Heavy Ion Escape From Martian Wake Enhanced by Magnetic Reconnection

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Abstract Mars is a dry planet with a history of a warm and wet environment. Hydrogen and oxygen continuously escape from the unmagnetized planet. Although the heavy ion escape rate in the wake region is low due to Mars' obstruction, there are reports of events with bursty and enhanced ion escape. Here, we first find the evidence of the Alfvenic dayside-produced plasma clouds accelerated by magnetic reconnection, which provides an explanation for the wake bursty mass escape by the observations from the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft. In the event reported by this study, two types of flux ropes were successively observed in the magnetic reconnection exhaust in the Martian wake. One is generated by the reconnection, while others are produced by dayside boundary instability. The ions convected from the dayside, as well as the local original ions, can both be accelerated to be Alfvenic and expelled in the Martian tail by reconnection. The oxygen escape rate in the reconnection exhaust is estimated to be a quarter of the previous statistical result in the entire wake region.

Plain Language Summary Although current Mars has a very thin atmosphere, it is generally believed that ancient Mars had a thicker atmosphere. Ion escape plays a key role in the Martian atmosphere evolution. The escape rate behind Mars should be low in the wake. However, recent observations find explosive bulk plasma escape processes in this region, which are poorly understood. Based on observations in the Martian tail region by the Mars Atmosphere and Volatile EvolutioN mission, we report observations of helical magnetic structures of different origins during a single crossing of MAVEN's nightside. For the first time, we propose that tail reconnection acts as an accelerator for the ions which are brought from the dayside ionosphere. These ions can speed up in the wake region and get expelled away from Mars. Our research enhances the role of magnetic reconnection on the ion escape process of Mars, compared with the previous understanding.

1. Introduction

Mars has no global magnetic field (Acuna et al., 1999; Jakosky, Grebowsky, et al., 2015), though there are localized regions across the planet's surface with crustal magnetization (Acuna et al., 2001). As a consequence, solar wind interacts almost directly with the Martian upper atmosphere and ionosphere. The solar wind erosion of the Martian atmosphere may explain the dehydration of present-day Mars (Brecht & Ledvina, 2007; Kass & Yung, 1995). Ion escape, in particular, through magnetotail or plasma wake, is a significant part of Martian atmospheric escape in the present time (Barabash et al., 2007; Dubinin et al., 1993). The main ion escape channels for Mars involve pickup ion plume, loss through tail plasma sheet, and loss due to pickup of exospheric oxygen upstream from the planet (Brain et al., 2015; Dong et al., 2015, 2017; Dubinin et al., 2011, 2017; Lillis et al., 2015; Lin et al., 2021). Ion escape through the tail or the wake region, however, should be inefficient because of Mars' obstruction. It has been reported that bursty and efficient ion escape processes exist in tail regions (Dubinin et al., 2012, 2021). A similar process occurs in the Venusian tail (Zhang et al., 2012), suggesting this process should be a common characteristic of unmagnetized planets.

Magnetic reconnection is a fundamental process that dissipates magnetic energy (Biskamp, 1996; Giovanelli, 1946; Priest & Forbes, 2000) and depletes celestial bodies' charged particles, resulting in phenomena such as solar coronal mass ejection (Chen, 2011), disconnection of the comet tail (Russell et al., 1986), and atmospheric ion loss
in planets (Russell et al., 1998). Magnetic flux ropes often are identified in reconnection exhaust and diffusion regions (Chen et al., 2007; Drake et al., 2006), with spatial scales ranging from electron inertial length (Wang et al., 2015) to ion inertial length (Eastwood et al., 2005). The flux ropes in the Martian ionosphere were first reported by Morgan et al. (2011) using observations by Mars express. Eastwood et al. (2012) found flux ropes associated with magnetic reconnection in the Martian tail by measurements from Mars Global Surveyor (MGS). Later, similar discoveries had been reported by DiBraccio et al. (2015) based on Mars Atmosphere and Volatile EvolutioN (MAVEN) data. They wrap substantial amounts of plasma and cause large-scale ion escape during their release from the planetary tail (Zhang et al., 2012). Such flux rope structures can also be formed in the Martian dayside ionosphere by macroscopic instabilities because of the plasma flow shear and subsequently dragged into the tail (Elphic & Russell, 1983; Wolff et al., 1980). Thus, to evaluate the effect of magnetic reconnection on ion escape, it is necessary to assess the ion content within flux ropes of different origins. Here we first report an event with two different types of flux ropes observed during a single crossing of the Martian magnetotail current sheet, which provides an opportunity to study the impact of the reconnection to the dayside-original flux ropes. We start with data and method introduction. A series of flux ropes during a tail current sheet crossing are presented in the observation. Finally, the discussion and conclusion are given.

2. Data and Methodology

The fields and particles data used in this study are from the MAVEN mission (Jakosky, Lin, et al., 2015). The calibrated 1 s magnetic field measurements are provided by the MAVEN magnetometers (MAG) (Connerney et al., 2015). The Suprathermal and Thermal Ion Composition (STATIC) instrument measures the energy spectra of ion fluxes in the range of 0.1 eV–30 keV and the ion composition (McFadden et al., 2015). Utilizing the publicly available Space Physics Environment Data Analysis System (SPEDAS) software (Angelopoulos et al., 2019), we calculate ion velocity moments from high time resolution (4 s) STATIC “d1” data products, which includes 32 energy bins, 8 ion mass bins, 16 azimuth bins, and 4 elevation bins. Electron measurements are made by the Solar Wind Electron Analyzer (SWEA) (Mitchell et al., 2016). It is designed to measure the energy and angular distribution of photo- and solar-wind electrons in the 3–4,600 eV energy range in 64 bins, with a resolution of ΔE/E ~ 17% and a maximum cadence of 2 s.

In this article, we introduce a method to calculate the axial orientation and the handedness of a flux rope. This method is valid regardless of whether or not the flux rope is force-free and is based only on single-spacecraft measurements. The magnetic observation signature of a flux rope is susceptible to its orientation, as well as the spacecraft trajectory through the flux rope. The LMN coordinates obtained from the minimum variance analysis (MVA) (Sonnerup & Scheible, 1998) has been proven to be advantageous in determining the orientation and structure (e.g., Bowers et al., 2021; Briggs et al., 2011; Hara et al., 2022; Sibeck et al., 1984; Vignes et al., 2004). The L, M, and N represent the maximum, intermediate, and minimum variance direction, and their corresponding eigenvalues are λ_L, λ_M, and λ_N, respectively. When the intermediate-to-minimum (λ_M/λ_N) eigenvalue ratio is greater than 5, the MVA coordinate system is well determined (Hara et al., 2014a, 2014b).

According to the characteristics of azimuthal and axial fields (bipolar for the azimuthal and unipolar for the axial) of flux ropes, we calculate [\sum B_ξ] / [\sum B_ξ] in the flux rope LMN coordinate system, where ξ represents L^FR or M^FR and j is the temporal index. The larger (smaller) one corresponds to the axial component (azimuthal component). We define the sign of the helicity as h = sign(S)·sign((V_p - V_q)·N^FR). The positive (negative) helicity means that the handedness of a flux rope is right-handed (left-handed). The term S = N^FR·[\sum B_ξ]·M^M,j+1 is the directional area on the B_L·B_M plane. Its magnitude denotes the integral area, and the positive (negative) sign denotes the +N^FR (−N^FR) direction. The term (V_p − V_q)·N^FR means the sign of observed helicity is also associated with the relative trajectory of crossing. V_p and V_q are the velocities of the protons and the satellite, respectively.

3. Observations

On 1 March 2020, the MAVEN orbiter experienced a southward crossing of the tail current sheet. It successively grazed three flux ropes, as depicted in Figure 1a. The spacecraft was located in the near-Mars tail at around [−1.2, 0.7, 0.4] R_M (radius of Mars, 1R_M = 3,389.5 km) in the Mars-centered Solar Orbital (MSO) coordinates. The MSO coordinate system is defined with the X-axis pointing from Mars toward the sun, the Z-axis perpendicular to the planet’s orbital plane and toward the geographic north, and the Y-axis completing the right-handed
coordinate system. The Magnetometer observed a reversal in the $B_x$ component (Figure 1c) and simultaneously a depression of $|B|$ (Figure 1b) around 10:14:30 UT, indicating that MAVEN crossed the tail current sheet (DiBraccio et al., 2015; Harada et al., 2020; Rosenbauer et al., 1989; Yeroshenko et al., 1990). The crustal magnetic field obtained from the spherical harmonic model (Morschhauser et al., 2014) is vanishingly small throughout the interval (Figure 1b). The energetic ion population (up to a few hundreds of eV) shown in Figure 1f also implies that MAVEN crossed the current sheet (Dubinin & Fraenz, 2015; Dubinin et al., 1993). Figure 1d shows that the current sheet is embedded in a relatively wide channel of plasma flow mainly in the anti-sunward direction. STATIC recorded multiple ion species, including $H^+$, $O^+$, and $O_2^+$ ions, across the current sheet (Figure 1g). Heavy ions are more abundant than protons (Figure 1e).

Referring to Figure 1b, three evident local magnetic field enhancements were detected during the current sheet crossing. Simultaneously, distinct bipolar variations in the $B_z$ component appear around $|B|$ peaks (Figure 1c), showing the characteristic features of flux ropes. For convenience, we name the three flux ropes FR1, FR2, and FR3.
FR3. Note that the axial core field of FR1 and FR3 is mainly in the \( X \) direction, while FR2 mainly aligns with the \( Y \) direction, implying that FR1 and FR3 may have different origins from FR2.

### 3.1. Magnetic Reconnection and the Flux Rope Embedded in the Current Sheet

As shown in Figure 2, we investigate the MAVEN measurements within the overall current sheet (CS) coordinates. To obtain the overall current sheet coordinate system, we apply MVA on \( \mathbf{B}_{\text{CS}} \) observed between 10:13:00 and 10:16:40, after removing the signals of the flux ropes (three intervals of 10:14:09–10:14:26 UT, 10:14:51–10:15:26 UT, and 10:15:41–10:16:16 UT) from original data (where \( \mathbf{B}_{\text{CS}} = \mathbf{B} - \mathbf{B}_{\text{FR}} \)). This yields \( \mathbf{I}_{\text{CS}} = [0.99, -0.12, 0.03] \), \( \mathbf{M}_{\text{CS}} = [0.09, 0.85, 0.53] \), \( \mathbf{N}_{\text{CS}} = [-0.08, -0.52, 0.85] \) relative to the MSO coordinates. The angular standard deviation of eigenvector \( \mathbf{L}_{\text{CS}} \) toward or away from eigenvector \( \mathbf{M}_{\text{CS}} \) is about \( \pm 0.2^\circ \). The ratio of eigenvalues \( \lambda_M/\lambda_N \sim 51.0 \) and \( \lambda_M/\lambda_N \sim 5.6 \), demonstrating a clear differentiation of the maximum, intermediate, and minimum variance axes. During this event, the ion flow speed is higher than the spacecraft’s on-orbit speed, corresponding to a crossing with the current sheet overtaking the spacecraft (Halekas et al., 2009; Harada et al., 2017). We determine the LMN coordinate by ensuring positive dot products between the speed, corresponding to a crossing with the current sheet overtaking the spacecraft (Halekas et al., 2009; Harada et al., 2017). Figure 2g exhibits the electron differential energy flux from SWEA. Enhancements of energetic electron flux above 500 eV can be seen during the crossing of the current sheet. Time slices of the electron phase-space density near the core regions of the three flux ropes are provided in Figures 2h–2j. The spectral shapes in these regions are different. Electrons within FR1 and FR3 display approximate Maxwellian distributions. Within FR2, there is a non-thermal population with a power-law distribution (within 177–251 eV with a power-law index \( \gamma \) of \( \sim 1.8 \)), which is consistent with the electron energy spectrum generated in magnetic reconnection exhaust (Egedal et al., 2012; Oka et al., 2018). This evidence indicates that FR2 is generated by reconnection and expelled quickly from the X-line in the exhaust.
3.2. Flux Ropes on the Edge of the Current Sheet

We also perform MVA on the magnetic field measurements of FR1 and FR3 (Figure 3). This yields \( \mathbf{L}_{\text{FR1}} = [0.68, -0.43, -0.59] \) MSO, \( \mathbf{M}_{\text{FR1}} = [-0.39, 0.47, -0.8] \) MSO, \( \mathbf{N}_{\text{FR1}} = [0.62, 0.77, 0.16] \) MSO, \( \lambda_{L}/\lambda_{N} \sim 52.8 \); \( \mathbf{L}_{\text{FR3}} = [-0.23, 0.2, -0.8] \) MSO.
−0.5, 0.83] MSO, \( M_{FR3} = [0.89, 0.24, 0.39] \) MSO, \( N_{FR3} = [-0.4, 0.83, 0.39] \) MSO, \( \lambda_M/\lambda_N \sim 10.5 \). The angular standard deviation between \( L_{FR1} (L_{FR3}) \) and \( M_{FR1} (M_{FR3}) \) is about ±4.5° (±5.2°). The axes of FR1 and FR2 are \( L_{FR1} \) and \( M_{FR3} \), respectively (Figures 3a and 3c). Both axes are quasi-perpendicular (128° and 119°) to the cross-tail direction of the current sheet. Hodograms on the \( L_{FR}–M_{FR} \) plane show that the magnetic field variations of FR1 occur mainly in quadrants 1 and 4 and rotate clockwise (Figure 3b), whereas that of FR3 occurs mainly in quadrants 1 and 2 and rotates counterclockwise (Figure 3d). Because the signs of \( (V_p - V_S) \cdot N_{FR} \) are positive for both of them, the helicity of FR1 and FR3 are left-handed and right-handed, respectively. The quasi-perpendicularity between the axis and \( M_{CS} \), as well as the opposite helicities of the flux ropes on either side of the current sheet, suggest they may be generated by dayside ionospheric instabilities and dragged into the tail by the solar wind. The criterion and result are consistent with previous research (e.g., Hara et al., 2022, 2017b; Luhmann & Cravens, 1991).

To compare the MAVEN observations with the theoretical prediction, we study the configuration of magnetic field lines hanging on the dayside ionosphere. In this event, MAVEN traveled from the nominal bow shock and magnetic pile-up boundary (Trotignon et al., 2006) to the site adjacent to the current sheet during 09:05:00–10:10:00 UT (Figure 4a). Four snapshots of the magnetic field clock angle \( \theta = \arctan(B_{MCS}/B_{NCS}) \) on the \( M_{CS}–N_{CS} \) plane are shown along the orbit. A clock angle of 0° (90°) corresponds to a direction in the +\( N_{CS} \) (MCS) direction. During this time, the clock angle changed less than ±15° from the Martian magnetosheath to the tail current sheet, suggesting that the orientation of the incoming and hanging interplanetary magnetic field (IMF) barely changed on the \( M_{CS}–N_{CS} \) plane. The magnetic field vector on the \( M_{CS}–N_{CS} \) plane is approximately along the \( -N_{CS} \) direction after MAVEN was deep into the near-Mars induced magnetosphere. FR1 (FR3) was observed by the spacecraft in the +\( M_{CS} \) (−\( M_{CS} \)) hemisphere. As shown in the schematic (Figure 4b), the velocity shear between the magnetosheath and the ionosphere could lead to field line twisting and rolling up to form a flux rope. In this scenario, the twisted field lines on the two sides of the current sheet rotate in opposite directions (Luhmann &
The observed opposite helicities of FR1 and FR3 are in good agreement with this theoretical prediction, given that FR1 and FR3 were observed on either side of the current sheet.

4. Discussion

As a helical twisted magnetic field structure, flux ropes have been observed throughout space plasma. At Mars, they are widely considered to form as consequences of reconnection between overlaid IMF and crustal field (e.g., Hara et al., 2014b; Vignes et al., 2004) or between the overlaid IMF (e.g., Eastwood et al., 2012), as well as plasma instability (e.g., Hara, Brain, et al., 2017). The event reported in this work provides a natural experiment to compare the characteristics of the two types of flux ropes under the same field and plasma condition and reveal the impacts of tail reconnection to the dayside-original plasmas.

Halekas et al. (2016) presented a preliminary interpretation of bulk plasma loss from Mars: planetary heavy ions derived from the Martian atmosphere can be lost in the form of coherent structures or clouds dislodged from the ionosphere by a “snowplow” effect. If continuous, this process could contribute up to 20% of the global total ion escape from Mars. Shear instabilities that occur at a low altitude between sheath plasma and ionosphere could play a role in the clouds’ initial developing stage. The plasma of dayside-clouds origin is frequently streaming into the magnetotail. This process continues to provide plasma sources for the wake region. Magnetic reconnections in the wake could efficiently accelerate the plasmas and cause bursty loss of heavy ions in the tail.

The mean tailward ion fluxes in the reconnection exhaust region are about $2.5 \times 10^6$ cm$^{-2}$s$^{-1}$ and $4.4 \times 10^6$ cm$^{-2}$s$^{-1}$ for O$^+$ and O$_2^+$, respectively (Figure 2e). Observations have found that the length of the cross-tail current of Mars is even larger than the diameter of the planet (Ramstad et al., 2020). We assume that the exhaust region extended to the length of the diameter of Mars. In the current sheet normal direction, we obtain the width of the exhaust by the time integration of the relative speed of the satellite and the current sheet. The O$^+$ escape rate during this reconnection (3.6 $\times 10^{23}$ s$^{-1}$) is estimated to be about 20%–28% of the average tailward ion escape rate (1.3–1.8 $\times 10^{24}$ s$^{-1}$) (Dong et al., 2015), and the total O escape rate (1.0 $\times 10^{24}$ s$^{-1}$) to be about 23% of the mean total O escape rate (4.4 $\times 10^{24}$ s$^{-1}$) in the wake region (Inui et al., 2019). Thus, the heavy-ion escape through the reconnection outflow region is significant for Martian ion escape. Note that the observed densities (about 0.7 cm$^{-3}$ for O$^+$ and 1.2 cm$^{-3}$ for O$_2^+$) of oxygen ions in this event are lower than that in the typical plasma sheet (Inui et al., 2019). The oxygen ion escape caused by the reconnection in this study may even have been underestimated. The oxygen ion fluxes within FR1, FR2, and FR3 are estimated to be $(4.8 \pm 1.5) \times 10^6$ cm$^{-2}$s$^{-1}$, $(1.2 \pm 0.6) \times 10^7$ cm$^{-2}$s$^{-1}$, and $(2.9 \pm 2.1) \times 10^6$ cm$^{-2}$s$^{-1}$. Note that the standard deviation is large because of the dispersive distribution of $\rho V$. The flux ropes convected from the dayside are embedded in the Alfvénic flow (Figure 1d), meaning they are...
pushed and accelerated by the reconnection outflows. If they haven’t been accelerated the fluxes would decrease by about 50%. Hence, we propose the possibility of enhanced ion escape caused by the dayside-produced flux ropes driven by reconnection. The bursty escape can also result from the acceleration of local ions by reconnection. They may both play important roles in global oxygen loss.

In the current sheet normal direction, the spacecraft velocity is about ~2.9 km/s, and the average proton velocity is ~3.6 km/s, so the half-width of the current sheet is ~720 km, given the crossing time is ~220 s. We also derive ion inertial lengths of ~700 km for H⁺ (dn), ~1,320 km for O⁺, and ~1,250 km for O²⁺ from the average ion densities during the crossing of the current sheet (see Figure 1e). Previous studies also demonstrated that the tail current sheet thickness is on the ion scale, and even the sub-ion scale (Grigorenko et al., 2019; Harada et al., 2015, 2020). Theoretically, magnetic reconnection can be triggered only after a current sheet becomes thinner than dn (Fujimoto, 2006; Paschmann et al., 2013). Thus, magnetic reconnections in the Martian tail may occur frequently and continuously enhance the loss of the mass originating from the wake and the dayside. This enhancement of ion escape due to reconnection should also occur on other non-magnetized planets like Venus.

5. Conclusion

In this article, a series of flux ropes were observed in the magnetic reconnection exhaust during the MAVEN's crossing of the Martian tail current sheet. This event shows characteristic reconnection features - Alfvénic outflows, Hall fields, and non-thermal electron distribution. The reconnection is a component reconnection with a weak guide field. The axis of one flux rope almost aligns with the cross-tail direction of the current sheet, suggesting that it is generated by magnetic reconnection. The other two were located on either side of the current sheet. Their axes are quasi-perpendicular to the tail current and exhibit opposite magnetic helicities, which are well consistent with the flux ropes formed in the dayside ionosphere due to the instabilities caused by the plasma flow shear and subsequently be dragged into the tail (Elphic & Russell, 1983; Harra, Harada, et al., 2017; Wolff et al., 1980). Interestingly, oxygen ions wrapped by the two types of flux ropes are both accelerated and expelled away from Mars by the reconnection, which advances our understanding of the role of reconnection for Martian ion loss.

Data Availability Statement

The data analyzed in this study are publicly available on NASA’s Planetary Data System: MAVEN calibrated MAG data (Connerney, 2017), MAVEN calibrated SWEA data (Mitchell, 2017), and MAVEN calibrated STATIC data (McFadden, 2021). All derived data products are available and hosted online (Wang, 2022).

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