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Key Points:

- Multiple bow shock crossings (flapping) at Mars occur in 9% of the MAVEN passes
- Flapping is more common on the flanks and at southern dayside latitudes but is also influenced by solar wind conditions and IMF orientation
- Bow shock dynamics can influence plasma processes in the magnetosheath and induced magnetosphere below

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Statistical Analysis of Multiple Bow Shock Crossings at Mars

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Abstract We conduct a statistical analysis of multiple bow shock (BS) crossings at Mars. Data from the magnetometer (MAG) and Solar Wind Ion Analyzer (SWIA) onboard the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft from its first 2 years in orbit is used to identify flapping events. These are interpreted as the bow shock moving toward and away from Mars. 9% of all MAVEN passes occur when the BS is flapping. Such events are more common on the flanks than on the ramside and more common at southern dayside latitudes than in the north. The probability of flapping increases with increased dynamic pressure and decreased Mach number. The distribution of shock velocity and shock jump differ from the single-BS cases. The shock moves in a swaying motion on the time scale of minutes, and such dynamics could influence other processes at Mars, such as plasma waves, wave-particle interaction, and ion acceleration.

Plain Language Summary At Mars, the bow shock is a boundary where the solar wind—a stream of charged particles from the Sun—slows down abruptly as it encounters the planet's atmosphere. Sometimes, this boundary is not stable but moves back and forth in a swaying, or “flapping,” motion. Using 2 years of data from NASA's MAVEN spacecraft, we found that such flapping occurs during about 9% of MAVEN's orbits. These events are more common at the sides of the planet (flanks) and in the southern part of the dayside. We also found that flapping is more likely when the solar wind pushes harder against Mars (higher dynamic pressure) and when the solar wind speed relative to the sound and magnetic wave speeds (the magnetosonic Mach number) is lower. When flapping occurs, the properties of the shock and magnetic field change in ways that suggest a more dynamic and variable environment. These shock motions can affect how energy and particles move around Mars, potentially influencing plasma waves, particle acceleration, and interactions between the solar wind and Mars' upper atmosphere. Understanding these dynamics helps us better grasp how solar wind shapes the space environment around unmagnetized planets like Mars.

1. Introduction

Mars' obstruction to the supermagnetosonic solar wind leads to the formation of a bow shock (BS), where the solar wind is rapidly slowed down. This boundary has been extensively investigated in the past several decades, and in particular its statistical location, average shape, and controlling factors, using measurements from numerous spacecraft (e.g., Edberg et al., 2008; Gruesbeck et al., 2018; Hall et al., 2016; Mazelle et al., 2004; Simon Wedlund et al., 2022; Slavin & Holzer, 1981; Trotignon et al., 2006; Vignes et al., 2000). From these studies, it is clear that the boundary is not stationary on the time scale of an orbital period of a spacecraft. The solar wind magnetosonic Mach number, dynamic pressure, interplanetary magnetic field (IMF), solar extreme ultraviolet radiation (EUV) and season (L_s) are external factors that have been reported to influence the shock location, while internal factors of importance include the properties of the ionosphere (e.g., its plasma density and pressure) and the crustal magnetic fields (Cheng et al., 2024; Edberg et al., 2009, 2010; Fang et al., 2017; Fruchtman et al., 2023; Garnier et al., 2022; Němec et al., 2020; Vignes et al., 2002). From one orbit to the next, the BS can be observed at significantly different locations. Furthermore, the solar wind parameters can change on timescales shorter than the typical spacecraft orbital period, and the BS presumably responds rapidly, within at least a few ion gyro-periods. Multiple shock crossings are also often observed in spacecraft data, interpreted as a response of the BS to a change in ambient conditions causing it to flap past the spacecraft several times. Such motion of the Martian BS has received less attention in past studies and is the prime focus of this paper.

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In addition to causing the BS to move, there are a number of upstream plasma processes and phenomena that can influence the local structure and properties of the BS. Rather than the BS moving, it can also reform or form ripples when the ambient conditions change, as shown to occur at, for instance, Earth and Venus (Dimmock et al., 2022; Johlander et al., 2016; Madanian et al., 2020). Due to the relatively low gravity of Mars, its exosphere is extended and the mass-loading of the solar wind (when exospheric neutral particles are ionized and picked up by the solar wind flow) reaches far beyond the BS. In this region, a variety of high- and low-frequency foreshock waves are common (Mazelle et al., 2004). Hot-flow anomalies (HFA) (Collinson et al., 2015; Shuvalov et al., 2019), and so-called short large-amplitude magnetic structures (SLAMS) (S. D. Shuvalov & Grigorenko, 2023) have been observed. Back-streaming ions and electrons from the BS form a large foreshock region on the quasi-parallel side of the upstream plasma environment. All of these processes build up a complex environment in which the BS forms.

Currently, there are three spacecraft operating in orbit around Mars that are capable of observing the BS: Mars Express, Mars Atmosphere and Volatile Evolution (MAVEN), and Tianwen-1. Cheng et al. (2023) built a case study of an oscillating movement of the BS, when MAVEN and Tianwen-1 were positioned favorably with respect to each other and the BS. They presented direct evidence that changes in the solar wind dynamic pressure and the IMF direction caused the BS to move on the time scale of minutes. Such a spacecraft configuration is not always present, and for a first statistical investigation of the flapping, we will use single-spacecraft measurements from MAVEN. Naturally, from single-spacecraft measurements, it is challenging to separate spatial from temporal changes in a plasma flow, such as the movement of a plasma boundary. However, from distributions and statistics, and with comparisons to single BS crossing statistics, there are discernible properties to study.

The motion of the BS is interesting to investigate in a broader context, since it can reveal features of the Mars-solar wind interaction important to consider for understanding the dynamics of the system and, in particular, the energy and momentum transfer. Multiple BS crossings are hitherto mostly left unattended in past research, and are therefore interesting to characterize in their own right, but also in the advent of upcoming dedicated multi-spacecraft missions.

In Section 2 we introduce the measurements and data used, show examples and statistics of multiple BS crossing events, and study potential controlling factors. In Section 3 we discuss the results before ending with our conclusions in Section 4.

2. Observations

The MAVEN spacecraft has been in an elliptic and precessing orbit around Mars since late 2014. Over the course of a Martian year, MAVEN's orbit changes with respect to the direction of the Mars-Sun line such that it often crosses the BS. With an orbital period of about 4 hr, some 2500 BS crossings occur every year, on average.

We use 1 Hz magnetometer (MAG, Connerney et al., 2015) data, combined with Solar Wind Ion Analyzer (SWIA, Halekas et al., 2015) data to identify shock crossings by MAVEN and to determine upstream/downstream solar wind/magnetosheath plasma and field properties. The SWIA time resolution of the plasma moment data products used here has a cadence of 4–8 s. The energy range and field of view also change throughout an orbit and the mission, which is described in more detail by Halekas et al. (2017).

To build statistics of flapping BS events, we have performed a by-eye search of multiple BS crossing events in the MAG data from the first 2 years of the mission. We restrict our study to a 2-year period, which provides reasonably good coverage of events around Mars while remaining manageable in terms of analysis time. The main criterion for a single BS crossing is a sharp and significant increase/decrease (when moving inbound/outbound, respectively) in the magnetic field magnitude that stands out from any other variation in the vicinity. The shock should be followed by turbulent magnetic fields in the magnetosheath/steady conditions in the solar wind. Further criteria also exist, such as a change in the ion and electron spectra and moments, which were used in only a few uncertain events in this study. A multiple BS crossing event is then a series of such BS crossings close in time (within minutes). One additional criterion for determining whether it is a shock crossing, and not some other plasma phenomenon, is to study the average amplitude of the magnetic field downstream of the BS. This can be assumed to have roughly the same magnitude between the individual crossings during flapping, or that there is at least a smooth gradient across the individual crossings. An eye search is inherently subjective, but the identification of multiple crossings is fairly straightforward. However, a few caveats should be mentioned; (a) it can be

difficult to separate BS fluctuations with a frequency less than about 1 min from other types of foreshock or magnetosheath waves, (b) the exact time of a crossing is more difficult to pinpoint when the BS is quasi-parallel due to enhanced wave activity, and it being less sharp than quasi-perpendicular shocks, (c) other upstream phenomena exist, such as SLAMS, HFA, proton cyclotron waves, steepened foreshock waves, shock ripples and reformation, which can make a shock crossing challenging to identify. However, the difference in amplitude, time scale, and frequency of the oscillations makes it relatively easy to separate them out. HFAs, for example, are estimated to occur once a day (Shuvalov et al., 2019) and last a few minutes each. Therefore, it is not likely that they would often occur at the same time as the BS crossing.

Figure 1 shows five examples of multiple BS crossing events, in time series of magnetic field and ion differential energy flux (DEF) data. In Figures 1a and 1b three clear crossings are observed sequentially with fairly steady upstream and downstream conditions. The ion spectrogram of differential energy flux confirms the transition from solar wind to heated magnetosheath plasma. Figures 1c and 1d shows another example, but now with generally higher wave activity in the sheath and solar wind, leading to a more uncertain timing for the final shock crossing. Figures 1e–1j show cases with five or seven crossings during a single pass, with a range of characteristics to illustrate the variability. A dashed vertical line indicates an inward-moving BS (toward the planet), while a dash-dotted line indicates an outward-moving BS. This is assuming that the spacecraft speed is much lower than the shock front moving back and forth, causing alternating forward and reverse shocks. A shock crossing can occur when the BS is stationary and the spacecraft moves past it, or due to the BS itself moving. At Earth, bow shock velocities are typically found in the range 10–100 km s⁻¹ (Kruparova et al., 2019). By analogy, the Martian bow shock is expected to move at least as rapidly, and possibly faster, owing to the absence of a magnetopause to buffer solar wind variations. Alternatively, the BS could also reform ahead of the spacecraft such that multiple crossings can occur, or the spacecraft crosses a rippled or filamented shock. However, the timescale of reformation should generally occur on time scales shorter than 1 min and closer to an ion gyro-period (on the order of seconds) and, in the case of ripples, more periodic (Dimmock et al., 2022; Johlander et al., 2016). We did not find any preference for small angles between the orientation of the shock and the spacecraft trajectory.

Of the ~4,000 orbits from the first 2 years (Nov 2014– Oct 2016) of MAVEN operation, ~1,500 were excluded from our analysis when apoapsis was not outside the model BS location. Of the remaining 2,364 orbits, a flapping BS was identified in 435 instances, corresponding to 18% of all orbits, or roughly 9% of all passes (inbound or outbound). A total of 2014 single BS crossings were recorded, such that on average there are five crossings during each flapping event. Having obtained a statistical set of multiple BS crossings, the next step is to investigate their properties.

2.1. Properties of Multiple Bow Shocks

Figures 2a–2d show the location of all BS crossings during flapping events, in aberrated (4°) MSO coordinates. The orbital coverage around Mars is fairly even after 2 years of measurements with respect to the $\pm y$ and $\pm z$ hemispheres, allowing us to limit our analysis to this interval. There are somewhat more multiple BS crossing events at southern latitudes than at northern latitudes (252 and 183, respectively), and more in +y hemisphere than in the -y hemisphere (247 and 188, respectively). Figure 2e shows the occurrence rate of the identified events, calculated as the number of passes with observed flapping in a bin divided by the total number of orbital passes through that bin. More events are observed on the flank than on the dayside, and the very few events just at the nose might bias the statistics in this particular area, but the overall statistics are still robust.

Figure 2f shows the time between each consecutive crossing during one pass and is subdivided into first to second, second to third and third to fourth crossing (ordered by decreasing distance to Mars). The time between crossings is around 2 min (median value) and does not seem to change significantly between the different populations, indicating that there is no significant acceleration or deceleration of the BS flapping with distance to Mars, at least not observable with one spacecraft. The time difference corresponds to a distance of around 0.1 R_M with a S/C velocity of a few km/s. The time it takes the spacecraft to cross the actual shock surface is typically a few seconds to tens of seconds. The BS does have a finite thickness, which also prevents the identification of higher frequency flapping.

To investigate the properties of multiple shock events, it is useful to compare with single BS crossings as a reference. For this, we have re-used the shock data base of Simon Wedlund et al. (2022), including only the crossings from the same time interval, and removed from that list all events identified by us as multiple crossings,

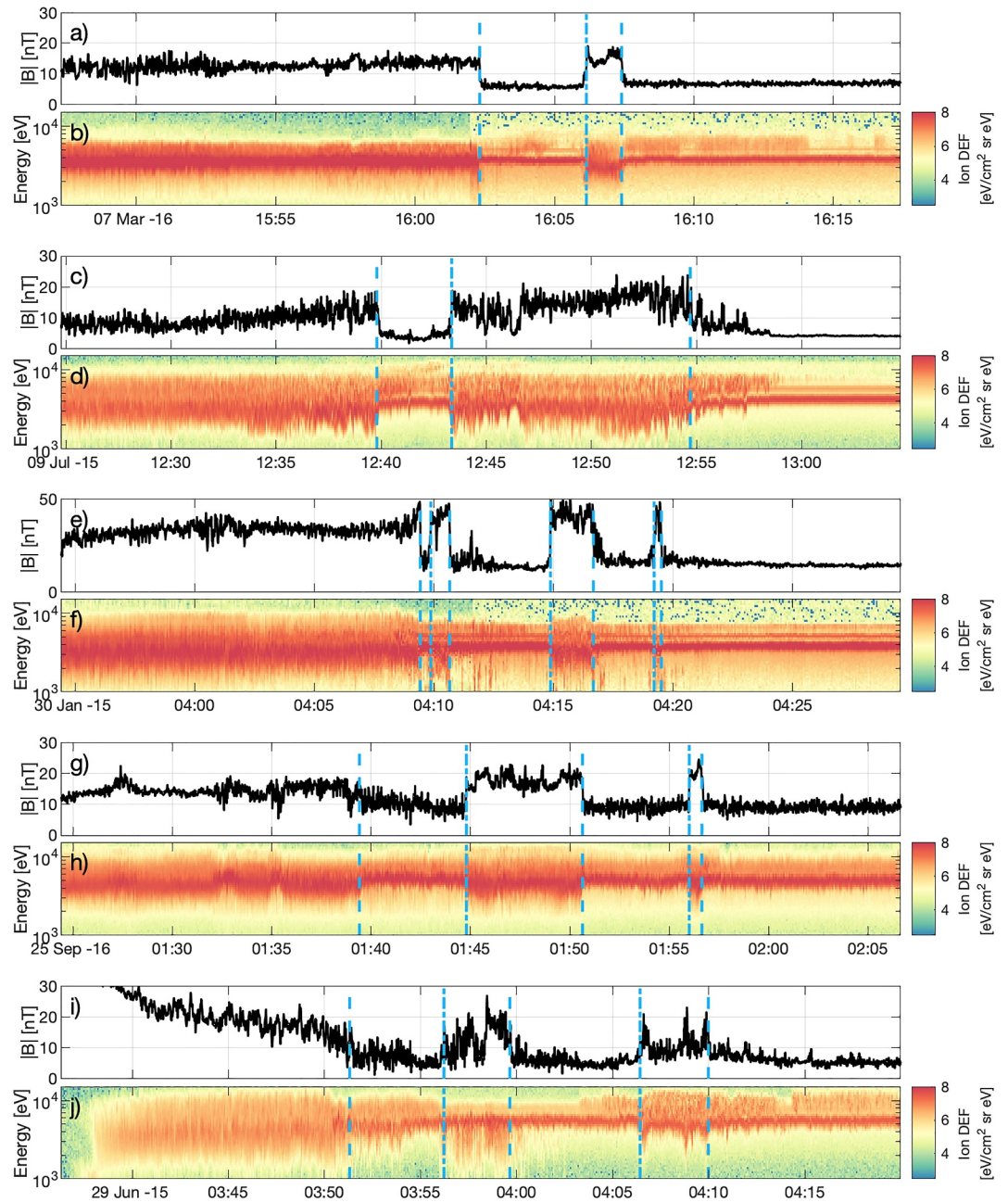


Figure 1. Five examples of time series of (a, c, e, g, i) magnetic field magnitude and (b, d, f, h, j) ion DEF spectrogram during multiple BS crossing events, which are interpreted as flapping motion of the boundary. The vertical blue lines indicate an individual BS crossing, with dashed and dash-dotted lines representing an inward and outward moving BS, respectively, if assuming the BS moves much faster than the S/C orbital speed. All five examples are from the outbound leg of the respective orbit, with the magnetosheath to the left and the solar wind to the right in each panel.

giving a total of 4,563 single BS crossings to compare with. Upstream and downstream plasma parameters (density n_u, n_d , temperature T_u, T_d , velocity $\mathbf{v}_u, \mathbf{v}_d$) and magnetic field ($\mathbf{B}_u, \mathbf{B}_d$) are estimated from SWIA moments and MAG measurements averaged over 3 min upstream/downstream of each individual shock. The averaged-over interval can be shorter than 3 min in the cases where two adjacent crossings are closer in time than that.

In Figures 3a and 3b we show the magnetic field shock jump $\Delta B = |\mathbf{B}_d| - |\mathbf{B}_u|$, normalized to the upstream field $|\mathbf{B}_u|$, for the multiple crossings and the single crossings separately. This property is clearly different between the

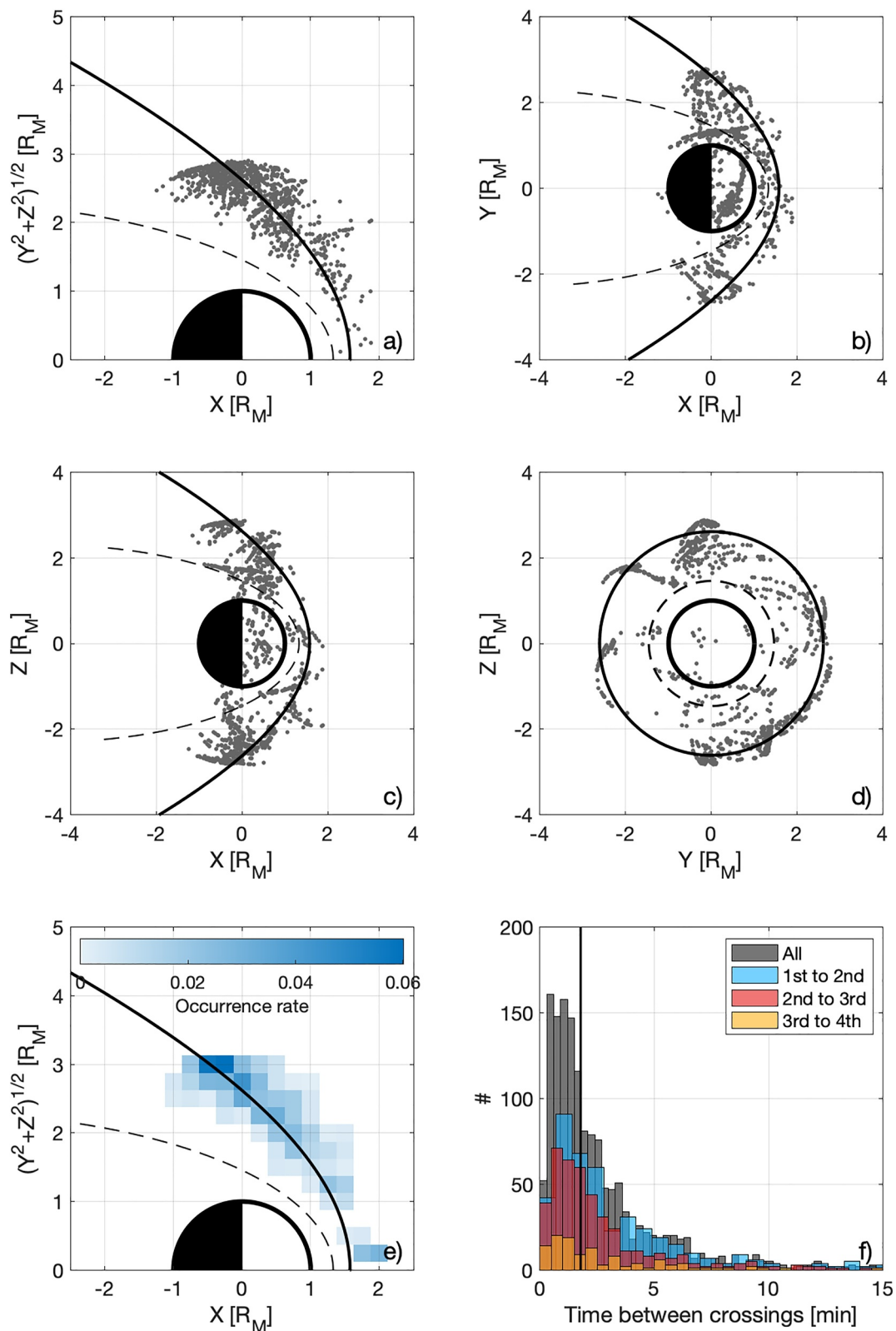


Figure 2. Location of all multiple BS crossings shown in aberrated MSO reference frame, in (a) cylindrical coordinates and (b, c and d) projections on three planes. (e) Occurrence rate of flapping, estimated as number of orbits with flapping in each bin divided by the total number of orbit passes through that bin. The model BS and IMB from Edberg et al. (2008) are shown in each panel as solid and dashed lines, respectively. (f) Time between consecutive crossings for multiple BS crossing events. The median value is indicated by the black vertical line.

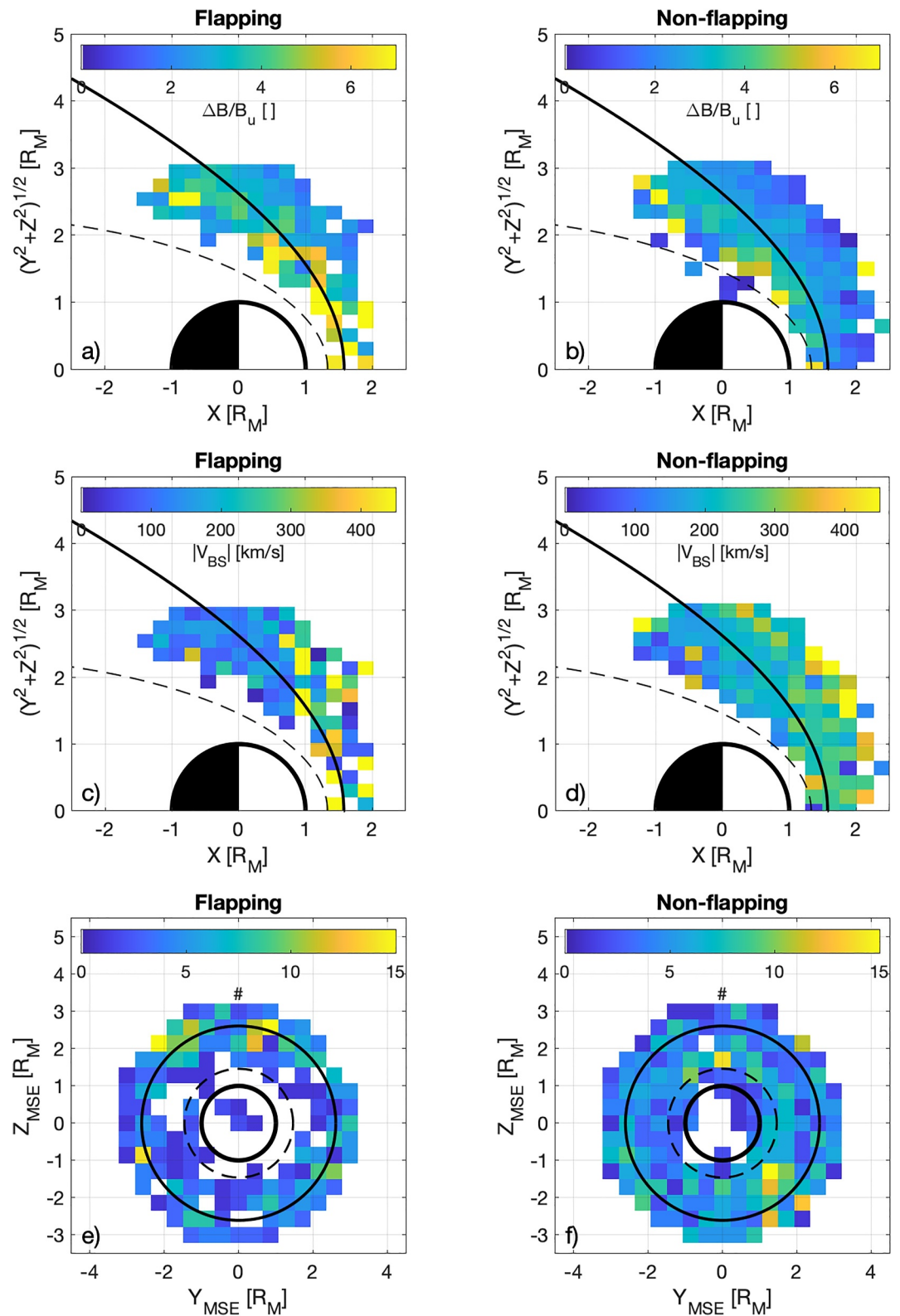


Figure 3. Comparison between multiple BS (left) and single BS (right, from Simon Wedlund et al. (2022)) of (a, b) the magnetic field strength jump across the shock, (c, d) the shock velocity from flux conservation laws, shown projected in aberrated MSO coordinates, and finally (e, f) the location of crossings in the MSE reference frame.

two populations, with the flapping BS having higher overall values, at least below the model shock location (solid black line).

Shock velocity cannot be estimated from the time difference between two consecutive crossings, as that would only give the spacecraft velocity. Instead, in Figures 3c and 3d we show the shock velocity for each single crossing calculated when assuming flux conservation across the shock $V_{BS} = \Delta(\rho\mathbf{v})/\Delta\rho \cdot \hat{\mathbf{n}}$ (Schwartz, 1998), where ρ is the plasma density and $\hat{\mathbf{n}}$ the normal direction of the shock, obtained from the co-planarity theorem. The shock velocity appears to generally be slower for the flapping shock, while for this population it is also generally higher on the dayside than on the flanks. The median magnitude of all of the multiple shocks' velocity is 84 km/s, while for single crossings it is 141 km/s, although both with considerable spread in their respective distribution.

In Figures 3e and 3f we also compare the influence of the convective electric field, by rotating the position of each crossing into the MSE frame, where the y-axis aligns with \mathbf{B}_u and the z-axis is parallel to $\mathbf{E}_{\text{conv}} = -\mathbf{v} \times \mathbf{B}_u$. There is a tendency to have more flapping in the +E hemisphere than in the -E hemisphere, which cannot be seen for the single crossings.

2.2. Solar Wind Influence

Next we investigate the possible influence of solar wind parameters, including IMF/shock geometries. For this, we compare the average ambient upstream solar wind conditions during orbits with BS flapping events to those during non-flapping events. Figure 4 shows comparisons of distributions of solar wind dynamic pressure P_{dyn} , magnetosonic Mach number M_{MS} , standard deviation of P_{dyn} and M_{MS} , as well as Martian season L_S and θ_{Bn} (angle between local shock normal and the IMF) for the flapping and the non-flapping populations. The ratio between each bin of the two populations are also shown. The upstream solar wind parameters are now calculated as median values over the fraction of the orbit when MAVEN was in the solar wind before/after crossing the shock. When the dynamic pressure increases, or when the Mach number decreases, the ratio of flapping to non-flapping BS increases to almost the double compared to the minimum values, noting that the (Poisson) error bars grow in size. The respective standard deviation (Figures 4c and 4d) could indicate a preference for flapping to occur during more variable upstream dynamic pressure, but again noting the large error bars. For L_S , shown in Figure 4e, there is no obvious trend emerging. Figure 4f displays distributions of θ_{Bn} , for flapping and non-flapping shocks. It should be noted that most of the single MAVEN BS crossings, which are used for the comparison here, are quasi-perpendicular (Simon Wedlund et al., 2022). The ratio between the two populations indicates a higher probability of flapping when the BS is quasi-parallel, but statistics is poorer for quasi-parallel cases.

3. Discussion

The Martian BS is a permanent feature arising from the solar wind interaction, but its location is not stable. It varies from orbit to orbit, as many previous studies have shown. Here we have provided a statistical analysis of the dynamic movement when it is observed to move back-and-forth rapidly past the spacecraft, that is, flapping. Such movement of the BS is observed with a probability of about 9% during a S/C pass. There are several properties and controlling factors of this dynamic feature that are worth discussing.

There are an equal number of crossings outside of the model BS as inside of it, suggesting that there is no altitude dependence on the flapping occurrence rate (Figure 2a). However, flapping occurs more frequently on the flanks than on the ram side (Figure 2e). This suggests a swaying or wavering motion of the BS, with a more fixed BS at the subsolar point than at the flanks, rather than a global expansion/contraction as a rigid surface. The orbital coverage of MAVEN reveals that flapping does not normally reach beyond $2 R_M$ on the dayside but is common to a distance of at least $3 R_M$ on the flank, where MAVEN reaches apoapsis. We also note that the median interval between two consecutive BS crossings is about 2 min, and longer than 3.5 min in 25% of the cases, although it is not possible to directly translate this to any relevant velocity with single-spacecraft measurements.

It is also interesting to note that the shock jump (Figures 3a and 3b) is generally higher for multiple BS than for single BS crossings, at least below the model BS location. The shock velocity distribution (Figures 3c and 3d) is also different, with generally lower values on the flanks than on the dayside, while for single crossings the shock

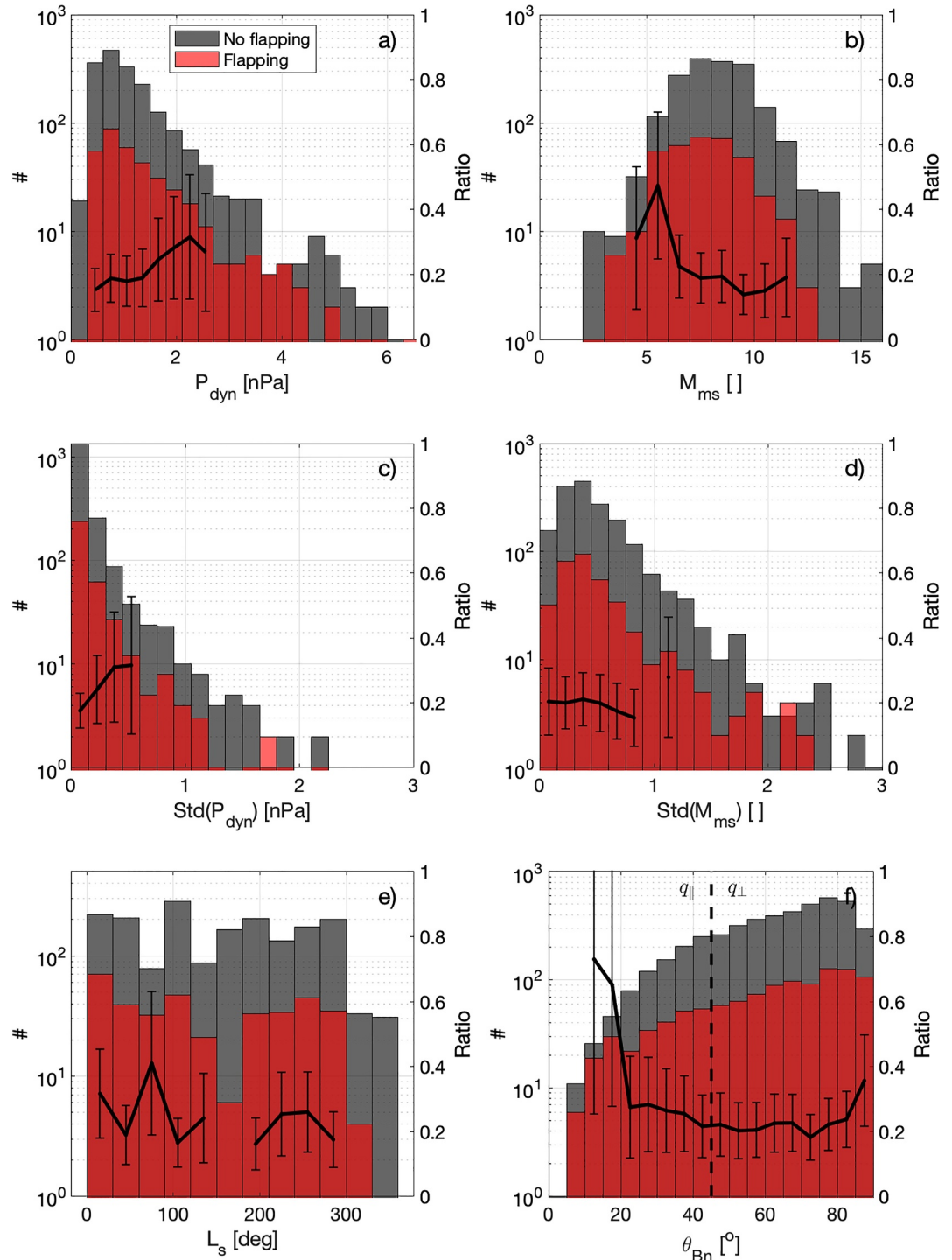


Figure 4. Comparison of solar wind conditions during orbits of flapping and non-flapping BS. The histograms show orbit-averaged (a) dynamic pressure, (b) magnetosonic Mach number, (c) standard deviation of the dynamic pressure, (d) standard deviation of the magnetosonic Mach number, (e) L_s and (f) θ_{Bn} . The ratio between each populations (excluding bins with less than 10 data points) is indicated by the solid black line, with the scale to the right.

velocity is generally higher farther away from the planet. This suggests a motion and dynamics of the BS during flapping events different from the single BS crossing cases.

The cause of the shock flapping seems to be multifaceted with several factors in play:

1. High dynamic pressure and low Mach number solar wind seem to be preferred conditions for BS flapping to occur (Figures 4a and 4b), but with large uncertainty judging from the error bars.
2. Flapping is somewhat more probable when the shock is quasi-parallel than when it is quasi-perpendicular (Figure 4f), although the statistics are poorer for quasi-parallel shocks. An asymmetry could also be caused by the solar wind convective electric field, pointing locally toward/away from the planet (Figures 3e and 3f).
3. There are more flapping BS events recorded in the southern hemisphere, where the crustal magnetic fields are predominantly located, than in the north (252 and 183, respectively). To rule out any orbital bias, we note that for the non-flapping BS crossings from Simon Wedlund et al. (2022), there is almost an equal number of non-flapping BS crossings in the southern and northern hemispheres for the same interval (2,270 and 2,294, respectively). If separated into dayside crossings alone ($x_{MSO} > 0.5 R_M$), there are still more multiple BS crossings in the south (80 and 52, respectively, while there are 1,246 and 1,443 single crossings in the respective hemisphere). However, on the flanks ($x_{MSO} < 0.5 R_M$), where most multiple crossings are found, there is no significant difference in the ratio to single crossings between south and north (172/1,024 compared to 131/851). Hence, only flapping on the dayside could be related to the presence of crustal magnetic fields, which locally add additional, and more variable, magnetic pressure and push the induced magnetosphere and BS outward.

We observed no trend in the flapping with L_S . It might be that 2 years of data, equivalent to one Martian year, is insufficient to see any trend and that further data is needed. We can speculate that as the EUV flux increases and the exosphere expands, the BS might behave differently, but the data used in this study does not seem to suggest this to be a major controlling factor. Additionally, we can speculate that upstream plasma processes, such as the aforementioned HFA or SLAMS could be occurring upstream and could effectively be the cause of the BS flapping further downstream. This, together with the IMF/shock geometry, crustal magnetic fields and convective electric field direction, implies that the BS can oscillate on one side of the planet while being steady on the other side, contributing to an asymmetric BS shape, while at the same time an intricate interplay between several factors drives the BS dynamics.

4. Conclusions

Multiple Martian BS crossings, interpreted as a back-and-forth motion of the shock on the time-scale of minutes, are frequently observed at Mars. Occurrence rate and distributions suggest a swaying/wavering motion, with a more stationary sub-solar BS location. The distributions of the shock jump and the shock velocity during flapping events differ from single-BS cases, also indicating a dynamic motion different from the non-flapping BS. Several factors are involved in causing the flapping, including solar wind dynamic pressure and magnetosonic Mach number, IMF orientation, and crustal magnetic fields. It should not be uncommon to have an asymmetric BS, when the BS oscillates on one side of the planet while remaining fixed on another. The flapping is more common when the solar wind dynamic pressure increases or the magnetosonic Mach number decreases.

Overall, dynamics of the BS is important in a broader geophysical context because it can have implications for energy and momentum transfer through the Martian system. Compression/rarefaction in the shock lead to variations in the magnetosheath plasma, which might enhance the wave activity and affect wave-particle interaction, or even reconnection which enhances the energy dissipation. Mirror-mode, ion-cyclotron or ULF waves are likely affected by an unsteady BS. Increased wave-activity, in general, could be modulating ion acceleration and ion pick-up, which in turn affect ionospheric outflow.

Because the BS moves rapidly and on short time scales, instantaneous upstream monitoring, or numerical simulations with time-varying boundary conditions, are needed to more properly study the flapping and its controlling factors, but here we at least provide the first statistical study of them. Studies of any effects the flapping might have on the plasma system beneath (wave enhancement, ionospheric outflow, aurora etc.) remains to be studied in the future, preferably with dedicated multi-spacecraft missions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The MAVEN data are publicly available from NASA's Planetary Data System (<https://pds-ppi.igpp.ucla.edu/mission/MAVEN>) and AMDA (<https://amda.irap.omp.eu/>). The data of the identified BS crossings including upstream solar wind parameters are available on Zenodo (N. Edberg, 2025).

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