South-north asymmetry of proton density distribution in the Martian magnetosheath

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Key Points:
- In the Martian Magnetosheath, protons are denser in the southern hemisphere than in the northern hemisphere.
- A south-north asymmetry of the crustal magnetic fields is the most likely cause of the observed asymmetry in proton number densities.
- The higher density of protons in the southern hemisphere is accompanied by high pressures.

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Abstract: We perform a statistical analysis of data from the Mars Atmosphere and Volatile Evolution (MAVEN) project on the global distribution of protons in the Martian magnetosheath. Our results show that the proton number density distribution has a south-north asymmetry. This south-north asymmetry is most likely caused by the south-north asymmetric distributions of the crustal magnetic fields at Mars. The strong crustal magnetic fields push the inner boundary of magnetosheath to a higher altitude in the southern hemisphere. Due to the outward movement of the inner boundary of the magnetosheath, a compressed magnetosheath forms, causing subsequent increases in proton number density, thermal pressure, and total pressure. Eventually, a balance is reached between the increased total pressure inside the magnetosheath and the increased magnetic pressure inside the induced magnetosphere. Our statistical study suggests that the Martian crustal magnetic fields can strongly affect the proton number density distribution in the Martian magnetosheath.

Keywords: Martian magnetosheath; south-north asymmetry; proton density distribution; crustal magnetic field

1. Introduction

Because it lacks an intrinsic global magnetic field, Mars has a magnetosphere distinct from that at the Earth (e.g., Acuña et al., 1998). The solar wind, which flows out from the Sun and pervades our solar system, is directly deflected by the Martian upper atmosphere and ionosphere. A plasma of Martian atmospheric origin forms the primary global obstacle to the solar wind, shielding the planet through induction and mass loading. This obstacle, termed the Martian induced magnetosphere, is much smaller than that formed by the terrestrial intrinsic magnetic field (Halekas et al., 2017b). Nevertheless, both Earth and Mars possess a bow shock and magnetosheath that decelerate and deflect the solar wind flow around their magnetospheres and magnetotails (Bertucci et al., 2011; Dubinin et al., 2006a; Mazelle et al., 2004; Nagy et al., 2004).

The solar wind directly interacts with Mars near the boundary between the Martian magnetosheath and induced magnetosphere, where the dynamic pressure of the solar wind is supposed to be balanced by the thermal pressure and magnetic pressure of the ionosphere. After having been decelerated and heated by the bow shock, the proton flows stop entering into the Martian ionosphere near a boundary, where the dominated plasma is converted to the planetary-originated plasma. This boundary is defined as the ion composition boundary (ICB) (Breus et al., 1991; Sauer et al., 1994). In the vicinity of the ICB, a sharp and strong magnetic field pile-up, termed the Magnetic Pileup Boundary (MPB), was detected by both the Mars Global Surveyor (MGS) and Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft. This boundary is also known as the Induced Magnetosphere Boundary (IMB), or Plasma Depletion Layer (PDL) (Acuña et al., 1998; Bertucci et al., 2005; Vignes et al., 2000; Øieroset et al., 2004; Matsunaga et al., 2017). MGS measurements have demonstrated that electrons drop significantly from the post-shock to the end of the magnetic field pile-up. Plasma is squeezed away by the high magnetic pressure along the field lines upstream of Mars, in common with the generation of the PDL upstream of the Earth’s magnetopause. However, the small scale of the Martian induced magnetosphere leads to a complicated magnetosheath, through the participations of picked-up heavy ions and cold proton corona from the exosphere (Chaffin et al., 2015; Dubinin et al., 2006b; Feldman et al., 2011).

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The Martian induced magnetosphere is partially due to localized crustal magnetic fields, mostly located in the planet’s southern hemisphere. The altitude of the MPB detected by MGS is higher in the southern hemisphere than in the northern hemisphere (Crider et al., 2002). Based on a statistical analysis by MAVEN, the IMB, the ICB, and the pressure balance boundary all tend to be located at higher altitudes in the southern hemisphere (Matsunaga et al., 2017). Apart from the Martian magnetospheric boundaries, the bow shock and magnetosheath structure are also perturbed by the crustal magnetic fields (Brain et al., 2005; Dong CF et al., 2015; Edberg et al., 2009; Fang XH et al., 2017; Luhmann et al., 2002; Ma YJ et al., 2014; Mazelle et al., 2004).

MAVEN, equipped with high-resolution magnetic field and particle instruments and having collected a sufficiently large data set, provides us an unprecedented opportunity to investigate features of the Martian magnetosheath.

2. Instruments and Data

The proton number density is detected by MAVEN’s onboard Solar Wind Analyzer (SWIA). The SWIA is an electrostatic analyzer able to measure ions over an energy range of 30 eV to 25 keV, at a maximum angular range of 360° × 90°, and with a 4 s intrinsic time resolution (Halekas et al., 2015). Through monitoring towards the Sun, the instrument provides adequate observations of solar wind and the heated solar wind ions behind the bow shock. In the Martian magnetosheath, the heated solar wind proton is the dominating ion species. Although some heavy ions can be picked up by the solar wind, the total ion number density is not greatly affected. Thus, we use ion densities calculated from the onboard ion distribution functions to represent the proton number densities in the Martian magnetosheath.

Based on the measurements from MAVEN/SWIA over the period between 10 October 2014 and 14 May 2017, we perform a statistical analysis of the global proton density distribution in the Martian magnetosheath. Similar to the case on Earth, the proton spectra in the Martian magnetosheath have significant wider energy ranges than those upstream of the bow shock, and have much more flux than those in the induced magnetosphere. Thus, the time intervals when MAVEN is located between the bow shock and the ICB are selected according to the proton spectra from the SWIA. In the present study, all measurements are in the Mars Solar Orbital (MSO) coordinates. In the MSO coordinates, the X-axis

![Figure 1](image)

Figure 1. The MAVEN trajectories in the Martian magnetosheath in the Mars-centered Solar Orbital (MSO) coordinates with units of Mars radii ($R_M = 3397$ km) from 10 October 2014 to 14 July 2017. Projections on (a) $X_{MSO}$-$Y_{MSO}$ plane with $|Z_{MSO}| < 1R_M$, (b) $X_{MSO}$-$Z_{MSO}$ plane with $|Y_{MSO}| < 1R_M$, (c) $X_{MSO}$-$Z_{MSO}$ plane, (d) a cylindrical $X_{MSO}\sqrt{Y_{MSO}^2 + Z_{MSO}^2}$ plane. The $0.15 \times 0.15R_M$ bins with number samples less than 100 are white color-coded.
points from Mars to the Sun, the Y-axis is opposite to Mars' orbital velocity, and then the Z-axis is defined to complete the right-handed coordinate system.

3. Statistical Results

Figure 1 shows the sample numbers of MAVEN observations in the XY_{MSO} plane with \(|Y_{MSO}| < 1 R_M\), XZ_{MSO} plane with \(|Y_{MSO}| < 1 R_M\), YZ_{MSO} plane and XR_{MSO} plane (\(r_{MSO} = \sqrt{Y_{MSO}^2 + Z_{MSO}^2}\)) with units of Mars radii (\(R_M = 3397\) km), respectively. The number of samples has a nearly uniform global distribution, thus providing enough data coverage to obtain the statistical properties of the global proton density distribution in the Martian magnetosheath. To make the statistical results meaningful, the 0.15 x 0.15 R_M bins with number samples less than 100 are white color-coded and are subsequently excluded from our study.

Figure 2, in the same format as Figure 1, shows the statistical properties of the global proton density distribution in the Martian magnetosheath. The proton number densities in the dayside (> 6 cm\(^{-3}\)) are obviously larger than those in the nightside (< 3 cm\(^{-3}\)). As they get closer to Mars, the proton number densities fall gradually from ~6 cm\(^{-3}\) down to 2 cm\(^{-3}\) in the flank regions (~1R_M < X_{MSO} < 0). Consistent with previous studies (Halekas et al., 2017a, b), as X_{MSO} decreases from 1.5R_M to -0.5R_M, the peaks of the proton number density are farther away from Mars (from ~1R_M to 2.5R_M). As shown in Figure 2a, the proton number densities show slight dawn-dusk asymmetry, particularly for those in the flank regions (|Y_{MSO}| > 1.5R_M). Besides the dawn-dusk asymmetry, the proton number densities also show notable south-north asymmetry in the dayside regions (X_{MSO} > 0, Figure 2b), especially for those in the regions of |Y_{MSO}| < 1R_M (Figure 2c).

To reveal the relationship between the south-north asymmetry and the crustal magnetic fields, Figure 3 shows the number of samples and the proton number densities as a function of geographic longitude and latitude, using the measurements at X_{MSO} > 0 and |Y_{MSO}| < 1R_M. The superposed black lines are contours of the crustal magnetic field at altitude = 400 km from Morschhauser’s model (Morschhauser et al., 2014). The number samples in each 12° x 12° bin are sufficiently large (> 500) to perform statistical analysis. Clearly, the proton number densities in the southern hemisphere are much larger than those in the northern hemisphere, namely “the south-north asymmetry”, which is caused mainly by the crustal magnetic field. The proton number densities show insensitivity to variations of longitude in the northern hemisphere; in the southern hemisphere, however, they are concentrated mainly in the longitude range of 120°–240°. The southern hemisphere crustal magnetic fields at Mars are strongest in this longitude range of 120°–240° (Morschhauser et al., 2014), and thus this feature probably is the greatest contributor to the
higher proton number densities observed in this region. According to a previous statistical research by MAVEN (Halekas et al., 2017a), interplanetary conditions have limited effect on the south-north asymmetry of proton number density in the Martian magnetosheath. The statistical results show that the density and velocity of the magnetosheath plasma appear remarkably symmetric in both the $X$-$Y$ and the $X$-$Z$ planes in aberrated Mars Solar Electric (MSE) coordinates, and both the IMF direction and the massloading process have a relatively weak effect on asymmetries of the magnetosheath (Halekas et al., 2017a). To explain the generation of the proton south-north asymmetry and the proton concentration in the southern hemisphere, we show the dynamic pressure (Figure 4a), thermal pressure (Figure 4b), magnetic pressure (Figure 4c) and total pressure (Figure 4d) in the same format as Figure 3. The dynamic pressure is nearly symmetric about the

Figure 3. The MAVEN trajectories and mean proton number densities in the magnetosheath as a function of areographic longitude and latitude with $X_{\text{MSO}} > 0$ and $|Y_{\text{MSO}}| < 1R_{\text{M}}$. The superposed black lines are contours of the crustal magnetic field at altitude = 400 km from Morschhauser’s model (Morschhauser et al., 2014).

Figure 4. The distribution of mean proton dynamic pressure, thermal pressure, magnetic pressure, and total pressure in Martian magnetosheath in the same format as Figure 3.
areographic equator. Unlike the dynamic pressure, the thermal pressure and the magnetic pressure in the southern hemisphere are generally stronger than those in the northern hemisphere, especially in the southern longitude range of 120° – 240°. In fact, the distributions of the crustal magnetic pressure are generally consistent with the distributions of the crustal magnetic field at Mars (Morschhauser et al., 2014; Connerney et al., 2015). Due to the existence of the crustal magnetic fields, the inner boundary of the Martian magnetosheath is pushed to a higher altitude in the southern hemisphere than in the northern hemisphere (Matsumaga et al., 2017). Consequently, the magnetosheath is compressed in the southern hemisphere, since the location of the bow shock (the outer boundary of the Martian magnetosheath) is slightly affected. The compressed magnetosheath further causes the increases in proton number density and in thermal pressure. Overall, the stronger total pressure in the southern hemisphere is generated to balance the increased magnetic pressure inside the induced magnetosphere.

4. Concluding Remarks
Using the MAVEN/SWIA data set from 10 October 2014 to 14 May 2017, we perform a statistical analysis of the global proton density distribution in the Martian magnetosheath. Although the protons show a slight dawn-dusk asymmetry, the day-night and south-north asymmetries of protons are more pronounced. The proton number densities in the dayside and southern hemisphere are obviously larger than those in the nightside and northern hemisphere, respectively. In the flank regions, more protons are distributed in the dawnside compared to those in the duskside. Approaching Mars, the proton number density gradually decreases in the flank regions. Additionally, we find that there is a close relationship between the south-north asymmetries of proton number density and the crustal magnetic field at Mars. The stronger crustal magnetic fields in Mars’ southern hemisphere push the inner boundary of the Martian magnetosheath toward a higher altitude, leading to the formation of a compressed magnetosheath. The compressed magnetosheath in turn causes a further increase in the proton number density and the thermal pressure in the southern hemisphere. Eventually, the stronger total pressure in the magnetosheath in the southern hemisphere, due to its stronger crustal magnetic fields, is generated to balance the increased magnetic pressure inside the induced magnetosphere.

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