

Statistical Differences of the Properties of the Martian Foreshock Boundary During the Selected High and Low Solar Activity Intervals

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Key Points:

- The mean decrease in solar wind velocity across the Martian foreshock boundary shows little variation with respect to the solar activity levels.
- Solar wind dynamic pressure decreases slightly less, while the solar wind density shows a stronger enhancement during the selected low-activity interval.
- The boundary of the Martian foreshock is located farther from the bow shock during the selected high-activity interval and exhibits systematic correlations with the solar wind velocity and density.

Abstract:

As the primary transition region in the solar wind–Mars interaction system, the Martian foreshock plays a significant role in the energy transfer and dissipation of the solar wind. Based on MAVEN observations during the selected solar high-activity interval over December 2014–February 2015 and solar low-activity interval over December 2018–February 2019, the properties of the Martian foreshock boundary are statistically studied. Distributions of solar wind parameters including the density, velocity, dynamic pressure, and magnetic field strength are investigated for analyses of their differences across the Martian foreshock boundary. Our results indicate that solar wind velocity across the Martian foreshock boundary shows little variation with respect to the solar activity levels. Solar wind dynamic pressure decreases slightly less during the selected low-activity interval, while the solar wind density shows a stronger enhancement during the selected low-activity interval. The boundary of the Martian foreshock is located farther from the bow shock during the selected high-activity interval and exhibits systematic correlations with the solar wind velocity and density. These findings support that the structure and dynamics of the Martian foreshock are different between the selected solar high- and low-activity intervals, which is important for improved understanding of the cross-scale interactions between the solar wind and Martian space.

Keywords: Foreshock, Martian space, solar wind, bow shock, MAVEN

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1. Introduction

As the second smallest planet in the solar system possessing an atmosphere, Mars differs from Earth in several fundamental physical characteristics. It is widely believed that the Martian core dynamo ceased approximately 3.7 Ga ago (Acuña et al., 1998; Weiss et al., 2002), rendering the planet unable to maintain a global dipole magnetic field. Consequently, the supersonic solar wind interacts directly with the upper atmosphere of Mars, driving ion escape and ongoing atmospheric loss (Jakosky et al., 2015a; Brain et al., 2015). Understanding the long-term evolution of the Martian climate relies heavily on the details and mechanisms of these processes, which occur in various regions of Martian space, including the Martian foreshock.

A foreshock refers to the region upstream of a planetary bow shock where interplanetary magnetic field (IMF) lines are connected to the shock surface, allowing reflected solar wind particles to travel along those lines back into, and interact with, the incoming solar wind flow (Eastwood et al., 2005). Such velocity distributions typically imply instabilities that result in the generation of various low-frequency waves, including magnetosonic waves, '1-Hz' waves, and ultralow frequency (ULF) waves (Blanco-Cano et al., 1999; Eastwood et al., 2005; Wang BY et al., 2021; Shan LC et al., 2020). These waves can further interact with particles to exchange energy and momentum through resonance, thereby playing a crucial role in ion energization and escape processes (Mazelle et al., 2004; Andrés et al., 2025). Recent MAVEN observations further demonstrated that ULF magnetic field fluctuations in the Martian foreshock can effectively modulate suprathermal electron fluxes through wave-particle interactions (Jin TF et al., 2025).

The Martian foreshock is unique not only due to the planet's weak gravity, which allows the exosphere (also known as the hydrogen corona) to extend beyond the bow shock and interact directly with the solar wind (Xu Q et al., 2020), but also because of the crustal magnetic fields distributed primarily in the southern hemisphere, which add asymmetry to the geometry of the shock surface (Acuña et al., 1999; Fan K et al., 2020; Hood et al., 2003; Chai LH et al., 2025), and can further modify the morphology of boundary layers and plasma flow patterns around Mars (Li SB et al., 2020). These features are expected to influence wave-particle interactions within this region.

Decades of exploration have revealed much about the Martian plasma environment, including its variation with solar activity and interplanetary conditions. The Martian plasma environment is highly sensitive to solar activity; variations in solar extreme ultraviolet (EUV) flux and solar wind dynamic pressure affect ionospheric density, bow shock location, and global plasma configuration. The orientation of the interplanetary magnetic field can modify ion current systems, plasma asymmetry, and atmospheric ion escape morphology around Mars (Du HL et al., 2026). Enhanced solar wind conditions, such as interplanetary coronal mass ejections (ICMEs), can compress the ionosphere

and alter plasma flow and escape processes (e.g., Halekas et al., 2017). Observations from Phobos 2 first confirmed the presence of electron plasma oscillations and foreshock wave activity upstream of Mars (Grard et al., 1989; Trotignon et al., 1991), while measurements from MAVEN have revealed backstreaming ion populations and ultra-low-frequency (ULF) waves, highlighting the role of wave–particle interactions in shaping the foreshock structure (Meziane et al., 2017; Andrés et al., 2025). However, little is known about the spatial features and variations of the Martian foreshock, particularly the response of its boundary to varying upstream conditions.

This study aims to statistically analyze the structure of the Martian foreshock and the magnetic field fluctuations within this region using MAVEN observations. We compare the boundary structure against various upstream parameters to investigate the response of the Martian foreshock to solar activity. Section 2 introduces the data and methods used in this study. Section 3 describes the results of the statistical analysis of key plasma parameters in the foreshock and their response to solar activity. Section 4 summarizes the conclusions and briefly discusses possible mechanisms for solar cycle modulation of the foreshock boundary.

2. Methods and Data

2.1 Data Sources

Data from the Mars Atmosphere and Volatile Evolution (MAVEN; Jakosky et al., 2015b) mission are utilized in this study. Specifically, we use data provided by the magnetometer (MAG; Connerney et al., 2015), solar wind ion analyzer (SWIA; Halekas et al., 2013), and solar wind electron analyzer (SWEA; Mitchell et al., 2016) to identify and analyze the foreshock region. The MAG instrument provides three-component magnetic field vectors at a sampling rate of 32 Hz. We utilize data in the Mars Solar Orbital (MSO) coordinate system, defined such that the X-axis points from Mars toward the Sun, the Z-axis is perpendicular to the Mars orbital plane pointing northward, and the Y-axis completes the right-handed system. SWIA measures solar wind ions with an energy range of 25 eV to 25 keV and an energy resolution of 15%. We primarily use the standard MAVEN Level 2 Key Parameter (KP) data products, which provide time-aligned physical parameters including proton density, velocity, and ion temperature. These KP data products integrate observations from multiple instruments into a unified format and have been standardized to a time resolution of 8 s. To ensure data quality, we use the SWIA Key Parameter quality flag to exclude measurements for which the ion velocity distribution may be incompletely sampled within the instrument field of view or energy range. In this study, only data with quality flags greater than 0.5 are retained as a quality-control criterion. The SWEA instrument measures solar wind electrons with energies from 3 to 4600 eV and an energy resolution of 17%. In this study, we use the Level 2 Survey mode omni-directional electron energy spectra (SWEA spec) with a time resolution of 2 s.

2.2 Selection of Solar High-Activity and Low-Activity Intervals

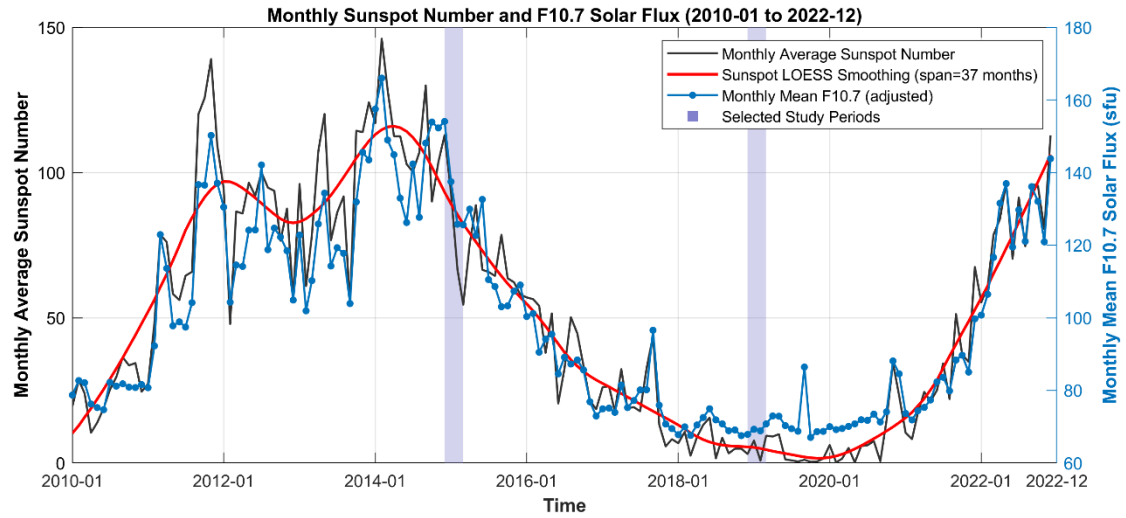


Figure 1. Monthly averaged sunspot number and adjusted F10.7 solar radio flux during 2010–2022, with the sunspot number shown in black and the adjusted F10.7 solar radio flux shown in blue. The red curve represents the 37-month smoothed sunspot number. The shaded areas mark the time intervals selected for this study. Sunspot number data were sourced from the SILSO World Data Center, while F10.7 data were obtained from the National Research Council Canada/Penticton through the NOAA Physical Sciences Laboratory.

The sunspot number and F10.7 solar radio flux are used as indicators of solar activity strength; a higher sunspot number or F10.7 solar radio flux indicates a higher level of solar activity. Figure 1 illustrates the sunspot number and F10.7 solar radio flux trend from 2010 to 2022. As shown, 2014–2015 corresponds to a period of high solar activity (hereafter referred to as high-activity), while 2018–2020 corresponds to a period of low solar activity (hereafter referred to as low-activity). Accounting for MAVEN's orbital coverage of the foreshock region, we selected the interval from December 2014 to February 2015 as the selected high-activity interval and from December 2018 to February 2019 as the selected low-activity interval. These represent two three-month intervals, totaling six months of observations.

Within the selected time intervals, the upper boundary crossings of the foreshock region were manually identified based on the temporal variations of physical parameters, including magnetic field strength, electron flux, and solar wind temperature and velocity. The upper boundary is defined as the interface between the foreshock region and the undisturbed solar wind. Correspondingly, the lower boundary refers to the bow shock, the interface between the foreshock region and the magnetosheath. Upon the transition from the pristine solar wind into the foreshock region, the magnetic field becomes increasingly disturbed, the electron flux rises, and the solar wind temperature and velocity show relatively small variations. In this study, the change in magnetic field and the enhancement in electron flux were used as the primary criteria for manually identifying the upper boundary of the foreshock. The power spectral density (PSD) is calculated by summing the PSDs of the three magnetic field components. The wave

amplitude in the 0.1–1 Hz frequency band is then obtained as the square root of the integrated PSD. The boundary was identified when (i) the mean magnetic field change exceeded 0.3 nT, (ii) the flux of 199 eV increased by at least $10^{0.1}$ (approximately 1.26) times, and (iii) the wave amplitude in the 0.1–1 Hz frequency band increased by more than 3 nT. Variations in solar wind temperature and velocity were used as supplementary criteria, with no substantial decrease in temperature or rapid increase in velocity required for a reasonable boundary identification. In the selected dataset, a total of 1,348 upper boundary crossing events were identified, including 662 events during the selected high-activity interval and 686 events during the selected low-activity interval.

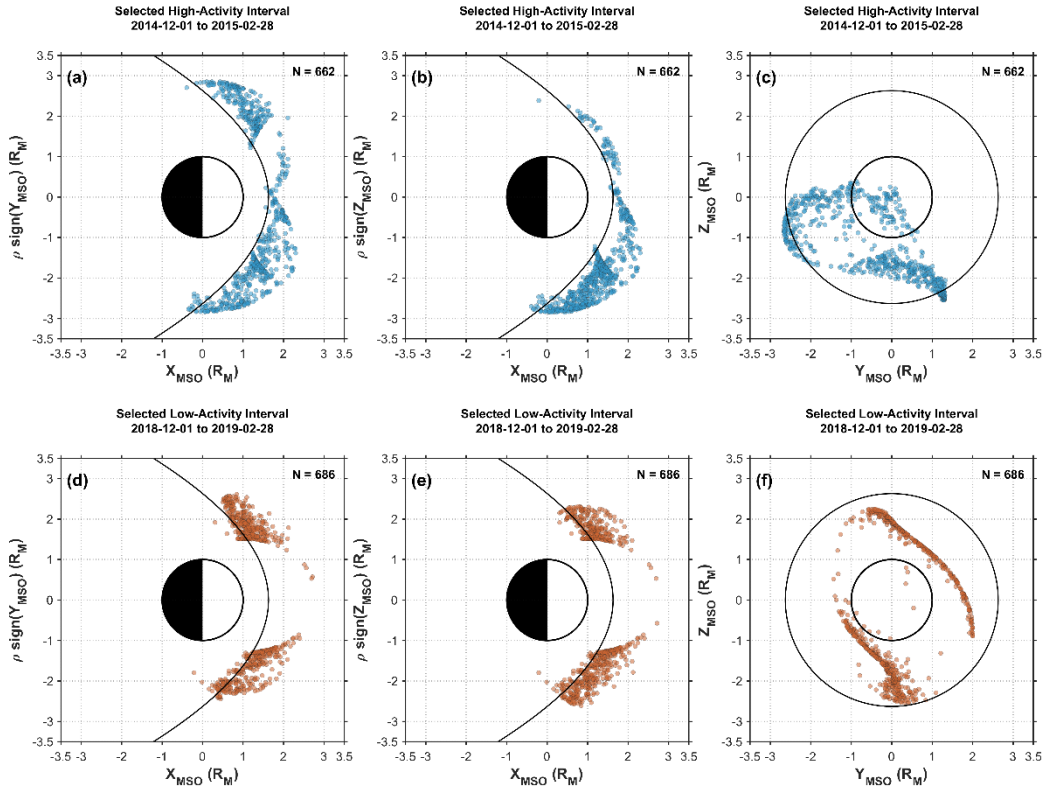


Figure 2. Spatial distributions of the identified foreshock upper-boundary crossings during the selected high-activity and low-activity intervals. (a)–(c) show the boundary crossings during the selected high-activity interval in the $X_{\text{MSO}}\text{-}\rho \text{ sign}(Y_{\text{MSO}})$, $X_{\text{MSO}}\text{-}\rho \text{ sign}(Z_{\text{MSO}})$, and $Y_{\text{MSO}}\text{-}Z_{\text{MSO}}$ projections, respectively; (d)–(f) show the corresponding distributions during

the selected low-activity interval. Here, $\rho = \sqrt{Y_{\text{MSO}}^2 + Z_{\text{MSO}}^2}$. Blue and orange dots represent crossings during the selected high-activity and low-activity intervals, respectively. The black solid curves denote the Trotignon et al. (2006) empirical bow-shock model, and the black circle/semicircle denotes Mars. The total number of crossings in each interval is indicated in the upper-right corner of each panel.

Figure 2 shows the spatial distributions of the identified foreshock upper-boundary

crossings during the two selected intervals. The crossings during both intervals cover broadly similar dayside upstream regions and show generally symmetric distributions in the dawn-dusk direction, although their north-south distributions differ to some extent: more crossings are located in the southern hemisphere ($Z_{\text{MSO}} < 0$) during the selected high-activity interval, whereas distribution in the selected low-activity interval shows more symmetry. The two intervals also occur in different Martian seasons, with , with $L_s = 243.79^\circ$ – 299.92° for the selected high-activity interval and $L_s = 298.17^\circ$ – 348.56° for the selected low-activity interval. Other differences also exist in SZA coverage, IMF geometry, and upstream solar wind conditions. These factors, some affected by the solar activity, may therefore contribute to the statistical differences between the two selected intervals. Although the strongest Martian crustal magnetic fields are concentrated mainly in the southern hemisphere (Acuña et al., 1999; Hood et al., 2003), previous studies suggest that their direct influence is mainly important at relatively low altitudes, extending to approximately 1300 km in some regions (Brain et al., 2003). The foreshock upper-boundary crossings analyzed here are located near and upstream of the bow shock, generally at substantially higher altitudes, so the direct influence of crustal magnetic fields on the present statistics is expected to be limited.

2.3 Comparative Analysis Methods for Key Physical Parameters

In this study, we select the magnetic field strength, solar wind density, velocity, and dynamic pressure as the parameters for statistical analysis to examine the influence of solar activity on the Martian foreshock region. For convenience of description, we define four regions: FS-OUT to denote the unperturbed solar wind region upstream of the foreshock, FS-IN to denote the foreshock region near the upper boundary, BS-OUT to denote the region immediately outside the bow shock, and BS-IN to denote the region inside the bow shock. To quantitatively analyze changes in the statistical parameters at the boundary, we select time intervals of 3 minutes immediately before and after each boundary (as illustrated in Figure 3), and compute the mean values and standard deviations of the aforementioned physical quantities in those intervals. In addition, we use the empirical bow shock model of Trotignon et al. (2006) to calculate the distance from the foreshock upper boundary to the bow shock along the MSO X-axis. This distance effectively represents the spatial extent of the foreshock region into the solar wind.

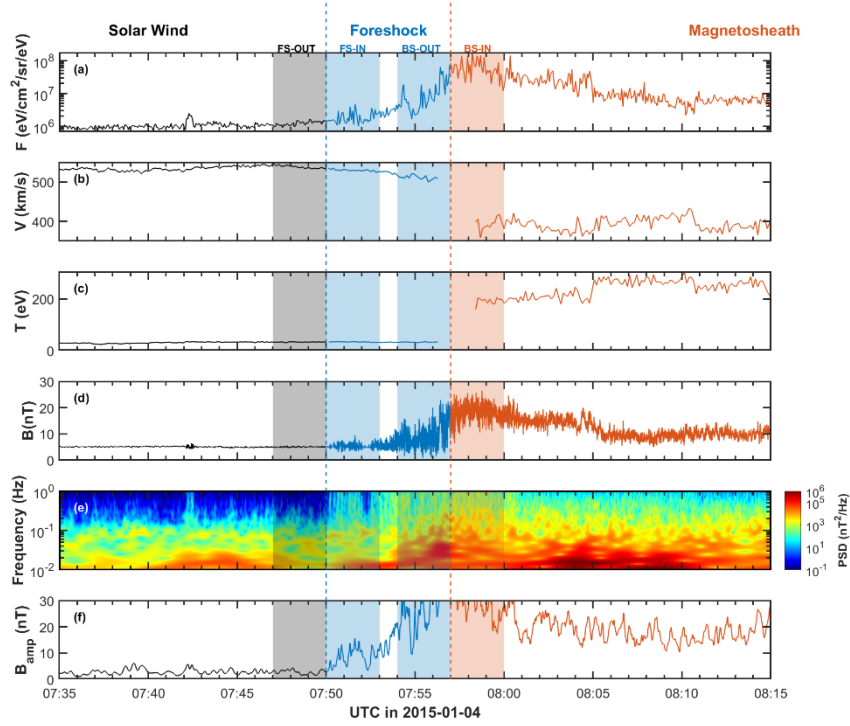


Figure 3. Example of foreshock crossing, on 4 January 2015. (a) differential flux of 199 eV electrons; (b) solar wind (H^+) velocity; (c) solar wind temperature; (d) magnetic field strength; (e) power spectral density; (f) wave amplitude integrated over the 0.1–1 Hz frequency band. Time intervals of ± 3 minutes around the identified upper and lower boundary times are selected to represent FS-OUT, FS-IN, BS-OUT, and BS-IN.

3. Results

3.1 Solar Wind Velocity Distribution Crossing Foreshock

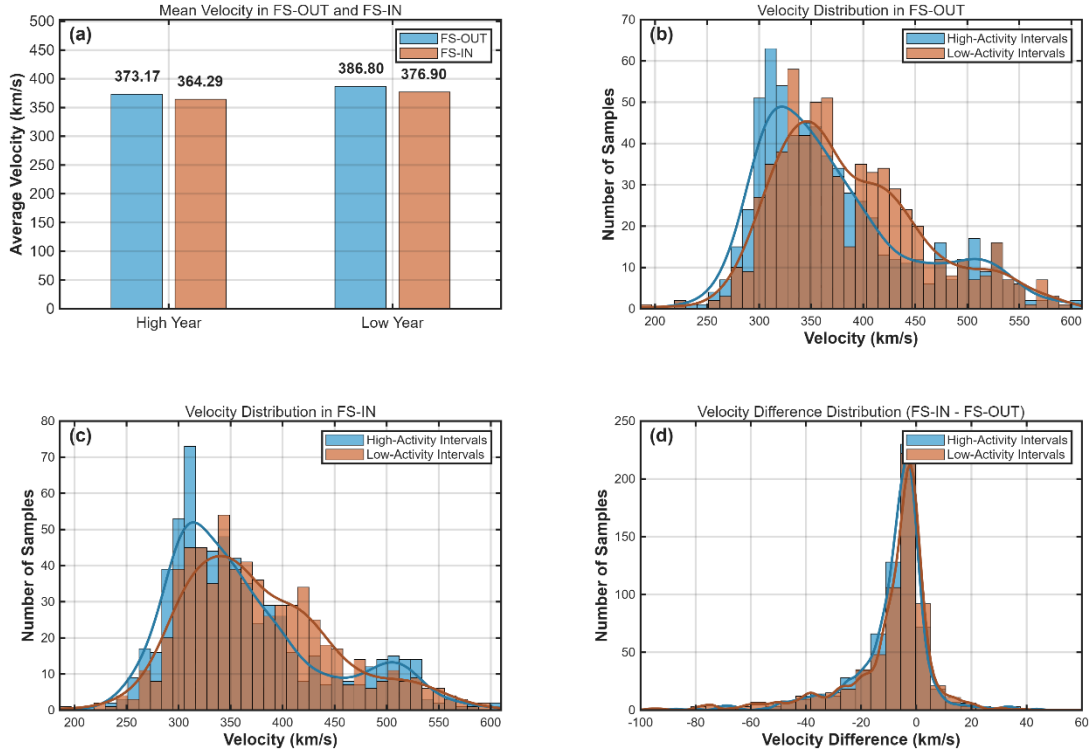


Figure 4. Comparison of solar wind velocity in the foreshock region near the upper boundary during the selected high-activity and low-activity intervals. (a) mean velocities in FS-OUT (blue) and FS-IN (orange) during the selected high- and low-activity intervals. In panels (b)–(d), blue and orange denote the selected high- and low-activity intervals. (b) histogram of velocity distribution in FS-OUT region. (c) histogram of velocity distribution in FS-IN region. (d) histogram of distribution of the velocity difference (FS-IN - FS-OUT) across the boundary. Blue and orange correspond to data from the selected high-activity and low-activity intervals in panels (b)–(d), with solid curves showing envelopes of distributions.

Figure 4 shows the statistical characteristics of solar wind velocity at the vicinity of the foreshock upper boundary during the selected high-activity and low-activity intervals. Figure 4(a) indicates that in both high-activity and low-activity intervals, the average velocity in the FS-IN region is lower than in FS-OUT. The overall average velocities (both FS-OUT and FS-IN) during the selected low-activity interval are higher than those in the selected high-activity interval. Histograms in Figures 4(b) and 4(c) reveal that, during the selected high-activity interval, the velocity distribution exhibits structure of two peaks (with a primary peak at 300–350 km/s and a secondary peak at 480–530 km/s), whereas the distribution in the selected low-activity interval is more concentrated to one peak. Figure 4(d) shows that the distributions of the velocity difference (FS-IN minus FS-OUT) for the selected high-activity and low-activity intervals resemble each other highly, being concentrated around –20 to 0 km/s with a peak near 0 km/s.

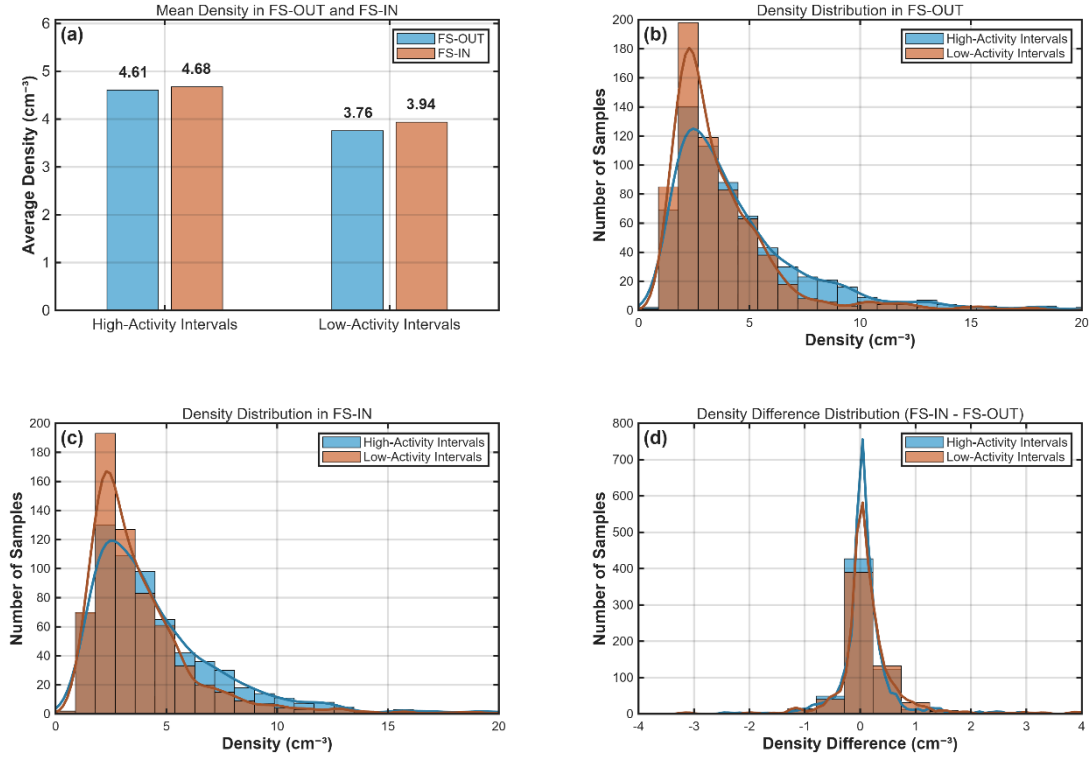


Figure 5. Comparison of solar wind density in the foreshock region near the upper boundary during the selected high-activity and low-activity intervals, using the same format as Figure 4

Figure 5 shows the comparison of solar wind density. Figure 5(a) shows that in both the selected high-activity and low-activity intervals, the mean density in the FS-IN region is slightly higher than that in FS-OUT, corresponding to the solar wind deceleration when crossing the boundary. It can also be seen that the density jump in the selected low-activity interval is noticeably larger than in the selected high-activity interval. Histograms in Figures 5(b) and 5(c) indicate that during the selected high-activity interval, the density distributions for both FS-OUT and FS-IN cover a wider range and have broader peaks, whereas during the selected low-activity interval the envelopes show sharper, more concentrated peaks.

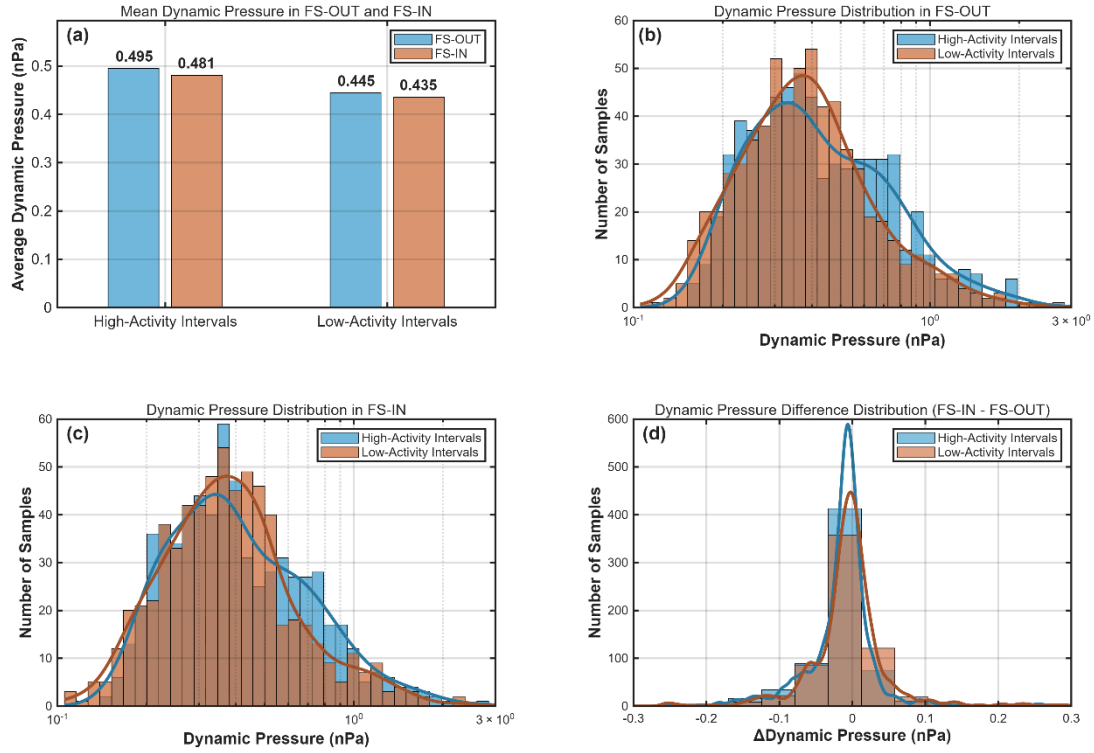


Figure 6. Comparison of solar wind dynamic pressure crossing the upper foreshock boundary during the selected high-activity and low-activity intervals, using the same format as Figure 4.

Figure 6 shows the comparison of the average solar wind dynamic pressure. Figure 6(a) shows that the mean dynamic pressure in the FS-IN region is lower than that in FS-OUT for both the selected high-activity and low-activity intervals. The dynamic pressure difference across the boundary is 0.014 nPa during the high-activity interval and 0.01 nPa during the low-activity interval, indicating a slightly greater decrease in dynamic pressure during the high-activity interval. Histograms in Figures 6(b) and 6(c) show that the distribution for the selected low-activity interval is more concentrated, while the distribution for the selected high-activity interval is more dispersed for both FS-OUT and FS-IN. Figure 6(d) shows that the distribution of the dynamic pressure difference (FS-IN minus FS-OUT) is mainly concentrated near zero, and the distributions for the selected high-activity and low-activity intervals are nearly identical. The magnitude of the dynamic-pressure decrease is only slightly larger during the selected high-activity interval (0.014 nPa) than during the selected low-activity interval (0.010 nPa).

3.2 Comparison of Magnetic Field Response

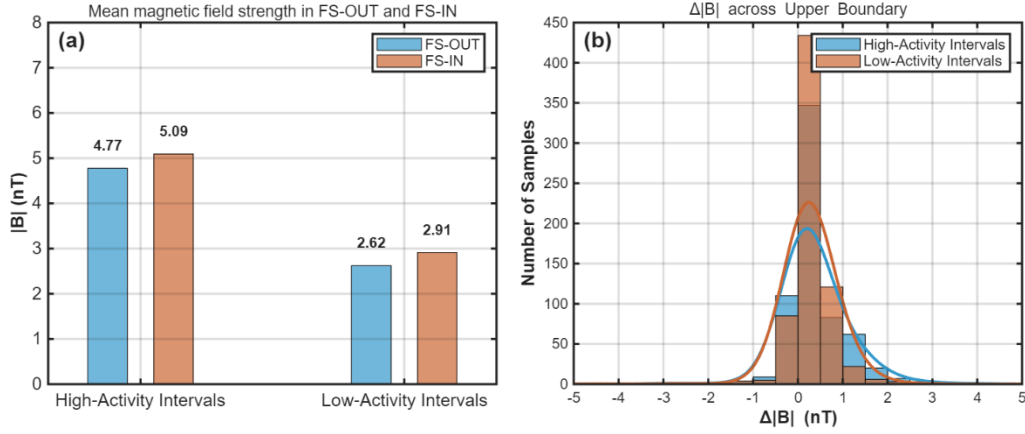


Figure 7. (a) Mean magnetic field strength in FS-OUT and FS-IN regions for the selected high-activity and low-activity intervals, (b) distribution of the magnetic field strength difference before and after the foreshock upper boundary. In panel (a), blue and orange denote FS-OUT and FS-IN, respectively; in panel (b), blue and orange denote the selected high- and low-activity intervals.

Presented in Figure 7 is the comparison of magnetic field characteristics across the Martian foreshock upper boundary during the selected high-activity and low-activity intervals. Figure 7(a) shows that the mean magnetic field strength in the FS-IN region is slightly higher than that in FS-OUT for both activity levels, with the increase being about 0.32 nT during the selected high-activity interval and 0.29 nT during the selected low-activity interval. The overall magnetic field strength is higher during the selected high-activity interval than during the selected low-activity interval in both regions. Figure 7(b) presents the distribution of the magnetic field strength difference $\Delta|B|$ across the upper boundary. The distributions for both the selected high-activity and low-activity intervals are concentrated near 0–0.5 nT, indicating that the average magnetic field variation across the boundary is relatively weak.

3.3 Boundary Distance and Parameter Correlations

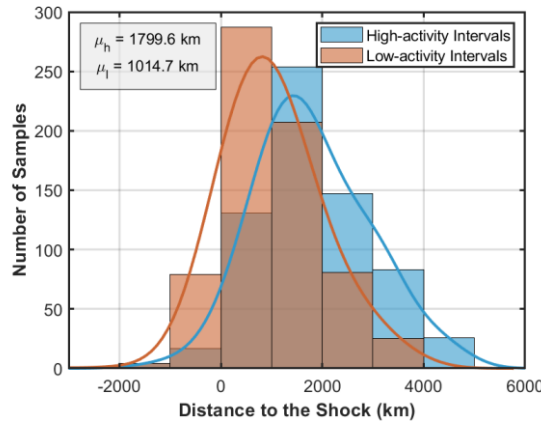


Figure 8. Distribution of the distance from the foreshock upper boundary to the bow shock along the MSO X-axis, based on the empirical shock model. The blue and orange refer to

distributions for the selected high-activity and low-activity intervals, with positive and negative distances indicating that the observed boundary is outside and inside the modeled bow shock, respectively.

Figure 8 presents the statistics of the distance from the foreshock upper boundary along the MSO X-axis to the modeled Martian bow shock. The results indicate that, in both high-activity and low-activity intervals, these distances are mostly concentrated within one Mars radius (~ 3390 km), presumably due to the observational constraints of the spacecraft orbit. The mean boundary distance is larger during the selected high-activity interval (1799.6 km) than during the selected low-activity interval (1014.7 km).

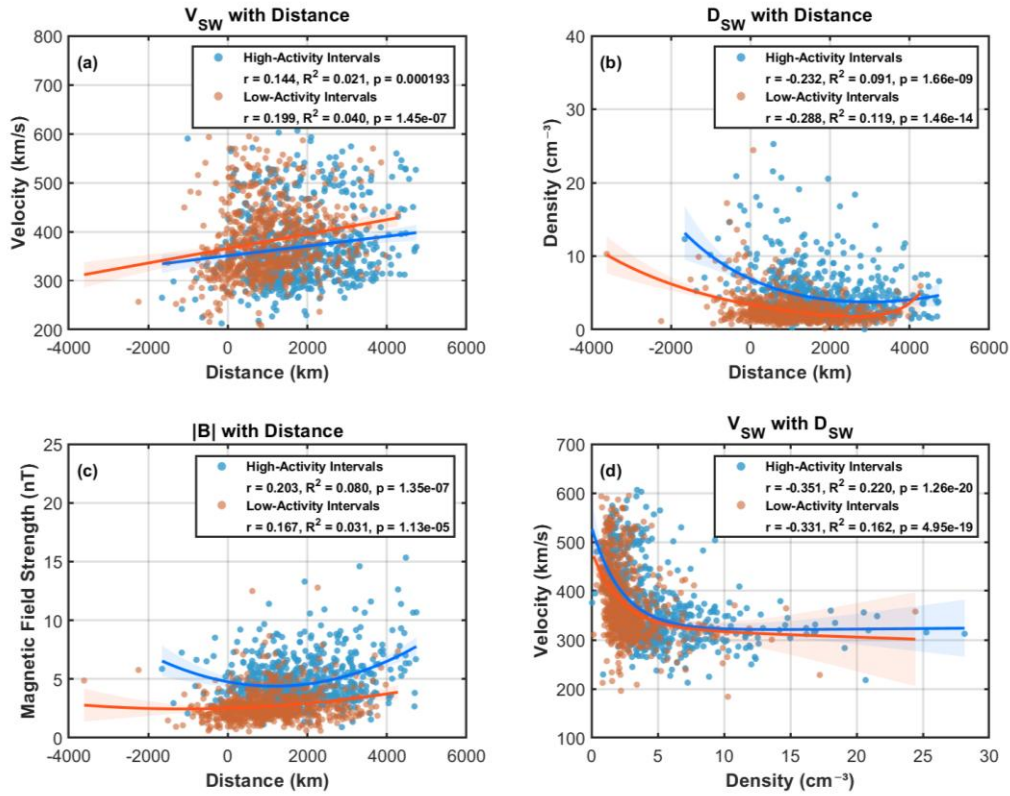


Figure 9. (a–c) Correlations of key parameters at the foreshock upper boundary (solar wind velocity, density, and magnetic field strength) with the distance of the boundary from the bow shock. (d) Correlation between solar wind velocity and density at the foreshock boundary. In all panels, blue markers and curves correspond to the 662 samples from the selected high-activity interval, while orange markers and curves correspond to the 686 samples from the selected low-activity interval. Solid curves represent the fitted relationships: a linear fit in panel (a), two-term exponential fits in panels (b) and (d), and a second-order polynomial fit in panel (c). The shaded regions indicate the corresponding 95% confidence intervals.

Further analysis on the relationships between key parameters at the foreshock upper boundary and the distance to the shock is shown in Figure 9. As the distance to the shock increases, the solar wind velocity increases (Figure 9(a)), while the density decreases (Figure 9(b)). This trend is found for both the selected high-activity and low-activity intervals. Given the same velocity level, the boundary during the selected high-activity interval is located farther from the shock than in the selected low-activity

interval. Overall, the density during the selected high-activity interval is slightly higher than in the selected low-activity interval. From Figure 9(c) we find that within the measured range of boundary distances, the magnetic field strength does not exhibit a systematic monotonic trend with distance. However, the field strength during the selected high-activity interval is higher than in the selected low-activity interval. Figure 9(d) shows an inverse relationship between solar wind velocity and density, and this trend is similar for both intervals. The correlation coefficients (r), p -values and R^2 values are provided in Figure 9.

4. Discussion and Conclusions

In this study, MAVEN observations during selected periods of high (2014–2015) and low (2018–2019) solar activity are utilized to identify and statistically analyze the properties of the Martian foreshock boundary, as well as the response of various parameters to solar activity levels. The main results are as follows: During the selected low-activity interval, the solar wind velocity in the foreshock region is generally higher, and the density jump across the boundary is more pronounced; in contrast, high-activity interval exhibits higher density levels and dynamic pressure, with the latter displaying a more dispersed distribution. Foreshock magnetic field strength is enhanced during the selected high-activity interval. The average distance from the foreshock upper boundary to the bow shock is larger during the selected high-activity interval than during the selected low-activity interval. The spatial position of the boundary shows statistical relationships with solar wind velocity and density: the closer the boundary is to the shock, the more pronounced the solar wind deceleration and density pile-up become.

The comparable change in velocity across the upper boundary during the selected high-activity and low-activity intervals indicates that solar activity has little impact on the velocity gradient at this boundary. The velocity distributions also show different characteristics between the two selected intervals, with a more evident bimodal structure during the selected high-activity interval. Such a structure may reflect different upstream or transient solar wind conditions (Coles, 1996).

During the selected low-activity interval, the solar wind density shows a larger increase across the foreshock upper boundary. Considering the statistical distribution of the distance between the upper boundary and the bow shock, the upper boundary during the low-activity period is located closer to the bow shock on average. Meanwhile, the solar wind density tends to decrease with increasing distance from the bow shock. Therefore, the larger density increase during the low-activity period may be related to the fact that the sampled upper boundary is closer to the near-shock region, where solar wind deceleration and density enhancement are more evident. The density within FS-IN is generally higher and more broadly distributed during the selected high-activity interval, whereas during the selected low-activity interval, the density distributions on both sides of the boundary are narrower, indicating a lower and more stable particle density, which may be related to the properties of the solar wind source regions during

high- and low-activity periods. From FS-OUT to FS-IN, the solar wind dynamic pressure generally decreases, reflecting energy dissipation due to deceleration. In FS-IN and FS-OUT, the dynamic pressure distribution for the selected high-activity interval is slightly shifted toward higher values compared to the selected low-activity interval.

During the selected high-activity interval, the overall field strength in the FS-IN region is higher, possibly reflecting persistent compression and reconfiguration of the induced or planetary magnetic field by the solar wind dynamic pressure. The distributions of $\Delta|B|$ across the foreshock upper boundary are similar during the selected high-activity and low-activity intervals, indicating that magnetic field variations near the upper boundary are not obviously affected by solar activity levels. We also find that the magnetic field strength near the foreshock upper boundary does not show a clear correlation with the distance from the bow shock, so we infer that the magnetic field strength is primarily due to the large-scale structure or turbulent fluctuations of the solar wind itself (e.g., Wang Y et al., 2018) and is not directly related to the distance from the bow shock.

Overall, the results of this study provide a preliminary statistical characterization of solar wind parameters around the Martian foreshock upper boundary, revealing the dependence of foreshock properties on solar activity. These results offer an important reference for understanding the interaction between unmagnetized planets and the solar wind. Future studies would benefit from larger datasets, which would allow the evolution of the foreshock boundary and its internal phenomena to be investigated over longer timescales. In particular, future work should examine how variations in solar activity influence the properties and evolution of the foreshock boundary, ultimately providing a better understanding of their potential impact on Martian atmospheric escape.

Acknowledgments

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were obtained at the Dominion Radio Astrophysical Observatory (DRAO) and are provided through the Solar Radio Monitoring Program of Space Weather Canada (<https://www.spaceweather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-3-en.php>). The program is operated jointly by the National Research Council Canada and Natural Resources Canada, with support from the Canadian Space Agency.

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