Statistical Analysis of the Distribution and Evolution of Mirror Structures in the Martian Magnetosheath

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Abstract

The mirror-mode structures in the Martian magnetosheath that were observed by Mars Atmosphere and Volatile Evolution during 2015–2018 are analyzed statistically. It is found that most mirror-mode events occurred close to the bow shock. Morphological categorization based on skewness of the magnetic field shows that ~46.57% of the observed mirror-mode events are peak-like, ~40.25% are wave-like, and ~13.18% are dip-like. The mirror-mode structures mostly saturate in a very short time after their formation near the bow shock, which is a result of the high temperature anisotropy and high plasma beta at this location. Carried downstream by the magnetosheath flow, the mirror-mode structures remain in nonlinear saturation states. Meanwhile, the dayside magnetosheath plasma largely deviates from marginal stability, which is a state commonly that is expected in the terrestrial magnetosheath. By flowline tracing in an MHD model, it is found the mirror structures can be divided into two groups: ~80% of the events that are observed near the bow shock evolve less than 10 s in plasma with high temperature anisotropy and high plasma beta value, keeping in saturated states; the other 20% of the events evolve following a similar process to that at the Earth, undergoing morphology transition in response to the local plasma conditions. However, the dayside magnetosheath is largely in an unstable condition, which prevents the mirror-mode structures from fully evolving into the decaying phase. Our results suggest that energy dissipation through wave-particle interaction might not be sufficient to remove the free energy that is introduced by the solar wind–Mars interaction.

Unified Astronomy Thesaurus concepts: Planetary magnetospheres (997); Mars (1007); Space plasmas (1544)

1. Introduction

The mirror-mode structure, which are commonly considered to be a consequence of the development of mirror-mode instability in plasma with temperature anisotropy, is widely seen in the magnetosheath of the Earth and other planets (e.g., Hasegawa 1969; Violante et al. 1995; Zhang et al. 2008; Volwerk et al. 2008), comets (e.g., Russell et al. 1987). Downstream of the quasi-perpendicular bow shock, the preference of heating plasma in the perpendicular direction leads to temperature anisotropy that favors mirror-mode instability to grow (e.g., Mckean et al. 1995; Scopke 1995). Thus, it is widely considered that the mirror-mode structures that are observed in the magnetosheath originate near the bow shock. After they are formed, the structures remain non-propagating in the reference frame of the plasma, convecting downstream with the magnetosheath flow toward the magnetopause, where plasma becomes mirror-stable and structures start to collapse. Recent multi-spacecraft observations have revealed that the propagation properties of the dip-like structure depends on its scale, and only the MHD-scale dips are frozen in the plasma flow (Yao et al. 2020).

Previous studies by Fuselier et al. (1994) and Anderson et al. (1994) confirmed that the mirror-mode instability contributes to keep the terrestrial magnetosheath marginally stable. Statistical analyses of various aspects of the mirror-mode structure have been carried out based on observations mainly near the Earth (e.g., Soucek et al. 2008; Génot et al. 2009; Dimmock et al. 2015). Dimmock et al. (2015) from THEMIS observations found dusk-favored asymmetry of ion temperature anisotropy distribution in the magnetosheath of the Earth, which is consistent with the asymmetrical distribution of the mirror-mode structures. From the Voyagers’ flyby of the magnetosheaths of Jupiter and Saturn, Cattaneo et al. (1998) found the shape of mirror-mode structures transit from a quasi-periodic waves downstream of the bow shock to more isolated, dip-like near the magnetopause, along with decrease in plasma beta. In a paper studying mirror-mode structures in the Jovian magnetosheath (Joy et al. 2006), the authors categorized the structures into three types (i.e., wave, peak and dip) according to their magnetic field amplitude waveform, and suggested that each type belongs to a different evolutionary stage. Comparing with the MHD simulation result, the authors estimate that structures would decay to dip-like about 40 hr after their formation near the bow shock. Similar studies were carried out by Soucek et al. (2008), who used Cluster data but a slightly different categorization method. The authors showed that more structures transit from peak-like to dip-like with increasing distance to the bow shock. They also suggest that the distance to the instability threshold (see Equation (1) for definition) is closely related to the shape of the structure, and that a declining skewness value is also accompanied by decreasing plasma beta and hence the distance to the threshold.

Both the anisotropic fluid theory (e.g., Hau & Sonnerup 1993) and the linear kinetic theory (Hasegawa 1969) can be used to describe the growth of mirror-mode structures in their linear phase; however, the behavior of the structure when saturated is not yet clearly understood. An early model...
predicted that the cooling of trapped particles will result in the formation of dips (Kivelson & Southwood 1996). Adopting a saturation mechanism by variation of the local ion Larmor radius, Kuznetsov et al. (2007) revealed the bifurcation feature of the mirror-mode where dips can exist both above and below the threshold. Numerical solution of the Vlasov-Maxwell equations indicates that peak-like structures develop directly from nonlinear saturation of the mirror-mode instability, while the equations have stable solutions both below and above the threshold in the form of large-amplitude magnetic holes (Califano et al. 2008). By comparing observation with hybrid simulation, Génot et al. (2009) proposed that the distance to the instability threshold is the key factor that influences the shape of the structure—as the plasma approaches the marginally mirror stable state, the mirror-mode structures transform from magnetic peaks to magnetic holes. In a following paper (Génot et al. 2011), using an analytic flowline model, the authors calculated the evolution time of structures emerging near the terrestrial bow shock. They estimated that structure decays at a similar position if scaled to the Jovian magnetosheath, which was qualitatively confirmed by a more recent PIC simulation study (Ahmadi et al. 2017).

Observations revealed that significant temperature anisotropies prevail throughout the Martian magnetosheath, which suggests favorable conditions for the growth of mirror and/or ion cyclotron instabilities in the magnetosheath (Halekas et al. 2017a). Actually, there have been several observational studies on the mirror-mode structures in the Martian magnetosphere. Using Mars Global Surveyor magnetic field and electron data, Bertucci et al. (2004) first reported observation of mirror-mode structures near the induced magnetopause. Further investigation by Espley et al. (2004) suggested that the mirror-mode is the dominant low frequency wave in the dayside magnetosheath. Ruhunusiri et al. (2015) presented a general picture of low frequency wave occurrence around Mars, which indicated that mirror-mode structures are mostly located in the magnetosheath but their occurrence is much lower than the other wave modes. Recently, by combining field, ion and electron data, Simon Wedlund et al. (2022) presented a case study of the mirror-mode structures that are observed in the magnetosheath near the induced magnetopause and suggested that these structures are most likely to have originated behind the quasi-perpendicular shock.

So far, compared with the extensive studies on the mirror-mode structures in the terrestrial magnetosheath, much less work has been done at Mars due to the lack of data support. There are still ambiguities in the distribution of mirror-mode structures at Mars. For an unmagnetized planet such as Mars, whose magnetosheath is much smaller than the terrestrial magnetosphere, the evolution of the mirror-mode structure inside such a magnetosheath is largely unknown. In this paper, using data from the MAVEN probe, we statistically study the spatial distribution and evolution of the mirror-mode structures.

2. Data and Data Processing

2.1. Data Usage

Data from MAVEN probe is adopted in this study. Since its arrival at Mars in 2014, MAVEN has been following an elliptic orbit and has provided abundant in situ measurements covering different regions in the Martian space environment. We use MAG (Connerney et al. 2015), SWIA (Halekas et al. 2013) and STATIC (McFadden et al. 2015) data from the year 2015–2018 in this study. MAG provides high-resolution magnetic field data in both 1 Hz and 32 Hz. SWIA and STATIC provide three-dimensional differential flux data of the solar wind proton and other ion species with a time resolution of 4 s (SWIA) and 128 s (STATIC d0 package), respectively. MAG data are down-sampled (from 32Hz) to match the SWIA time resolution as required by the wave identification algorithm that will be described in Section 2.2. Corresponding to the temporal resolution of SWIA(4s), the frequency of the wave that we can identify is low (<0.125 Hz). Hence, we can only identify structures with a scale that is larger than 1200 km, supposing that the structure propagates at a speed of 150 km s\(^{-1}\). Consequently, we will only discuss large-scale mirror-mode structures in this paper.

2.2. Plasma Parameters in the Magnetosheath and Identification of Mirror-mode Structures

After the magnetosheath regions are isolated according to the magnetic field fluctuation, plasma density, velocity and temperature (Halekas et al. 2017b), the plasma parameters, including moments and derived parameters such as thermal and magnetic pressure, are calculated at each sampling point of the STATIC d0 data package. The moments calculated from STATIC are cross checked with SWIA onboard-calculated plasma moments. All coordinates are then converted into the MSO cylindrical X–R plane (with X-axis identical to that in MSO frame and \( R = \sqrt{Y^2 + Z^2} \)), within a range of \(-3R_M \leq X \leq 3R_M\) and \(0 \leq R \leq 3R_M\) (\(R_M\) is Mars’ radius, \(1R_M = 3396\) km). The plane is divided into 0.05\(^{-1}\)SZA bins, and within each bin, median values of observations are calculated to represent plasma characteristics at given location. The magnetosheath data cover a range radially up to \(\sim 2.9R_M\), azimuthally up to solar zenith angle (SZA) \(\sim 145^\circ\).

Next, the mirror-mode structures are identified using an automatic algorithm which utilizes the magnetic field and particle data to distinguish the compressed and anticorrelated features between \(|B| \) and particle density (Song et al. 1994; Ruhunusiri et al. 2015). MAG data are hence down-sampled to match SWIA data. We use a 5 minutes window with 1 minute sliding step. For each auto-selected sample, another method using magnetic field data alone is used for further screening. This method, which is also widely used in identifying mirror-mode structures (e.g., Soucek et al. 2008; Génot et al. 2009), examines the amplitude of magnetic field fluctuation (requires \(\delta B/|B| > 15\%\)) and the direction of the maximum variance (requires the angle between the maximum variance and the background field less than 20\(^\circ\)). After manual inspection to eliminate any false-positive events, 6567 samples in total remain. These samples satisfy both identification criteria.

2.3. Morphology Categorization of Mirror-mode Structures

For each sample of the mirror-mode structures, we calculate the skewness of the magnetic field amplitude. Skewness is a parameter that is used in statistics to describe the symmetry of data distribution. A positive skewness indicates that more data points are located below the average value, while a negative skewness shows the opposite. Ideally, a set of data with skewness of zero means that data are perfectly symmetrically distributed. In the context of the magnetic field amplitude, a positive skewness reflects a peak-like structure...
and a negative skewness reflects a dip-like structure. Similar categorization of the mirror-mode structure, together with examples for positive/negative skewness cases, can be found (for example) in Soucek et al. (2008), Génot et al. (2011), and Dimmock et al. (2015). In this study, a ±0.1 threshold is used for categorization. Any sample with skewness in section [−0.1, 0.1] is marked as wave-like. Two examples for positive and negative skewness of magnetic field data from the selected mirror-mode structure samples are shown in Figure 1, together with the variation of the ion density. One can see clearly dip-like shapes in sample (a), and peak-like in (b), with antiphased fluctuations between field intensity and particle density.

3. Statistical Results

3.1. Plasma Parameters in the Martian Magnetosheath

Figures 2(a) and (b) give the distributions of ion temperature anisotropy and perpendicular plasma beta of $H^+$ in the Martian magnetosheath, with red and blue curves depicting the nominal locations of the induced magnetopause and the bow shock specified by the empirical models (Edberg et al. 2008). From Figure 2, one can see that the plasma beta in the Martian magnetosheath is rather large, on average greater than 6. Higher beta values present near the flank bow shock, decreasing toward the magnetopause. Consistent with Halekas et al. (2017a), temperature anisotropy $T_\perp/T_\parallel$ (ratio of ion temperature perpendicular and parallel to the magnetic field) prevails on dayside, higher near the subsolar bow shock, and decreasing azimuthally toward high SZA. Generally, both plasma beta and temperature anisotropy are larger when compared with values in the terrestrial magnetosheath (Dimmock et al. 2015).

It is convenient to define a parameter $C_M$ based on the mirror-mode instability condition, such that $C_M > 1$ represents the distance to the instability threshold (e.g., Soucek et al. 2008):

$$C_M = \beta_\perp(T_\perp/T_\parallel - 1)$$

where $T_\perp$ and $T_\parallel$ are plasma temperatures in the perpendicular and parallel direction, respectively, and $\beta_\perp(\parallel) = \frac{n k_B T_\perp(\parallel)}{B^2/\mu_0}$ is the perpendicular (parallel) plasma beta, $n$ is the plasma number density, $k_B$ the Boltzmann constant, $B$ the background magnetic field, and $\mu_0$ the magnetic permeability in vacuum. $C_M > 1$ represents the mirror-unstable condition, and $C_M < 1$ for mirror-stable condition. Meanwhile, $C_M = 1$ corresponds to marginal stability. Based on the measured plasma parameters, $C_M$ in the magnetosheath is also calculated and shown in Figure 2(c). One can see that the plasma becomes more unstable from the magnetopause radially outward to the bow shock, especially in the dayside low SZA region, where high $T_\perp/T_\parallel$ together with large plasma beta favors development of the mirror-mode instability.
Figure 2. Spatial distribution of (a) \(H^+\) temperature anisotropy; (b) perpendicular plasma beta \((\beta_\perp)\); and (c) mirror-mode instability parameter \(C_M\) calculated according to MAVEN observations.
3.2. Spatial Distribution of Observed Mirror-mode Events

Given the overall plasma conditions in the magnetosheath, we will next see how observed mirror-mode structures are distributed corresponding to the local plasma conditions. Figure 3 shows the coverage of MAVEN probe orbit and the occurrence rate of the mirror-mode events observed in the MSO cylindrical frame. The orbital coverage is defined as the ratio of the total time MAVEN stayed in a given region divided by the time span of the data (4 yr). The occurrence rate is then calculated by event counts over orbital crossing counts at given locations. One can see that most of the events occur in the flank region close to the bow shock. A considerable portion of events are located upstream of the nominal bow shock, possibly due to deviation of the bow shock from the nominal position. The relative absence of events near the subsolar region might be due to the low orbital coverage, as shown in Figure 3(b).

Figure 4 shows the occurrence rates of all three types of events (top: dip-like, mid: peak-like, and bottom: wave-like) distributed in the Martian magnetosheath. In total, 46.57% among 6567 samples are categorized as peak-like, 40.25% as wave-like, and 13.18% as dip-like. Most events are observed close to the bow shock, regardless of their categorized types; dip-like structures are rarely seen in the subsolar region, where other two types are observed more frequently. When compared to Figure 2, one can see the correlation between the distribution of different types and $C_M$ in that peak-like and wave-like structures seems abundant in the mirror-unstable region, as indicated by large $C_M$, which is consistent with the observations by Cluster in the terrestrial magnetosheath (Génot et al. 2009; Soucek et al. 2008). In addition, near the magnetopause, dips are found at higher SZA, where $C_M$ deceases but seems still above 1; whereas in the case of the Earth, they are exclusively observed in the stable region (Soucek et al. 2008).

The shape of the mirror-mode structure depends not only on $C_M$ but also on plasma beta, as indicated in Figure 5, with a group of histograms of parallel plasma beta for each type of structure. The plasma beta is calculated for each event by taking the average value of all of the data points within the event’s duration. From Figure 5 it can be seen that the peak-like and wave-like structures cover much wider ranges of beta value (up to ~30) than dip-like structures, which occur almost exclusively for beta less than 4. The peak-, wave-, and dip-like are most frequently seen at plasma beta values of about 6, 4,
and 2, respectively. Similar results are also found in the terrestrial (Soucek et al. 2008) and Jovian (Joy et al. 2006) magnetosheath. This suggests that the mirror-mode structures in the Martian magnetosheath might follow a similar evolution process as those at other planets (see also Cattaneo et al. 1998). The mirror-mode structure emerges just downstream of the bow shock in the form of waves, it then evolves into peaks at the middle of the magnetosheath, and decays into dips near the

Figure 4. Spatial occurrence rates of three types of events: (a) dip-like, (b) peak-like, and (c) wave-like.
magnetopause. However, the high plasma beta tails in Figures 6(b) and (c) suggest that some wave-like structures are converted into peak-like in the high beta region that is near the bow shock (see Figure 2(b)).

3.3. Local Time Distribution of Mirror-mode Events

Figure 6(a) shows the distribution of event occurrence rate via the local time (LT), together with averaged $H^+$ temperature anisotropy $T_{\perp}/T_{\parallel}$, based on observations in the range of $|Z| < 0.5R_M$. The colored bars indicate the occurrence rates of different types of event in each hour, while the marked curve shows temperature anisotropy averaged in the magnetosheath. The temperature anisotropy reaches maximum at $\sim 1200$ LT. This indicates the strongest magnetic field compression that leads to perpendicular heating occurring near the subsolar region (Halekas et al. 2017a), where peaks are most frequently seen, which is compatible with high plasma beta and $C_M$ there (Figure 2). Downstream in the magnetosheath, one may also see increases in dip-like structures. $T_{\perp}/T_{\parallel}$ at dusk side is overall slightly higher than at dawn side with a dusk/dawn ratio of 1.08, which is slightly larger than that at Earth ($\sim 1.04$, average based on Figure 9 in Dimmock et al. 2015). However, the main contribution to the dusk/dawn asymmetry comes from data in 0900 $\sim$ 1200 LT sector, where insufficient orbital coverage likely results in unreliable statistics. The occurrence rates form two peaks around 0800 and 1600 LT, respectively, showing dusk-dawn asymmetry consistent with the distribution of temperature anisotropy, with the peak at dusk side higher than that at dawn. The ratio of occurrence rates (dusk/dawn) is approximately 1.40, which is higher than the average ratio of 1.18 in the terrestrial magnetosheath (Dimmock et al. 2015).

At Earth, the Alfvén Mach number ($M_A$) and Parker spiral angle are two key parameters driving temperature anisotropy and its dusk/dawn asymmetry. Temperature anisotropy and asymmetry decrease with increasing $M_A$; dusk-favored asymmetry of mirror-mode structure occurrence decreases for increasing $M_A$ (Dimmock et al. 2015). MAVEN observations show a similar trend in that with increasing $M_A$, the plasma is more isotropic in the Martian magnetosheath (Halekas et al. 2017a). Generally, due to expansion of the solar wind, Mars has larger $M_A$ and Park spiral angle. Assuming that the Martian magnetosheath is analogous to the terrestrial magnetosheath, Mars should have lower temperature anisotropy, and lower asymmetry both in anisotropy and mirror-mode structure occurrence. The opposite result shown in Figure 6(a) suggests other factors are affecting the distribution. The dusk/dawn asymmetry of plasma beta might be a candidate. Greater perpendicular and parallel compressions are observed by MAVEN downstream of the quasi-perpendicular and quasi-parallel bow shocks, respectively (Halekas et al. 2017a). This is compatible with dusk-favored asymmetry in perpendicular beta.
(Figure 6(b)), which would contribute to asymmetry in instability threshold and hence mirror-mode structure occurrence rate. Larger $M_A$ means higher perpendicular compression through perpendicular shock, thus it would be possible for Mars to have a higher dusk-favored occurrence asymmetry. However, we could not conclude for the time being without comparing with observations from the Earth.

3.4. Evolution Time of Events

It is commonly considered that mirror-mode structures in the magnetosheath originate near the bow shock (e.g., Tsurutani et al. 2011). Meanwhile, mirror-mode structures frozen in the plasma are convected from the bow shock to the inner regions of the magnetosheath along flowlines. If a mirror-mode structure is detected in the magnetosheath, then its propagation time depends on the length of the flowline connecting the bow shock and the local plasma velocity. The morphology of the structure may evolve en route of the convection, for example from wave-like to peak-like. Using a flowline model of the magnetosheath, assuming that the convection time from the bow shock equals the structure evolution time, the evolution time can be calculated through integration along a flowline tracing back to the bow shock. In this study, we adopt a single-fluid, multi-species MHD model (Ma et al. 2004) to obtain the velocity and density in the magnetosheath, under the nominal upstream solar wind conditions at Mars orbit: density $n = 2.5 \text{ cm}^{-3}$, bulk velocity $v = 400 \text{ km s}^{-1}$, magnetic field $B = (-1.67, 2.49, 0.0) \text{nT}$ and temperature $T = 3.5 \times 10^5 \text{K}$. Starting from the mirror-mode structure observation point, we trace back along the flowline according to the velocity specified by the MHD model, with a time step length of $0.01 \text{s}$, until the boundary condition (density close to the upstream solar wind value) is satisfied. The total evolution time $t$ then is the number of steps multiplied by step length of time. Finally, a scaling factor based on the observed bow shock location (nearest the shock crossing) is multiplied by $t$ for approximate correction of deviation of the model bow shock. Figure 7 gives some examples of traced flowlines in the MSO cylindrical $X-R$ frame. Three types of event are traced along flowlines back to the bow shock, the details are given in Table 1.
Figure 8 shows the distributions of the evolution times for all of the sample events calculated in terms of the MHD model. One can see that most of the events have rather short evolution time, with a mean value of $\sim 7.5$ s; while nearly 80% of the events evolve less than 10 s, with the longest being 78.14 s. Due to fixed MHD bow shock position, a portion of the events (\sim 1/3) located upstream of the MHD model bow shock are not included in the statistics. Nevertheless, considering the fact that the MHD simulation gives the averaged magnetosheath conditions, together with 4395 samples in total, the results are statistically meaningful. Meanwhile, considering that not all of the observed structures necessarily originate near the bow shock (see, e.g., Tátrallyay & Erdős 2002), the calculated evolution time by flowline tracing provides an upper limit. This implies that the actual evolution time of some structures might be considerably shorter than the estimation.

According to the expression of the maximum linear growth rate of the mirror-mode instability $\gamma_{\text{max}}$ (e.g., Pokhotelov et al. 2008)

$$\frac{\gamma_{\text{max}}}{\omega_{ci}} = \frac{1}{4\sqrt{3}\pi} \left( \frac{T_i}{T_i} \right)^{\frac{1}{2}} \left( \frac{T_e}{T_i} - 1 - \frac{1}{\beta_i} \right)^{\frac{1}{2}} \left( 1 + \frac{\beta_e - \beta_i}{2} \right)^{-\frac{1}{2}},$$

where $\omega_{ci}$ is the local ion gyrofrequency, we calculate the theoretical maximum linear growth rate of the mirror-mode instability in the Martian magnetosheath, as shown in Figure 9(a), with different colors indicating the growth rate normalized by $\omega_{ci}$. Points with $C_M$ smaller than unity, or mirror-stable points, are excluded. The typical growth rate is \sim 0.020 $\omega_{ci}$ in the magnetosheath, while much higher values are present near the bow shock.

The linear growth rate can also be estimated through observations. Figure 9(b) shows the variation of amplitude with the evolution time of the mirror-mode structures. Interestingly, there are two discernable trends in the scatter plot. The majority of data points vary around a constant mean amplitude at a rather high level (\sim 6 nT), which suggests that the instability is saturated. Some of the structures saturate even at the bow shock ($t = 0$). This can be justified considering that with a fixed bow shock position from the MHD simulation, those structures emerging upstream of the modeled bow shock could have evolved into large amplitudes when entering the modeled magnetosheath region. Meanwhile, data points with low amplitudes (\sim 1 nT) show linear growth with time. Therefore, we consider those points located near the lower boundary of scatters as a better indication of the linear growth of the instability. Following the assumption that $\delta B$ varies proportionally to $\exp(\gamma t)$, linear regression gives an estimation of $\gamma = 0.047$ s$^{-1}$, which is consistent with our theoretical calculation (\sim 0.019 s$^{-1}$, under a typical magnetic field strength of 10 nT inside the Martian magnetosheath), which is much higher than the growth rate in the terrestrial magnetosheath (Tátrallyay & Erdős 2002).

The linear growth rate $\gamma$ is much higher than the averaged value near the low SZA bow shock (Figure 9(a)). If the

Table 1

| Event Type | Observed Time and Location (UTC, $R_M$ in MSO frame) | Flowline Length (km) | Convection Time (sec) |
|------------|-----------------------------------------------------|----------------------|-----------------------|
| dip-like   | 2015-11-13 23:30 (0.65, -0.61, 1.03)                | 4830.20              | 44.68                 |
| peak-like  | 2016-07-16 19:13 (0.37, -0.87, 1.26)                | 5275.78              | 25.20                 |
| wave-like  | 2016-07-30 05:08 (0.27, -1.05, 1.35)                | 4880.23              | 18.84                 |

Figure 7. Examples of flowline tracing. The traced flowlines are represented by color-changing curves, the color indicating local plasma beta value calculated based on the magnetosheath parameters from the MHD model. See Table 1 for details of the examples.
observed mirror-mode structure is formed at the bow shock, then its amplitude will grow exponentially and saturate in a very short time. Actually, despite a rather low threshold value adopted in identification ($\delta B/|B| > 0.1$), the mirror-mode structures that we find in the magnetosheath mostly saturate with amplitude $\delta B/|B| > 0.5$ (as shown in Figure 10(a)). This suggests that the bow shock region might be quite turbulent. Accompanying nonlinear saturation of the mirror-mode instability, peak-like structures form, which result in a higher percentage of peak-like structures in the low SZA region (Figure 4(b)).

3.5. Structure Evolution Along the Flowline

Under the conditions in the terrestrial magnetosheath, numerical simulations (e.g., Génot et al. 2011; Ahmadi et al. 2017) reveal that when the plasma flows downstream in the magnetosheath, the plasma beta decreases and $T_\perp/T_\parallel$ increases. This is accompanied by a variation in the skewness of the magnetic field amplitude, which rises to a high positive value and then drops to negative. This indicates a transition of structure type from peak- to dip-dominant. For the observed events, variations of amplitude (a) and skewness (b) of the magnetic field over evolution time are shown in Figure 10, where the instability parameter $C_M$ from the place of the events is given in (c). According to the trends shown in Figure 10, the events can be roughly divided into two groups (refer to Figure 9(b)): those having an evolution time shorter than 10 s, and longer ones. Assuming that all the events are born at the bow shock, the short evolution time group corresponds to the structure observed in the vicinity of the bow shock, where $C_M$ is very large (Figure 10(c)) and the plasma is far from marginal stability. Positive skewness (Figure 10(b)) indicates that peak-like structures are dominant, and their averaged amplitude is rather large (Figure 10(a)). Away from the bow shock, $C_M$ decreases. This indicates that the magnetosheath plasma free energy is being dissipated. However, for the structure with evolution time within $\sim$10 s, the skewness and amplitude only show minor changes. This suggests that most of the structures are in states of nonlinear saturation, which can be also seen in Figure 9(b). For the group with longer evolution time ($\geqslant$10 s), the amplitude and skewness of the mirror-mode structure exhibit dependence on the environmental change: when $C_M$ drops, a decrease is seen in skewness, which is a signature of peak collapse or dip formation. Interestingly, the wave activity keeps enhancing and reaches a higher amplitude. Finally, when the plasma is relaxing toward a marginally stable state ($C_M = 1$), the data show some tendency of decrease in the field fluctuation and the appearance of negative value of skewness, informing the formation of dip-like structures. Here we should note that less than 10% of the mirror-mode events evolve more than 20 s (Figure 8), so statistics based on fewer samples after 20 s have higher uncertainty.

Compared with the Cluster observations and the hybrid simulation (Figure 4 in Génot et al. 2011), the longer evolution time group shows a similar evolution process to that observed in the terrestrial magnetosheath. However, the dayside magnetosheath or even higher SZA region covered by the MAVEN orbit (up to SZA $\sim$145°) keeps in a state with $C_M > 1$, thus events could not evolve into a dip-like structure, which explains the low percentage of such type at Mars.

What is unique at Mars is the short time group, which accounts for 80% of the observed mirror-mode events. According to simulation (Qu et al. 2008), under strong drive ($\beta_\perp = 12, T_\perp/T_\parallel = 5$), saturation is achieved through relaxation to the marginal stability at the same time, which seems to have some contradiction with the results in Figure 10. The structures are mostly saturated during evolution. Although the distance to the marginal stability decreases as indicated by continuous drop of $C_M$, it seems that the plasma does not relax to marginal stability in the dayside magnetosheath, as shown in Figure 11. The plasma parameters are generally far above the instability threshold $C_M = 1$, although there is a weak trend showing anticorrelation between $T_\perp/T_\parallel$ and parallel plasma beta ($\beta_\parallel$). This implies that the energy dissipation through
wave-particle interaction might be incapable of setting the dayside magnetosheath in a marginally stable state.

4. Summary and Discussion

We have statistically analyzed mirror-mode structures and related plasma features in the Martian magnetosheath based on 4 yr MAVEN data (2015 ~ 2018). The Martian magnetosheath is characterized by high plasma beta and high ion temperature anisotropy. On average, both plasma beta (≈6) and anisotropy (≈2.01) are higher than the typical values (≈4.55 and 1.18) in the terrestrial magnetosheath (Song et al. 1993; Dimmock et al. 2015). High beta and high anisotropy suggest that the sheath plasma is usually unstable to the mirror-mode instability. The main results are summarized as follows:

1. Most observed mirror-mode events are found in the vicinity of the bow shock, peak-like structures dominate among observed events, with a percentage higher than the statistical results from the terrestrial and Jovian magnetosheaths; while the dip-like structures are relatively sparse, and are usually seen in the high SZA region. The mirror-mode structure occurrence exhibits dusk/dawn asymmetry that is consistent with, but more pronounced than, the situation at Earth.
2. The linear instability growth rate is rather high at Mars. Consequently, mirror-mode instability grows quickly into

![Figure 9](image-url)
nonlinear phase and saturates, which produces peak-like structures near the bow shock. Most structures seem to be saturated in the dayside magnetosheath, where the distance to the instability threshold is large. Accordingly, we find that, unlike the Earth, the day magnetosheath is largely not in a state of marginal stability. Our results

Figure 10. Variation with evolution time of averaged (a) magnetic field fluctuation amplitude, (b) skewness value with evolution time of structures, and (c) mirror-mode instability parameter $C_M$ at the places where the structures are observed, with error bars indicating $\pm \sigma / \sqrt{N}$ range, $N$ is the number of events.
imply that the energy dissipation through wave-particle interaction might not be an efficient way to remove anisotropy in the dayside Martian magnetosheath.

3. The evolution of observed structures is investigated by flowline tracing based on the MHD simulation result. The events can be divided into two groups: the first group is located near the bow shock, which keeps saturated when propagating toward downstream; and the second group follows the evolution process similar to that observed in the terrestrial magnetosphere, but mostly could not evolve into the final phase (dip-like structure) in the dayside magnetosphere, where the plasma is usually unstable to the mirror-mode instability.

In our study, we assume that all of the mirror-mode structures form at the bow shock. However, is there a possibility that some of the structures originate upstream? There have been reports on magnetic depressions observed in the solar wind (e.g., Winterhalter et al. 1994), which are likely to be remnants of mirror-mode instability in the interplanetary medium. Grib & Leora (2015) proposed that magnetic holes consisting of two tangential discontinuities could survive after passing through the bow shock. However, they also pointed out that only less than half of the magnetic holes have the feature of tangential continuities. Madanian et al. (2020) estimated that the occurrence rate of magnetic holes upstream of the bow shock is \( \sim 2.1 \text{ day}^{-1} \). Since the quasi-parallel shock is more permeable to wave transmission (Simon Wedlund et al. 2022), if 1 event/day (\( \sim 1400/4 \) yr) would survive the quasi-parallel shock, then the local time distribution of dip-like structures would show prominent dawn-favored asymmetry. However, the higher occurrence of dips at dusk side in Figure 6(a) suggests that the upstream origin of magnetic dips might be unlikely.

When studying the evolution of the mirror-mode structures, we assume that these structures are non-propagating in the plasma frame. However, recent MMS observations in the terrestrial magnetosphere have demonstrated that the propagation properties of magnetic dips depend on their scale sizes, and only dips at MHD scale are frozen in the plasma flow (Yao et al. 2020). As noted in Section 2.1, for a wave propagating at a speed of 150 km s\(^{-1}\), the wavelength that we can identify is \( \sim 1200 \) km. Correspondingly, assuming the proton gyroradius \( r_p \) to be 75 km in the magnetosheath, the scale size of our mirror-mode structure samples are larger than 16 \( r_p \), but possibly smaller than the MHD scale. This means that the “frozen in” assumption might break down for some of our observed mirror-mode events. Further work will be done to discriminate the scale size of the events and evaluate its effect on the statistic results.

Although various simulation studies about evolution of mirror-mode structures have been conducted so far, few are comparable to the Martian case, under conditions of large-scale
size (comparable to the magnetosheath) and highly unstable plasma environment in the magnetosheath. Further simulation works, adopting models and parameters better describing Mars unique plasma environment, would further our understanding about the behaviors of mirror-mode structures in the Martian magnetosheath, including the evolution of saturated structures in a mirror-unstable environment.

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