Statistical Properties of Solar Wind Upstream of Mars: MAVEN Observations

Di Liu1,2, Zhaojin Rong1,2,3, Jiawei Gao1,2, Jiansen He4,5, Lucy Klinger5, Malcolm Wray Dunlop6,7, Limei Yan1,2,3, Kai Fan1,2,3, and Yong Wei1,2,3

1 Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, People’s Republic of China
2 College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, People’s Republic of China
3 Mohe Observatory of Geophysics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, People’s Republic of China
4 School of Earth and Space Sciences, Peking University, Beijing, People’s Republic of China
5 Beijing International Center for Mathematical Research, Peking University, Beijing, People’s Republic of China
6 Space Science Institute, School of Astronautics, Beihang University, Beijing, People’s Republic of China
7 RAL, Chilton, Oxfordshire, UK

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Abstract

Using the data sets of Mars Atmosphere and Volatile EvolutioN and OMNI for the period 2014 October 10–2020 February 14 and the heliocentric distance of 1–1.66 au, we investigate the statistical properties of solar wind upstream of Mars for the first time. The key parameters, including interplanetary magnetic field (IMF), proton density (N), bulk velocity (V), and dynamic pressure (Pdyn), are surveyed with regard to variations of solar activity level and heliocentric distance. We find that the parameters |IMF|, N, and Pdyn monotonously decrease with heliocentric distance. Both |IMF| and Pdyn are generally stronger at a higher solar activity level (F10.7 70 sfu), while such activity has little relevance to N. In contrast, V basically keeps a median of about 370 km s−1 and is insensitive to the solar activity level and heliocentric distance. We also find that the IMF upstream of Mars at the higher solar activity level has a much smaller spiral angle in the inward sector; thus, IMF seems “straighter” than that in the outward sector, although that is not so for the inward sector of the upstream of Earth. Our statistical survey can be used as a reference for upstream solar wind of Mars at 1.4–1.7 au, and could unified the studies on solar wind as well as the Martian space environment.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Mars (1007); Solar activity (1475); Interplanetary magnetic fields (824); Planetary science (1255)

1. Introduction

It is well known that solar wind is a continuous flow of charged particles that emits radially outward from the Sun with an average speed of 400–500 km s−1 at 1 au (1 au ≈ 1.5 × 108 km). Solar wind is composed mainly of electrons, protons, and alpha particles (~3%–4%), and carries the “frozen-in” interplanetary magnetic field (IMF).

Earlier spacecraft missions measured the solar wind widely, such as Helio 1 and 2 (at 0.3–1.0 au; Rosenbauer et al. 1977); Pioneer 10, Pioneer 11, Voyager 1, and Voyager 2 (in the outer heliosphere; Burlaga et al. 1980, 1984; Collard et al. 1982); Ulysses (with the larger elliptical orbit covering almost all the heliolatitudes; Goldstein et al. 1995); and the Advanced Composition Explorer (ACE; at 1 au, monitoring the upstream solar wind of Earth; Chiu et al. 1998). The combined observations of these missions have largely improved our knowledge of solar wind (e.g., Behannon 1978; Slavin et al. 1984; Gruebeck 2017; Hanneson et al. 2020) and confirm the Parker theory regarding the general pattern of solar wind and IMF (Parker 1958, 1963). Additionally, the variations of solar wind and IMF also show a correlation with the solar cycle (Neugebauer 1975; Gazis 1996; Richardson & Kasper 2008).

The solar wind plays an important role in driving the dynamics of the planetary magnetosphere and the evolution of planetary climate (Lammer et al. 2008; Arridge 2020). Due to the wide measurements of earlier spacecraft missions, e.g., the ACE mission (Chiu et al. 1998), we are able to measure and monitor the upstream solar wind of Earth constantly. The “big” data set of solar wind, like the OMNI data set (King & Papitashvili 2005), facilitates studies of the Earth’s magnetosphere dynamics and terrestrial space weather.

In contrast to Earth, we know little about the solar wind around other planets, although our knowledge of solar wind in the heliosphere has improved significantly in recent decades. Measurements of solar wind, including IMF, require well-calibrated plasma instruments and magnetometers. Fortunately, the recent mission of the Mars Atmosphere and Volatile EvolutioN (MAVEN) carried both high-performing plasma instruments and a magnetometer to explore the Martian space environment (Jakosky et al. 2015). This provided a good opportunity to study solar wind upstream of Mars within RMS = 1.38–1.66 au (RMS is the heliocentric distance of Mars). MAVEN has successfully operated for about six years since its orbit insertion around Mars on 2014 September 21. MAVEN has an elliptical orbit with an apoapsis of ~6200 km and a periapsis of ~150 km (Jakosky et al. 2015), and can regularly sample upstream solar wind every 4 or 5 months. The data set accumulated by MAVEN makes us able to survey the upstream solar wind more comprehensively.

Investigating solar wind upstream of Mars is crucial to probe the processes by which solar wind interacts with Mars. However, to our knowledge, there is no comprehensive study that targets the solar wind upstream of Mars exclusively, though some
preliminary results of solar wind have been reported in Halekas et al. (2017) and Lee et al. (2017). Therefore, in this study, we are motivated to focus on characterizing the properties of solar wind upstream of Mars based on the data set collected by MAVEN during 2014 October to 2020 February. This study is organized as follows. We describe the instruments and data sets used in Section 2. In Section 3, we show the statistical histograms of solar wind upstream of Mars and make a comparison with solar wind upstream of Earth. Variations of solar wind with heliocentric distance and with solar activity level are studied in Section 4. Finally, we discuss and summarize the results in Sections 5 and 6, respectively.

2. Instruments and Data Set

2.1. Instruments

The MAVEN data set we use is derived from measurements of the Solar Wind Ion Analyzer (SWIA; Halekas et al. 2015) and the Magnetometer (MAG; Connerney et al. 2015a). SWIA is a toroidal electrostatic analyzer that measures ion fluxes over a broad energy range from \(\sim 25\) eV to 25 keV, and a maximum angular range of \(360^\circ \times 90^\circ\), with a time resolution of 4 s (Halekas et al. 2015). SWIA measures the 3D ion velocity distribution of solar wind and provides the plasma moments including solar wind density and bulk velocity. The plasma moments of SWIA were computed by assuming that all detected ions are protons. The assumption is invalid within the Martian magnetosphere but reasonable for solar wind. For solar wind, \(\sim 94\%–97\%\) of ions are protons; the derived density and velocity moments are thus reliable in most cases, whereas the temperature derived cannot be safely reliable since even a small alpha population (3\%–6\%) could introduce an artificially large temperature moment (Halekas et al. 2017). Thus, we only focus on moments of velocity and number density measured by SWIA.

MAG can measure magnetic field vectors at 32 Hz frequency (Connerney et al. 2015a, 2015b). In this study, we use the magnetic field data with 1 Hz for IMF measurement in Mars-centered Solar Orbital (MSO) coordinates, where \(+X\) points sunward, \(+Z\) is perpendicular to Mars’s orbital plane and positive toward the ecliptic north, and \(+Y\) completes the right-handed system.

2.2. Data Set

To extract observations of pristine solar wind by MAVEN, we selected the interval when MAVEN was far enough from the Martian bow shock. We first identified bow shock crossings manually by looking at the jump variation of magnetic field strength and the energy spectrum of SWIA per orbit (Gruesbeck et al. 2018).

We examined the data of SWIA and MAG, spanning from 2014 October 10 to 2020 February 14, and identified 7684 orbits that had significant signatures of crossing bow shock for both inbound and outbound crossings. We further specified the solar wind interval between neighboring crossings of bow shock should be larger than 1.5 hr, and finally selected 5780 intervals. For each selected interval, we resampled the MAG data and the SWIA data of plasma moments, using a cadence of 45 s in a 30 minute window at the center of each interval. In this way, we could minimize the disturbance brought by bow shock and foreshock to some extent. The resampled data points in these 30 minute windows are grouped as the data set for this study.

The average locations of MAVEN within these 30 minute windows are shown in Figure 1. The horizontal red line in (c) represents \(F_{10.7} = 70\) sfu (sfu is the unit of \(F_{10.7}\) flux, and 1 sfu = \(10^{-22}\) W m\(^{-2}\) Hz\(^{-1}\)), above which the solar activity is higher, and vice versa.

The average locations of MAVEN within these 30 minute windows are labeled as dots in Figure 1(a). As expected, most of the locations are far away from the nominal bow shock location (Trotignon et al. 2006); thus, the disturbance induced by bow shock or foreshock could be negligible.

We show the time series of \(R_{MS}\) of our data set in Figure 1(b). Obviously, for the whole data set, \(R_{MS}\) is periodically varied within the range 1.38–1.66 au. Meanwhile, to study the correlation with solar activity, the adjusted daily \(F_{10.7}\) solar flux (solar radio flux at a wavelength of 10.7 cm), which was observed by the solar radio telescope on Earth, was used as a proxy of solar activity (Tapping 2013). The corresponding \(F_{10.7}\) flux of our data set is shown in Figure 1(c), which demonstrates that the solar activity was in a declining phase of the 24th solar cycle from 2014 to 2020.
Figure 2. Diagrams illustrating the definition of clock angle (left) and cone angle (right).

3. Distributions

To describe the orientation of IMF, we defined its cone angle and clock angle in the XY and XZ planes of MSO, respectively. As shown in Figure 2, the cone angle $\theta_{cone}$ is defined as the angle between the projected IMF and $+X$ in the $XY$ plane, and rotationally increased from $+X$ toward $+Y$. The Parker spiral angle for inward IMF is estimated as $180^\circ - \theta_{cone}$ when $\theta_{cone} \geq 270^\circ$, while the Parker spiral angle for outward IMF is estimated as $180^\circ - \theta_{cone}$ when $90^\circ \geq \theta_{cone} \geq 180^\circ$. Similarly, the clock angle $\theta_{clock}$ is defined as the angle between the projected IMF and $+Z$ in the $YZ$ plane, which is rotationally increased from $+Z$ toward $+Y$. $\theta_{clock} = 90^\circ$ ($270^\circ$) means that IMF points toward a $+Y$ ($-Y$) direction.

In order to compare contemporaneous solar wind observations at Earth and at Mars, the OMNI database that provides the shifted solar wind observations to the nose of Earth bow shock from several spacecraft was also used (King & Papitashvili 2005). Since the time resolution of our MAVEN solar wind data set is 45 s, we used an OMNI data set with a resolution of 1 minute covering the same period. The coordinate system used for this OMNI data set is geocentric solar ecliptic (GSE), where $+X$ points sunward, $+Z$ is perpendicular to Earth’s orbital plane and positive toward ecliptic north, and $+Y$ completes the right-handed system. Note that GSE is basically the same as MSO, but the origin is at the Earth’s center, not Mars’.

3.1. The Distributions of IMF Upstream of Mars

In Figures 3(a)–(c), we show histograms of IMF for the whole MAVEN data set. The distribution shape of IMF strength, $|\text{IMF}|$, is similar to a chi-square distribution (Larrodera & Cid 2020, and references therein) and reaches the peak at 1.87 nT. (We fitted the probability density function using a kernel smoothing method (Hill 1985) and calculated the most probable value (MPV) that corresponds to the maxima of the probability density function.) Correspondingly, $\theta_{clock}$ reaches its MPV at $(89^\circ.6, 270^\circ.8)$, implying that IMF is mostly orientating toward either a $+Y$ or $-Y$ direction with a minor $B_z$ component. Meanwhile, $\theta_{cone}$ reaches its MPV at $(115^\circ.9, 310^\circ.2)$, which means that the MPV of the Parker spiral angle is about $64^\circ.1$ for the outward sector and $49^\circ.8$ for the inward sector.

For the data set of perihelion with LSA, as shown in Figures 3(d)–(f), $|\text{IMF}|$ reaches the peak at 2.01 nT, while the MPVs of $\theta_{clock}$ and $\theta_{cone}$ are $(96^\circ.3, 271^\circ.9)$ and $(122^\circ.3, 301^\circ.6)$, respectively. The distribution of $\theta_{cone}$ implies that the Parker spiral angle is about $57^\circ.7$ for the outward sector and $58^\circ.4$ for the inward sector. In contrast, when Mars was subjected to HSA near perihelion, we find $|\text{IMF}|$ becomes stronger (MPV = 2.35 nT). Meanwhile, the MPV of $\theta_{cone}$ is $113^\circ.8$ in the outward sector (spiral angle is $66^\circ.2$) and $313^\circ.5$ in the inward sector (spiral angle is $46^\circ.5$), indicating a significant spiral angle discrepancy between the two sectors. The clock angle still keeps MPV as $(84^\circ.7, 267^\circ.6)$, though solar activity level is higher.

In Figures 3(g)–(i), we can find similar kinds of solar activity when Mars is near the aphelion. In this case, $|\text{IMF}|$ in HSA is comparable (MPV = 1.80 nT) to $|\text{IMF}|$ in LSA (MPV = 1.75 nT). Again, we notice the significant discrepancy in spiral angle between the inward and outward sectors in HSA: the MPV of $\theta_{cone}$ is $110^\circ.8$ for the outward sector (spiral angle is $69^\circ.2$) and $310^\circ.4$ for the inward sector (spiral angle is $49^\circ.6$). In LSA, however, the MPV of $\theta_{cone}$ is $122^\circ.6$ in the outward sector (spiral angle is $57^\circ.4$), and $308^\circ.7$ in the inward sector (spiral angle is $52^\circ.0$). The MPV of $\theta_{clock}$ in HSA is $(91^\circ.6, 273^\circ.8)$, which is basically the same in LSA as $(90^\circ.7, 271^\circ.1)$.

A comparison between Figures 3(d)–(f) and (g)–(i) demonstrates that the MPV of $|\text{IMF}|$, under the same solar activity level, is stronger near perihelion. However, we do not find
significant dependence of the MPV of $\theta_{\text{clock}}$ or $\theta_{\text{cone}}$ (spiral angle) on $R_{\text{MS}}$.

We tabulate the MPV of these parameters in Table 1.

3.2. The Distributions of Solar Wind Upstream of Mars

Using the same format of Figure 3, Figure 4 shows histograms of number density $N$, bulk speed $|V|$, and dynamic pressure $P_{\text{dyn}}$ ($P_{\text{dyn}} = m N V^2$, $m$ is proton mass), respectively, in the left, middle, and right columns.

For histograms of the whole data set shown in Figures 4(a)–(c), we find that the MPVs for $N$, $|V|$, and $P_{\text{dyn}}$ are $1.40 \text{ cm}^{-3}$, $368.9 \text{ km s}^{-1}$, and $0.39 \text{ nPa}$, respectively. The bulk speed is dominated by the $V_x$ component and the MPV for the $V_z$ component is negligible (see Table 1). The MPV of the $V_y$
component (22.2 km s\(^{-1}\)) was compared with the average orbital speed of Mars around the Sun (24.1 km s\(^{-1}\)), which suggested that SWIA resolves the off-axis flow velocity with an excellent accuracy and precision of \(~\sim 1\) km s\(^{-1}\), as previously pointed out by Halekas et al. (2017).

Histograms for solar activity near the perihelion (see Figures 4(d)–(f)) demonstrate that the MPVs of \(N\), \(|V|\), and \(P_{\text{dyn}}\) in LSA are comparable to those in HSA. Similarly, near the aphelion (see Figures 4(g)–(i)) we find that, except for \(P_{\text{dyn}}\), the MPVs of \(N\) and \(|V|\) in LSA are also comparable to those in HSA. Thus, it seems, that the solar activity level cannot significantly affect the MPVs of \(N\) and \(|V|\).

By comparing Figures 4(d)–(f) and (g)–(i), we find that, under the same solar activity level, the MPV of \(N\) is stronger near the perihelion, while the MPV of \(|V|\) seems independent of \(R_{\text{MS}}\).

### 3.3. Comparison with Solar Wind Observations at 1 au

In order to check the results we obtained in Sections 3.1 and 3.2, we compared MAVEN’s data set with a contemporaneous OMNI data set at 1 au. The OMNI data set covering 2014 October 10–2020 February 14 was similarly partitioned into two subsets, that is, LSA (\(F_{10.7} \geq 70\) sfu) and HSA (\(F_{10.7} = 70\) sfu).

Using the same format as Figures 3 and 4, the histograms of IMF and solar wind moments at 1 au are plotted in Figures 5 and 6, respectively. Accordingly, the MPVs of these histograms are tabulated in Table 1.

Obviously, as a whole, IMF at 1 au has a stronger field strength (MPV = 4.13 nT) relative to Mars. The MPVs for both \(\theta_{\text{clock}}\) and \(\theta_{\text{cone}}\) suggest that IMF is mostly orientating toward a \(+Y\) or \(−Y\) direction and the Parker spiral angle is about 43\(^\circ\)4 (45\(^\circ\)1) for the outward (inward) sector. The increased spiral angle and decreased \(|\text{IMF}|\) from Earth to Mars are consistent with the general IMF pattern. The response of IMF to solar activity level at 1 au shows some similarities with the case at Mars. We find that \(|\text{IMF}|\) in HSA (MPV = 4.50 nT) is stronger than that in LSA (MPV = 3.65 nT). However, in contrast to the case of Mars, no matter what the solar activity level is, the Parker spiral angle at 1 au shows little discrepancy between the inward and outward sectors (the largest discrepancy is 12\(^\circ\)8 in LSA).

With regard to the plasma moments, the MPV of solar wind at 1 au has a higher density (3.67 cm\(^{-3}\)), a comparable flow speed (351.1 km s\(^{-1}\)) with a much smaller \(V_y\) component, and a higher dynamic pressure (1.51 nPa) relative to the solar wind upstream of Mars. In contrast to the case of Mars, the MPV of solar wind in HSA at 1 au shows higher flow speed (369.4 km s\(^{-1}\)) and lower density (3.13 cm\(^{-3}\)) relative to that in LSA, while the MPV of dynamic pressure still seems insensitive to the solar activity level.

### 4. Variations in Heliocentric Distance

In this section, we examine the radial dependence of solar wind parameters (\(|\text{IMF}|\), \(|V|\), \(N\), and \(P_{\text{dyn}}\)). To study the radial profile, the range of \(R_{\text{MS}}\) (1.38–1.66 au) observed by MAVEN is equally divided into six bins of the same width, and the median within each bin is calculated. At the same time, the medians at 1 au are calculated using the OMNI database. In comparison with MPV, the median value better indicates the whole level of data points within the bin. In Figures 7(a)–(d), using the calculated medians, we show the radial variations of \(|\text{IMF}|\), \(|V|\), \(N\), and \(P_{\text{dyn}}\), respectively, as well as responses to different solar activity levels.

These radial profiles covering heliocentric distance 1 \(\sim\) 1.66 au demonstrate that:

1. \(|\text{IMF}|\) in LSA monotonously decreases with heliocentric distance, whereas \(|\text{IMF}|\) in HSA decreases with heliocentric distance but is almost constant beyond 1.45 au. We also note that \(|\text{IMF}|\) in HSA is generally stronger than that in LSA by about 0.5 nT. The enhanced \(|\text{IMF}|\) in HSA could be induced by solar wind structures of a large scale, i.e., interplanetary coronal mass ejections or corotating interaction regions, which appear more frequently in HSA.

2. Like the profile of \(|\text{IMF}|\), \(N\) also monotonously decreases with heliocentric distance in LSA, but keeps almost constant beyond 1.45 au in HSA. In contrast to \(|\text{IMF}|\), it seems that the profile of \(N\) is insensitive to the level of solar activity within 1.38–1.66 au.

3. The median of \(|V|\) is basically varied within 360 \(\sim\) 420 km s\(^{-1}\), which has no significant correlation with heliocentric distance or the level of solar activity.

4. The comparison between Figures 7(b) and (c) suggests that \(|V|\) is anticorrelated with the variation of \(N\). This anticorrelation has been reported in some previous studies (e.g., Richardson & Kasper 2008).
5. $P_{\text{dyn}}$ monotonously decreases with heliocentric distance regardless of the solar activity level, and $P_{\text{dyn}}$ is generally stronger in HSA than in LSA by about 0.1 nPa.

5. Discussion

It is well known that typical solar wind near the Earth’s orbit (1 au) has $N \sim 3–6$ cm$^{-3}$, $|V| \sim 400$ km s$^{-1}$, $P_{\text{dyn}} \sim 1–2$ nPa, $|\text{IMF}| \sim 4–5$ nT, and a Parker spiral angle of $\sim 45^\circ$ (Neugebauer & Snyder 1966; Bothmer & Zhukov 2007; Hansteen et al. 2010; Larrodera & Cid 2020). Our statistical analysis of the OMNI data set in Figures 5 and 6 confirms these parameters. In comparison, our statistical investigation of solar wind upstream of Mars ($R_{\text{MS}} = 1.38–1.66$ au) suggests that solar wind has a comparable $|V| (\sim 370$ km s$^{-1}$), a lower $N (\sim 1.4$ cm$^{-3}$), a lower $P_{\text{dyn}} (\sim 0.39$ nPa), a lower $|\text{IMF}|$...
(\sim 1.87 \text{nT}) \), and a larger spiral angle of 57° (see Table 1). This \( |V| \), the radial decreased trend of \( N \), \( P_{\text{dyn}} \), and \( |\text{IMF}| \), and the increased spiral angle from Earth to Mars are roughly consistent with the Parker theory (Parker 1958, 1963). It is worth noting from Table 1 and Figure 7(b) that the radial profile of \( N \) basically satisfies the falloff of the inverse square of the heliocentric distance within 1–1.66 au, which implies that the flux of solar wind stays constant within this range. However, considering the scale of a heliosphere of \sim 100 \text{au} (Burlaga et al. 2005), the narrow range of 1–1.66 au from Earth to Mars does not favor a direct comparison with the Parker theory. Interested readers can refer to many previous solar winds regarding the radial profile (Richardson et al. 1995; Köhnlein 1996; Richardson & Wang 1999; Hanneson et al. 2020).

Previous studies suggested that each solar wind parameter can experience a corresponding solar cycle variation. \( |V| \) is usually higher and \( N \) is lower during the solar maximum, because the coronal holes with tenuous high-speed flow could excurse to the elliptical plane during the solar maximum. Meanwhile, \( P_{\text{dyn}} \) usually reaches a minimum near the solar maximum, and arrives at a peak in the declining phase, roughly three years after the solar maximum (Richardson et al. 1995, 2003; Richardson & Wang 1999; Richardson & Kasper 2008). Due to the available period of the MAVEN data set, which covers 2014 to 2020, however, we are unable to study the variation of solar wind parameters over a complete solar cycle. The \( F_{10.7} \) solar flux shown in Figure 1(c) demonstrates that the highest period of HSA (2015–2017) corresponds to the declining phase of the 24th solar cycle, and \( P_{\text{dyn}} \) in HSA, which we reported as stronger, is consistent with the previous conclusion that \( P_{\text{dyn}} \) usually peaks in the declining phase. Therefore, although we found that \( N \) and \( |V| \) are insensitive to the solar activity level as we defined it here, this does not necessarily contradict previous studies on the modulation of solar cycles.

From Table 1, we notice that solar wind speed upstream of Mars has a minor \( V_y \) component (\sim 22 \text{km s}^{-1}), but a negligible \( V_y \) component (\sim 2.5 \text{km s}^{-1}), at 1 au. Considering the orbital speed of Earth (30 \text{km s}^{-1}) and Mars (24 \text{km s}^{-1}), this may suggest that the traverse component of solar wind velocity in the elliptical plane is comparable to the Earth orbital velocity at 1 au, and that the traverse component becomes negligible at the orbit of Mars.

We find that IMF upstream of Mars is “straighter” in the inward sector (spiral angle \sim 46°.5 near perihelion, and 49°.6 near aphelion) than that in the outward sector (spiral angle \sim 66°.2 near perihelion, and 69°.2 near aphelion) in HSA. Meanwhile, both sectors in LSA show comparable spiral angles (57°.4 \sim 57°.7 for the outward sector and 52°.0 \sim 58°.4 for the inward sector). One may argue that smaller spiral angles in the inward sector would imply a higher \( |V_x| \) there. However, by

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Histograms of |\text{IMF}| (left column), \( \theta_{\text{clock}} \) (middle column), and \( \theta_{\text{cone}} \) (right column) at 1 au. The format is the same as Figure 3.}
\end{figure}
comparing the medians of $|V_x|$ for the two sectors in HSA, we did not observe a higher $|V_x|$ in the inward sector (not shown here). From Table 1, we do not find a significant discrepancy of spiral angles between the two sectors at 1 au. Thus, the true reason why IMF upstream of Mars in HSA is “straighter” in inward sector remains an unknown and open question.

It is noteworthy that we chose $F_{10.7} = 70$ sfu to distinguish the solar activity level. Although a minor change of criterion would slightly affect the quantitative results, the qualitative results of our conclusion remain robust.

6. Summary

In this study, we use the data set of MAVEN, spanning from 2014 October 10 to 2020 February 14, to characterize the properties of solar wind upstream of Mars for the first time. Our results demonstrate that typical solar wind density is about $1.4 \text{ cm}^{-3}$, velocity is almost radially outward with a speed about $370 \text{ km s}^{-1}$, and dynamic pressure is about $0.4 \text{ nPa}$. The IMF “frozen-in” to the solar wind basically lies on the ecliptic plane with a field strength about $1.9 \text{ nT}$. The spiral angle of IMF is about $50^\circ$ in the inward sector and $64^\circ$ in the outward sector. Thus, IMF in the inward sector seems “straighter” than that in the outward sector.

Combining our results with the data set of solar wind upstream of Earth, the variations of solar wind with the solar activity level and heliocentric distance within $1 \sim 1.66 \text{ au}$ demonstrate that:

1. The strength of IMF decreases with heliocentric distance, and is generally stronger in HSA.
2. IMF upstream of Earth has a comparable spiral angle ($\sim 45^\circ$) for both inward and outward sectors, regardless of the solar activity level. On the other hand, IMF upstream of Mars evidently shows a smaller angle or “straighter” field lines in inward sectors in HSA.
3. The density of solar wind decreases with heliocentric distance, roughly satisfying a falloff of inverse square of heliocentric distance, but does not show any significant correlation with a solar activity level within $1.38 \sim 1.66 \text{ au}$.
4. The median of solar wind speed basically stays at $\sim 370 \text{ km s}^{-1}$, and is insensitive to the solar activity level and heliocentric distance.
5. The solar wind speed is anticorrelated with the variation of solar wind density.
6. The median of dynamic pressure monotonously decreases with heliocentric distance, and is generally stronger in HSA.
Figure 7. The radial profiles of $|\mathbf{B}|$, $N$, $|V|$, and $P_{\text{dyn}}$, with different levels of solar activity based on the joint database of MAVEN and OMNI. The red (blue) dots are the data points in HSA (LSA). For each panel, the range of heliocentric distance is equally divided into six bins, and the median value with quartiles of data points in each bin is calculated. The red (blue) squares with error bars represent the median values with quartiles in HSA (LSA).

The data set of MAVEN is publicly available in NASA’s Planetary Data System (https://pds-ppi.igpp.ucla.edu/search/?t=Mars&sc=MAVEN&facet=SPACECRAFT_NAME&depth=1). OMNI data were obtained from the GSFC/SPDF OMNIWeb interface (https://omniweb.gsfc.nasa.gov), and the data of the $F_{10.7}$ solar flux were provided by the National Research Council and Natural Resources Canada (https://www.spaceweather.gc.ca/solarflux/sx-3-en.php). This work was supported by the National Natural Science Foundation of China (grant Nos. 41922031, 41774188, and 42074207), the Strategic Priority Research Program of Chinese Academy of Sciences (grant No. XDA17010201), and the Key Research Program of the Institute of Geology & Geophysics, CAS (grant No. IGGCAS-201904).

ORCID iDs

Di Liu @ https://orcid.org/0000-0001-7636-7245
Zhaojin Rong @ https://orcid.org/0000-0003-4609-4519
Jiawei Gao @ https://orcid.org/0000-0003-4432-1132
Jiansen He @ https://orcid.org/0000-0001-8179-417X
Limei Yan @ https://orcid.org/0000-0002-1402-923X
Kai Fan @ https://orcid.org/0000-0003-2572-1587
Yong Wei @ https://orcid.org/0000-0001-7183-0229

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