnetic field lines and the speed of the MAVEN spacecraft around
its orbital periapsis, it becomes clear that averaging 4 years of data is necessary to show the effect of crustal fields on high energy O$^+$ ions. Four years of observations also average out the influence of the Martian atmospheres' seasonal variations and short time variations of the solar wind. We should also mention that the past 4 years had a relatively weak solar activity. An average over data from 7075 orbits with 4-s time resolution, as presented here, cannot be caused by just a few extreme space weather events. Our results suggest that each time when crustal fields rotate toward a sunward direction, they will reduce the outward energetic O$^+$ ion outflow at altitudes between 300 and 600 km, and we can call this a shielding effect of the Martian crustal field.

In order to figure out the effective range of the crustal field's shielding effect, we choose the altitude profiles of two different regions for comparison (Figure 2a). One is the region of the strongest crustal field in the southern hemisphere within the low flux region while the other is at the same longitude but without crustal fields in the northern hemisphere, using the crustal field model by Cain et al. (2003). When we calculate the gyro radius of the high energy O$^+$ ions using the local magnetic field measured by the MAVEN onboard magnetometer (Figure 2b), the gyro radii above the crustal field region are much smaller than above the region with no crustal field. This indicates that ions in regions without crustal fields are more easily transported to a higher altitude (Figure 2c). This phenomenon still can be observed even above 600 km, where the strength of the model crustal fields becomes minor. This effect of crustal fields reducing the high energy O$^+$ ion outflow becomes more clear if we use the model of the Martian crustal field by Cain to map the outward fluxes as a
function of model field strength and altitude (Figure 2d). The reduction effect appears to depend linearly on the field strength and linearly decreases with altitude from 400 to 1,000 km, as the dash black line emphasizes. For high energy O$_2^{+}$ ions one may also observe a similar effect, but much less clear than for O$^{+}$ ions, since the O$^{+}$ ions' gyro radius is a half that of the O$_2^{+}$ ions moving at the same speed (Figure 2e). Our observations suggest that the strongest crustal fields can trap O$^{+}$ ions to move along the field lines to lower altitudes, similar to the results from ionospheric models by Matta et al. (2015).

Figure 3a provides a more detailed plot of outward high energy O$^{+}$ ions being controlled by crustal fields at different altitudes. Statistical results here are consistent with Figure 2d and also show a clear linear decrease of O$^{+}$ ion fluxes with increasing crustal magnetic field strength. This dependency changes as altitude increases and reaches a best linear fit between 300 and 600 km, which confirms the conclusions drawn from Figure 1. The dayside Martian ionospheric structure strongly depends on solar zenith angle.
In Figure 3b we show the outward high energy O\(^+\) ion fluxes at altitudes of 250, 350, and 450 km for different SZA bins. The first observations are that the reduction effect of the crustal fields is independent on SZA. Second, in the near subsolar region (SZA less than 30°), outward fluxes are higher than in the terminator region (SZA near 90°). This observation can be explained by the higher

Figure 3. (a) Outward fluxes of O\(^+\) ions above 30 eV as a function of total crustal magnetic field strength from 250 to 750 km. (b) Outward fluxes of O\(^+\) ions above 30 eV as a function of crustal field strength in three different solar zenith angle (SZA) bins. (c) Net flux (outward minus inward) of O\(^+\) ions above 30 eV as the strongest region of Martian crustal field rotates to the dayside (red) or back to the nightside (blue). Strong crustal field region here means the longitude range between 120° and 240° on Mars. Both three figures show fluxes with standard errors.
ionization rate and peak density of the ionosphere in the subsolar region. The observations above show that Martian crustal fields reduce the dayside outward energetic $O^+$ ion flux, but we need to calculate the net flux of these $O^+$ ions to quantify the crustal field’s protective effect on global escape rates. The averaged flux is calculated through the average flux in $5 \times 5$ bins of longitude and latitude. We define net flux as the averaged upward flux minus the averaged downward flux and separately compute these when the strongest crustal fields (longitude between $120^\circ$ and $240^\circ$) face to the Sun or when they rotate to the nightside (when the weak crustal field region points sunward, Figure 3c). The red solid line in Figure 3c shows the averaged net flux of high energy O$^+$ ions when the strongest crustal field points sunward and the blue solid line when the weak crustal field points sunward. Standard errors of both lines are also shown in the figure. The averaged net flux is much lower when the strongest crustal field points sunward at altitudes below 1,000 km, which confirms the observations shown in Figures 1 and 2d and is consistent with model results by Ma and Nagy et al. (2004) and Ma et al. (2015). The difference reaches a maximum at 400 km of nearly 35% of the net flux above the strongest crustal fields. Above 1,000 km the effect of the crustal field declines quickly in agreement with earlier observations by the Mars Express mission (Ramstad et al., 2016).

4. Discussion

Four years of statistical results presented in Figure 1 show a low flux region of high energy $O^+$ ions above Martian crustal fields. Earlier observations by the Mars Express spacecraft (Lundin et al., 2011) show a north-south asymmetry in the global $O^+$ flux pattern, but escape rates for the two hemispheres in the Martian tail were almost equal. Nilsson et al. (2011) used more than 4 years of MEX observations from the Martian day, night, dusk, and dawn regions and also identified a north-south asymmetry in ion escape rates, suggesting that crustal fields may reduce heavy ion escape rates. Model results by Fang et al. (2010) show that without the shielding effect by crustal fields, the escape rates in the Martian tail would increase by a factor of two. Another study using 8 years of observation by MEX showed that escape rates calculated in the nightside of the planet are almost the same for the two hemispheres and are also independent of SZA (Ramstad et al., 2016). In this work we also showed that the crustal field’s reduction effect on high energy $O^+$ ions is more clearly observed in the near subsolar region than at the terminator in Figure 3b.

To address the question whether the observed minimum of upward energetic O+ fluxes is reflected in the O+ densities, we show in Figures 4a–4c the density distribution of energetic O+ ions as a function of latitude and longitude for different altitudes. We observe that regions of low upward flux above crustal fields correspond to regions of low energetic O+ density. This indicates that the flux depletion above strong crustal fields may be caused by limited supply of energetic O+ ions. When we now compare the global density distribution of high energy $O^+$ ions with the respective low energy density distribution between 300- and 500-km altitude (Figures 4d–4f), one can observe that exactly in the region where a depletion appears in the high energy $O^+$ distribution, a corresponding accretion emerges in the distribution of low energy $O^+$ ions. This phenomenon of higher densities of low energy particles above crustal fields is also consistent with observations of the total plasma density made over 10 years by the Mars Advanced Radar for Subsurface and Ionospheric Sounding instrument onboard Mars Express (Andrews et al., 2015). These observations by Andrews et al. (2015) reveal an enhancement of plasma densities above crustal field regions between 300- and 1,200-km altitude, similar to our results in Figures 4d–4f. Observations by the MGS spacecraft also suggest that the temperature of the neutral atmosphere in the southern hemisphere is lower than in regions without crustal field (Krymskii et al., 2003). The stronger crustal fields may trap low energy $O^+$ ions, but above region without crustal field low energy plasma is free to expand to higher altitudes, as indicated by model results from Matta et al. (2015).

Our results support the concept that crustal fields can trap low energy ions and prevent them from being accelerated to a higher speed (e.g., Brain et al., 2017; Fang et al., 2017). Brecht and Ledvina (2014) investigated the velocity distribution of O+ ions in a numerical model, and their results show that solar minimum loss rates above crustal field regions are one order lower than above regions without crustal field. A more detailed model by Fang et al. (2015) suggests that the crustal field may reduce planetary ion loss rates when it rotates to the subsolar region, consistent with our results of a low flux region forming above crustal magnetic fields between 300 and 600 km in high energy $O^+$ ions. But Fang et al. (2015, 2017) also suggest an
increase of ion loss rates when crustal fields rotate to the terminator by an enhancement of day-night transportation. This might be observable in low energy ions, but these are not being discussed in this paper. When considering altitudes above 1,000 km, the difference of escape rates between crustal field regions and regions without crustal fields is very small, also in agreement with the model results by Egan et al. (2019).

5. Conclusions
In summary, both outward fluxes and averaged net fluxes of high energy O\(^+\) ions show a distinctly low flux region above the strongest crustal field region for altitudes below 1,000 km. The maximum reduction of the global escape flux reaches nearly 35% when the strongest crustal field region faces toward the Sun. This indicates a "shielding" effect of the Martian crustal field. Physical processes of how this low flux region forms still need to be investigated, but a tentative explanation may be that the crustal field prevents the low energy ions from being captured or accelerated by the induced interplanetary electric field which acts at higher altitudes. This can explain the higher density of low energy O\(^+\) ions above the crustal field region. As for high energy O\(^+\) ions, these cannot be generated within the crustal field loops because the external accelerating field cannot act there. But outside of the crustal field region ions can flow upward uninhibited and easily reach altitudes where the external accelerating field can act (e.g., Dong et al., 2015; Luhmann, 1991; Wei et al., 2017). The Martian crustal field’s "shielding" effect at lower altitudes may prove that the Martian crustal field can protect a planet's atmospheric ions from erosion by the solar wind (Lundin et al., 2011; Nilsson et al., 2011). The presence of a global magnetic field may increase the interaction area and the energy received from the

![Figure 4](https://example.com/figure4.png)

Figure 4. Maps of the density distribution of the O\(^+\) ions as a function of aerographic latitude and longitude from 375- to 475-km altitude. Colors depict the median density in log10 scale. Figures (a)-(c) are for O\(^+\) ions with energy above 30 eV as (b)-(d) are for less than 30 eV. The black line is contour of crustal field regions.
solar wind, but these extra energies may not be available to be transferred to low energy ions directly. Earth's strong intrinsic magnetic field probably protects its atmospheric particles from being lost and has a significant effect on the evolution of Earth's atmosphere and life. A lack of an Earth-like dipole magnetic field may result not only in the disappearance of surface water but also in a much lower probability for a planet's habitability (e.g., Lammer et al., 2008; Wei et al., 2014).

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