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A. P. Dimmock  
*Emory-Riddle Aeronautical University*

A. Osmane  
*Emory-Riddle Aeronautical University*

T. I. Pulkkinen  
*Emory-Riddle Aeronautical University*

K. Nykyri  
*Emory-Riddle Aeronautical University*, nykyrik@erau.edu

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A statistical study of the dawn-dusk asymmetry of ion temperature anisotropy and mirror mode occurrence in the terrestrial dayside magnetosheath using THEMIS data

A. P. Dimmock¹, A. Osmane¹, T. I. Pulkkinen¹, and K. Nykyri²

¹School of Electrical Engineering, Aalto University, Espoo, Finland, ²Department of Physical Sciences, Embry-Riddle Aeronautical University, Daytona Beach, Florida, USA

Abstract

We present a statistical study of ion temperature anisotropy and mirror mode activity in the Earth’s dayside magnetosheath using 6 years of Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations focusing on the quantification of dawn-dusk asymmetry as a function of upstream conditions and distance from the magnetopause. Our statistical data show a pronounced dusk favored asymmetry of $T_{\parallel}/T_{\perp}$ which drives a similar asymmetry of mirror mode activity. $T_{\parallel}/T_{\perp}$ decreases with increasing solar wind Alfvén Mach number, whereas mirror mode occurrence increases. In both cases, the relative asymmetry between the dawn and dusk flanks decrease with increasing Alfvén Mach number. In addition, during the transition from low/moderate $M_a$, there was a shift in our data set from dips to peaks, suggesting that the magnetosheath strongly favors peaks during intervals of higher Mach number. We also observed more mirror modes and larger asymmetry during atypical inward ortho-Parker spiral interplanetary magnetic field compared to the more statistically relevant Parker spiral configuration. Our results are consistent with previous experimental studies of mirror modes and to some extent, numerical models.

1. Introduction

Recent observations of dawn-dusk asymmetries in the magnetosphere [Paularena et al., 2001; Hasegawa et al., 2003; Némecék et al., 2003; Wing et al., 2005; Longmore et al., 2005; Lavraud et al., 2013] have led to a resurgence of magnetosheath studies aimed at quantifying the evolution of global and local properties of the plasma transitional from the solar wind to the magnetopause boundary [Walsh et al., 2012; Dimmock and Nykyri, 2013; Dimmock et al., 2014; Nykyri, 2013]. It is well known that numerous processes ranging from magnetohydrodynamic (MHD) scales to kinetic scales are responsible for plasma transport at the magnetopause [Dungey, 1961; Sagdeev and Galeev, 1969; Nykyri and Otto, 2001; Nykyri et al., 2006; Johnson and Cheng, 1997a, 2001]. However, all of these processes are dependent on the plasma state of the magnetosheath. For example, it has been demonstrated that during faster solar wind speeds, the level of turbulence in the magnetosheath is enhanced, impacting the onset of magnetic reconnection and plasma transport [Dimmock et al., 2014].

In this report we have extended previous statistical studies of the magnetosheath and its association with solar wind drivers [Dimmock and Nykyri, 2013; Dimmock et al., 2014] by conducting a 6 year Time History of Events and Macroscale Interactions during Substorms (THEMIS) survey of mirror modes (MMs) in the Earth’s magnetosheath. MMs are nonpropagating kinetic structures commonly observed in planetary magnetosheaths with high $\beta = 2\mu_0 n k_B T / B^2$ and as a consequence of temperature anisotropies $T_{\parallel}/T_{\perp} > 1$. MMs have been theoretically predicted [Chandrasekhar et al., 1958; Shapiro and Shevchenko, 1963; Hasegawa, 1969] and were first observed by Kaufmann and Honig [1971]. They have since been detected among a wide range of space plasmas [Tsurutani et al., 1982; Neubauer et al., 1993; Sahraoui et al., 2004; Joy et al., 2006; Génot, 2008; Génot et al., 2009a; Soucek et al., 2008; Balikhin et al., 2009, 2010; Soucek et al., 2015] which have been inferred to regulate weakly collisional astrophysical plasmas as a result of turbulent motion [Schekochihin et al., 2008].

MMs are ubiquitous in space plasmas, but they are particularly abundant in the terrestrial magnetosheath. Although they are kinetic by nature and exist on scales of ~13 s [Soucek et al., 2008] in the terrestrial...
magnetosheath, it has been shown that they can impact magnetosheath properties on a global scale and therefore are fundamental in modifying the state of the magnetosheath. They appear in spacecraft measurements as sharp enhancements and decrease in magnetic field (peaks and dips) as well as sinusoidal structures which are anticorrelated with density perturbations. They are identifiable by their linear polarization and large amplitudes with respect to the ambient magnetic field. A focus on MMs in the Earth’s magnetosheath is therefore not fortuitous. Even though kinetic in nature, mirror structures are central for the dynamical evolution of plasma properties on global scales. In fact, magnetosheath plasma in the presence of MMs tend to follow the marginal stability path [Soucek et al., 2008] and dominate the turbulent energy spectra up to 1.4 Hz [Sahraoui et al., 2004]. Estimated to occur 30% of the time across a variety of upstream solar wind conditions [Lucek et al., 1999], MMs are not only a common occurrence in magnetosheath environments but are also fundamental in the regulation of local and global plasma properties [Soucek et al., 2008].

Theoretical studies also indicate that MMs can couple a significant amount of energy from the magnetosheath to the magnetopause and result in additional plasma transport [Johnson and Cheng, 1997b]. Due to the global impact of MMs on the Earth’s magnetosheath, the determination of MM locations and properties as a function of solar wind conditions are particularly relevant to recent efforts in developing space weather models accounting for ion kinetic processes [Karimabadi et al., 2006; Alftthan et al., 2014]. For such models to include ion kinetic processes, this clearly requires determining the mechanisms through which MM structures saturate and regulate the plasma.

The role of MMs as regulating agents has been highlighted by Soucek et al. [2008] in a survey of MMs in the Earth’s magnetosheath between 15 November 2005 and 14 January 2006 using Cluster data. In their report, Soucek et al. [2008] quantified the correlation between the statistical properties of the MM (peakness (skewness of distribution), depth, and temporal scale) to local plasma conditions such as plasma $\beta$.[2008] quantified the correlation between the statistical properties of the MM (peakness (skewness of distribution), depth, and temporal scale) to local plasma conditions such as plasma $\beta$ and a measure of the plasma instability $R = \beta_\parallel (T_\perp/T_\parallel - 1)$. Values above 1 indicate plasma which is mirror unstable whereas below 1 are believed to be mirror stable. Their statistical data, consistent with the work of Génot et al. [2009b], suggest that dips are most frequent when $\beta_\parallel < 5$, whereas peaks are typically observed for $2 < \beta_\parallel < 15$.

The authors also report that peaks are present during unstable plasma conditions, whereas dips are able to survive the transition to more stable states. As a result, the peakness is heavily dependent on the spatial distribution of the magnetosheath plasma conditions where peaks are mainly present closer to the bow shock boundary but decay to dips moving toward the magnetopause (as the plasma becomes more stable). This process is reported to take place over a 2–3 Rs scale [Soucek et al., 2008].

Despite the recognition of the central role MMs occupy in regulating the magnetosheath, the question as to which mechanisms operate to saturate the instability remains an open one [Kuznetsov et al., 2007]. It has been argued by Gary et al. [1996] that scattering by enhanced fluctuations from the electromagnetic proton cyclotron instability imposes the upstream bound on the proton temperature anisotropy of the form $T_\perp/T_\parallel = 1 - S_p/\beta_\parallel^3$, for fitting parameters $0.85 \geq S_p \geq 0.58$ and $0.5 \geq \alpha_p \geq 0.4$. Hence, the temperature anisotropy and the plasma beta are anticorrelated. This result has been interpreted as a consequence of enhanced scattering and stabilization of the proton instability thresholds as forcing is increased. In the context of planetary magnetosheaths, the temperature anisotropy and associated instabilities are driven by high Mach numbers $M_p = V_p/V_a$, where $V_p$ and $V_a$ are the shock and Alfvén speed, resulting in higher beta plasma downstream of the shock.

The numerical and observational results of Gary et al. [1996] for the proton cyclotron instability are also conceptually consistent with gyrokinetic numerical studies of MM saturation for high and low driving conditions [Qu et al., 2008]. Through the use of a gyrokinetic simulation, Qu et al. [2008] demonstrated that for low driving ($\beta_\parallel = 2$ and $T_\perp/T_\parallel - 1 = 1$), the mirror instability saturation was achieved by physically trapping the ions, with no relaxation through wave-particle scattering. For high driving of the mirror instability ($\beta_\parallel = 12$ and $T_\perp/T_\parallel - 1 = 4$), the saturation was achieved through relaxation to marginal stability by wave-particle scattering. Whereas physical trapping was present for high driving, it was insufficient for quenching the instability. However, an important difference between the numerical studies of Gary et al. [1996] and Qu et al. [2008] is that the latter uses a gyrokinetic code, resulting in the elimination of high-frequency modes and pitch angle scattering by ion cyclotron waves. Their results are nonetheless indicative of the possibility to quench the instability for high driving as a result of wave-particle scattering. Using the magnetosheath coverage of THEMIS over 6 years, we can statistically characterize the occurrence rate and properties of MM for large Mach

\[ R = \beta_\parallel (T_\perp/T_\parallel - 1) \]
numbers generating higher $\beta$ and compare these observational results with those of Gary et al. [1996] and Qu et al. [2008].

The aim of the following report is twofold. First, we provide a 6 year THEMIS survey of MM properties as a function of solar wind drivers. In continuation to earlier studies [Walsh et al., 2012; Dimmock and Nykyri, 2013; Dimmock et al., 2014; Nykyri, 2013], we focus particularly on the dawn-dusk asymmetry of MMs as a function of magnetosheath location and upstream conditions. Second, we evaluate, statistically, the evolution of MM occurrence rate as a function of driving parameters $M_s$ and $\beta$. We are therefore interested in characterizing global constraints on the Earth's magnetosheath imposed by the dynamical evolution of kinetic MM under various solar wind conditions. In section 2 we describe the data set and the MM selection criteria. Section 3.1 presents the main results of the 6 year survey. In section 4 we compare our results with previous studies with a focus on dawn-dusk asymmetries and the properties of MM for various solar wind properties. Section 5 summarizes the main findings of our studies.

2. Data and Processing

2.1. Data Sets and Instrumentation

Our magnetosheath statistical data are compiled from measurements collected by the array of instrumentation onboard each of the THEMIS spacecraft [Angelopoulos, 2008] between October 2007 and December 2013. Magnetic field measurements are provided by the FluxGate Magnetometer (FGM) onboard each probe [Auster et al., 2008], and since MMs can range from timescales upward of 4 s [Soucek et al., 2008] in the Earth’s magnetosheath, we use the 4 Hz resolution data to avoid missing these events. Ion temperature, used to compute the MM instability criterion, is obtained through the electrostatic analyzer (ESA) instrument [McFadden et al., 2008] using the L2 spin resolution data.

2.2. Preliminary Data Processing

To isolate magnetosheath measurements from the complete THEMIS database we make use of our existing data analysis tool [Dimmock and Nykyri, 2013; Dimmock et al., 2014] that was developed to study the response of the magnetosheath to solar wind conditions. For this particular study, we apply a transformation to each THEMIS data point in the Geocentric Solar Ecliptic (GSE) frame so that spacecraft locations are rotated to the Magnetosheath Interplanetary Medium (MIPM) reference frame [Verigin et al., 2006]. The MIPM frame organizes data points on each magnetosheath flank as a function of the interplanetary magnetic field (IMF) vector, effectively placing data points with respect to the bow shock geometry. The purpose of this transformation is to ensure that the dawn flank remains quasi-parallel whereas the dusk is quasi-perpendicular. This transformation avoids the case where data points could be placed at the same physical location but processed by contrasting shock geometries (e.g., with GSE frame and no upstream filtering). To allow for motion of the magnetosheath boundaries, each data point is placed at a fractional distance ($F_{mipm}$) across the model magnetosheath using the bow shock model by Verigin et al. [2006] and the magnetopause model by Shue et al. [1998]. A value of $F_{mipm} = 0$ corresponds to the magnetopause which then increases moving outward until reaching the bow shock ($F_{mipm} = 1$). The magnetosheath boundaries (and GSE-MIPM transformation) are evaluated using a 20 min mean average of the OMNI data, whereas magnetosheath conditions are estimated based on the plasma conditions within a 3 min window. In this case, the presence of MMs in each 3 min window is verified, and depending on the result from this, certain properties are calculated and then recorded.
In addition, using the OMNI data, we prefilter the complete magnetosheath database to study the impact of increasing Alfvén Mach number on MM activity. We also compare data on the dawn ($Q_\parallel$) and dusk ($Q_\perp$) flanks to quantify dawn-dusk asymmetry of MM occurrence rates ($\mathcal{O}$) and dependence on $M_A$. We define $\mathcal{O}$ as the number of MMs normalized by the number of observations. We eliminate from these statistics intervals where data were unavailable to evaluate the full selection criteria.

### 2.3. Event Classification and Selection Criteria

We adopt several criteria to determine the presence of MMs within each 3 min window. Our primary criterion utilizes the (ideally) linearly polarized property of MMs to distinguish from the array of other wave modes and instabilities prominent in the magnetosheath. In practice, we require the angle between the maximum variance direction ($\hat{B}_m$) and the background field ($\hat{b}_0$) direction ($\theta_{bm}$) to be less than 20°. To verify that $\hat{B}_m$ is well defined we also compute the ratios between the eigenvalues of the maximum ($\lambda_{max}$), intermediate ($\lambda_{int}$), and minimum ($\lambda_{min}$) variance directions. Similar to Soucek et al. [2008], for a sufficient estimate of $\hat{B}_m$, we require that $\lambda_{max}/\lambda_{int} > 1.5$ and $\lambda_{min}/\lambda_{int} > 0.3$. To ensure the presence of large amplitude perturbations we also compute the variance of $|\vec{B}|$ for each 3 min window, which must exceed 10% of the background field strength. As a final check to eliminate potential outliers, we require that $\beta_\parallel > 1$ and $|\vec{B}| > 10$ nT. These selection criteria are summarized in Table 1. To differentiate between MMs in either a peak or dip regime, we evaluate the skewness ($\gamma$) over the magnetic field values in each 3 min interval. Peaks produce a positive skew of the distribution and dips a negative one. Therefore, the direction of $\gamma$ is used to categorize the MMs in each window. The application of this criteria provides a statistical database of 33,669 MM intervals covering the dayside magnetosheath.

### 2.4. Example: Mirror Mode Intervals Identified From the Selection Criteria

Presented in Figure 1 are two examples of MM intervals as (a) peaks and (b) dips observed on 5 December 2009 UTC. Although each of the windows shown in Figure 1 spans a time period of 9 min and 15 s, MMs are identified based on data covering a 3 min interval. The red vertical lines plotted in each panel highlight one of the 3 min intervals considered by the statistical software during this interval. The MMs shown in Figure 1 appear as

![Figure 1](image-url)

**In addition, using the OMNI data, we prefilter the complete magnetosheath database to study the impact of increasing Alfvén Mach number on MM activity. We also compare data on the dawn ($Q_\parallel$) and dusk ($Q_\perp$) flanks to quantify dawn-dusk asymmetry of MM occurrence rates ($\mathcal{O}$) and dependence on $M_A$. We define $\mathcal{O}$ as the number of MMs normalized by the number of observations. We eliminate from these statistics intervals where data were unavailable to evaluate the full selection criteria.**

### Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Peak</th>
<th>Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{R}$</td>
<td>1.18</td>
<td>1.09</td>
</tr>
<tr>
<td>$b_0$</td>
<td>[0.28, 0.30, −0.91] nT</td>
<td>[0.49, 0.25, −0.84] nT</td>
</tr>
<tr>
<td>$B_m$</td>
<td>[0.20, 0.49, −0.85] nT</td>
<td>[0.44, 0.20, −0.87] nT</td>
</tr>
<tr>
<td>$\theta_{bm}$</td>
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<td>4.37°</td>
</tr>
<tr>
<td>$\lambda_{max}/\lambda_{int}$</td>
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<td>3.04</td>
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<tr>
<td>$\lambda_{min}/\lambda_{int}$</td>
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<td>0.36</td>
</tr>
<tr>
<td>$\gamma$</td>
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<td>−0.92</td>
</tr>
<tr>
<td>$\beta_\parallel$</td>
<td>4.59</td>
<td>2.02</td>
</tr>
</tbody>
</table>
abundant “trains” of peaks and dips which are common in time series data of planetary magnetosheaths. As a result, there is an adequate number of MMs (dips ~ 8 and peaks ~ 12) to produce a measurable skew of the distribution. Since the temporal scale of MMs in the terrestrial magnetosheath ranges from around 3.5 to 24 s and a mean of 12 s [Soucek et al., 2008], a 3 min interval is more than adequate for detection. The properties of the peaks and dips over the 3 min intervals are described in Table 2. For both cases, the instability threshold exceeds 1, but the peaks are present during periods of more unstable plasma which falls in line with previous observations [Soucek et al., 2008; Génot et al., 2009b]. In both cases the angles between $b_0$ and $b_m$ are small and measure approximately 12.3° and 4.4° for peaks and dips, respectively. The definite positive and negative values of skewness reflect the classification of the MMs and the fact that peaks were identified for larger $\beta_∥$ consistent with previous observations of MMs [Soucek et al., 2008; Génot et al., 2009b].

3. Results

3.1. Magnetosheath Ion Temperature Anisotropy

Figure 2 shows statistical maps of the ion temperature anisotropy in the dayside magnetosheath for a typical Parker-spiral IMF, $M_A < 10$, and $M_A > 10$. Each map was produced using our statistical databases which are independent of our MM selection criteria. The maps were produced using an $X$-$Y$ grid resolution of $0.5 \times 0.5 R_E$ of which linear interpolation was performed to determine intermediate points between each discrete bin. Each statistical map shows convincingly that the dusk flank produces larger values of $T_{⟂}/T_∥$ compared to the dawn resulting in a pronounced dusk-favored asymmetry. In general, $T_{⟂}/T_∥$ increases from the bow shock to the magnetopause, consistent with the decrease in $\beta$ and in agreement with the inverse relationship between these two quantities (shown later in Figure 7). Figure 3 shows the statistical averaged cuts as a function of the angle from the subsolar location. Each point in these cuts contain mean-averaged data within sectors of width 10°. The top three panels correspond to the individual dawn and dusk flank profiles of each $M_A$ data set whereas the bottom, single panel shows a comparison between each one. Each panel confirms the dusk-favored asymmetry and the general decrease in $T_{⟂}/T_∥$ moving tailward. It is clear that for larger solar wind $M_A$, the magnetosheath ions are more isotropic but the asymmetry favoring the duskside remains. In general, the asymmetry also similarly depends on $M_A$, and we calculate the maximum asymmetry (dusk/dawn in %) of $M_A < 10$ and $M_A > 10$ to be 12.1% and 6.92%, respectively. The mean anisotropy asymmetries, 6.9% and 3.9% for $M_A < 10$ and $M_A > 10$, also suggest a similar dependence on $M_A$. Figure 4 shows a comparison of the dusk/dawn ratios which provide a quantitative measure of the asymmetry. Here we have added an additional criterion where the IMF is only composed of Parker-spiral IMF orientations. The difference between

Figure 2. Statistical maps of the ion temperature anisotropy in the dayside magnetosheath. Each panel (left to right) corresponds to a typical Parker-spiral IMF, $M_A < 10$, and $M_A > 10$. In each panel the dusk-favored asymmetry is pronounced, implying that there should be a similar asymmetry of mirror mode activity.
this one and the “All” data set is that the latter is statistically Parker-spiral but may contain other IMF orientations or weaker Parker-spiral intervals. What becomes immediately obvious is that the stricter Parker-spiral IMF data set shows the largest dusk-favored asymmetry implying a greater impact than $M_A$. As a result of the dusk-favored asymmetry, MMs should strongly favor the dusk flank and a similar asymmetry should arise also coupled to $M_A$ and IMF orientation.

3.2. Mirror Mode Properties as a Function of Solar Wind Mach Number and Local Plasma $\beta$

Figure 5 (left) shows a 3-D scatter plot of skewness $\gamma$ versus plasma $\beta_\parallel$ with color indicating the Alfvén Mach number $M_A$ for each MM event. Figure 5 (right) shows the same quantities, but the $X$ axis has been replaced by the distance from the MM threshold $R$. Figure 5 is similar to Figure 2 in the article by Soucek et al. [2008] in which they show almost identical dependencies between these parameters. Dips are associated with a lower range of $\beta_\parallel$ (<10), contrary to peaks which develop under higher values of plasma $\beta$, typically between 2 and 20. Figure 5 (right) also shows that dips are mostly present when the plasma is closer to a mirror-stable regime, and only isolated cases of dips occur past $R = 5$. Peaks, on the other hand, are observed under more unstable conditions past $R > 2$ to which they remain beyond $R > 6$. It should also be noted that although MMs were still observed below the instability threshold, the bulk of MMs will be observed for $R > 1$, but this is not a strict prerequisite. The color coding in each panel shows some clear trends. During low to moderate ($5 < M_A < 15$) values of $M_A$, both peaks and dips are present. However, for high ($M_A > 17.5$) values corresponding to the tail of the distribution, almost all of our statistical data comprise peaks. In a similar manner, the most
mirror-stable plasma \((R < 2)\) corresponds to moderate upstream \(M_A\). Highly unstable mirror conditions are found to be associated with \(M_A > 15\), indicating that more mirror-unstable plasma in the magnetosheath is driven by higher \(M_A\) in the solar wind. Both panels agree favorably with each other in the sense that higher \(R\) is driven by higher \(M_A\), which in turn should appear in the time series data as MM peaks. In Figure 6 we plot the ratio of the number of dips with respect to the number of peaks as a function of \(M_A\). For \(M_A < 6\), the data set is primarily composed of dips. During intermediate \(M_A\) the data set is almost evenly split between both varieties. For \(M_A > 15\) the data set transitions to mostly peaks.

Figure 7 presents 3-D scatter plots of \(T_\perp/T_\parallel\) plotted against \(\beta_\perp\) color coded by \(M_A\) and \(\gamma\) for Figures 7a and 7b, respectively. The solid black line represents the MM threshold criterion and therefore all data points above (below) are considered mirror unstable (stable). Figure 7a indicates that the majority of the data set lies in the mirror-unstable regime but substantial statistical data still fall below, into the mirror-stable region. In general, as \(\beta_\perp\) increases, the ions become more isotropic, but even at large \(\beta_\perp > 40\) the values in our data do not reach unity. From visual inspection, the data plotted below the threshold are primarily dips except for large \(\beta_\perp\) exceeding 10. As expected from Figure 5, during larger values of \(\beta_\perp\), the data set is mostly in the form of peaks. Figure 5 (left) below implies that larger values of \(\beta_\perp\) are present during higher \(M_A\), and when \(\beta_\perp > 30\), almost all of the statistics were recorded when \(M_A > 25\).

### 3.3. Mirror Mode Dawn-Dusk Asymmetry as a Function of Solar Wind Mach Number

Plotted in Figure 8 (left) are the occurrence rates of MMs plotted as a function of upstream \(M_A\) for the dawn flank, dusk flank, and the entire dayside magnetosheath. In our study, the dawn and dusk flanks are strictly defined as the dayside magnetosheath (nose until the terminator) regions which are less than and greater than \(Y_{\text{mipm}} = 0\), respectively. In addition, due to the organization of data points in the MIPM frame, we will also refer to the dawn and dusk flanks as \(\Theta_\parallel\) and \(\Theta_\perp\), respectively. The increase of \(\Theta\) with \(M_A\) indicated by the solid black line suggests the statistical probability of MM increases with \(M_A\) up until \(M_A \sim 18\). According to the same quantities plotted separately for the dawn and dusk flanks,
Figure 7. Three-dimensional scatter plot of $T_{\perp}/T_{\parallel}$ versus $\beta_{\perp}$ color coded by upstream (a) $M_A$ and (b) skewness. A similar relationship is observed and the break point of $\varnothing$ occurs at approximately the same value of $M_A$. For the dayside magnetosheath, $\varnothing$ increases from 3% to over 30%, consistent with previous experimentally based studies [Génot et al., 2009b]. More specifically, this result is equivalent to that of Figure 7 in Génot et al. [2009b]. What becomes apparent is that there is a difference between $\varnothing$ on the dawn flank compared to the dusk. In general, $\varnothing$ is higher on the dusk flank than on the dawn, conveying a notable dusk-favored asymmetry. Figure 8 (right) shows the ratio $\chi_{\text{dusk}}/\chi_{\text{dawn}}$ so that values above and below 1 correspond to dusk- and dawn-favored asymmetries, respectively. The availability of data for $M_A < 5$ is very poor and is reflected by the substantial error bar for the first point, and therefore, not much can be inferred from this. The largest dusk-favored asymmetry is present for $M_A \sim 7.5$, which then decreases afterward to $M_A = 20$. The final point in Figure 8 (left) implies an increase in the asymmetry corresponding to a decrease in $\varnothing$. However, taking into account the significant error for very high $M_A$, this cannot be confirmed since the two last points overlap. Since $\varnothing$ is intrinsically related to $M_A$, we plot the normalized (by maximum) distribution of $M_A$ for the dawn and dusk flank data in Figure 9. The negligible differences between the distributions convey that the asymmetry estimated from our data is likely to be physical, as opposed to that driven by any statistical bias.

To quantify the dependence of the dawn-dusk asymmetry both as a function of $M_A$ and distance from the magnetopause, we isolated data at various proximities from the magnetopause for low and high $M_A$ on each flank. For each of these subdata sets, we calculate the asymmetry which is summarized in Table 3. Columns in this table are organized with respect to $M_A$: all $M_A < 10$ and $M_A > 10$. We chose $M_A = 10$ to split the initial data set, since this value corresponds to the peak of the distribution shown in Figure 9. Each row represents an individual region across the magnetosheath sorted by the ranges: $0 < F_{\text{mipm}} < 1$, $0 < F_{\text{mipm}} < 1/3$ (magnetopause), $1/3 < F_{\text{mipm}} < 2/3$ (central magnetosheath, CMS), and $2/3 < F_{\text{mipm}} < 1$ (bow shock). It should be noted that since MMs convex with the magnetosheath flow, then this table should be interpreted in terms of the spatial distribution of the MM asymmetry. For exclusively studying the properties of MMs as they convect, a methodology utilizing temporal coordinates mapped to the flow lines may be better suited, e.g., Génot et al. [2011] and Soucek et al. [2015]. On the $\Theta_{\perp}$ flank, $\varnothing$ is largest in the CMS, which holds for each range of $M_A$. On the $\Theta_{\parallel}$ side, this is not the case in which values of $\varnothing$ at the magnetopause and CMS are very similar. Interestingly, during lower $M_A$, the CMS contains the largest asymmetry which is contrary to the higher $M_A$ case in which the largest values of $\varnothing_{\text{dusk}}/\varnothing_{\text{dawn}}$ were observed behind the bow shock. A value of 2.35 was

Figure 8. (left) Mirror mode occurrence rate as a function of Alfvén Mach number computed for both flanks and then for the dusk and dawn flanks separately. (right) The relative asymmetry ($\varnothing_{\text{dusk}}/\varnothing_{\text{dawn}}$) where points $> 1$ represent a dusk-favored asymmetry.
the largest estimation, suggesting over twice as many MMs were observed on the dusk flank compared to the dawnside during low $M_a$. For large $M_a$, the asymmetry decreases moving from the bow shock toward the magnetopause in which the value reduces from 1.68 to 1.07.

3.4. Mirror Mode Dawn-Dusk Asymmetry as a Function of IMF Spiral Angle

Figure 10 shows the occurrence rate $\Theta$ plotted as a function of the IMF spiral angle ($\phi$). Figure 10a shows results for the full data set and both flanks separately, whereas the dusk/dawn ratios are plotted in Figure 10b. In each panel, values of $+135^\circ$ and $-45^\circ$ represent inward and outward Parker-spiral orientations, respectively, whereas $-135^\circ$ and $+45^\circ$ are inward and outward ortho-Parker spiral, respectively. Interestingly, the peaks of $\Theta$ in Figure 10a suggest a visible dependence on $\phi$. Clearly, the largest occurrence rates are present for either typical Parker-spiral or atypical ortho-Parker spiral IMF orientations. What is particularly interesting though is the fact that the largest values of $\Theta$ occur for the less common ortho-Parker spiral IMF orientations ($-135^\circ$ and $+45^\circ$). These data also imply that the largest asymmetry is present during the inward ortho-Parker spiral orientation. Although the error bars in Figure 10b are significant for the positive spiral angles, this trend is intriguing. It should also be mentioned that since the MIPM frame organizes points with respect to the IMF orientation, there is no difference in shock geometries between the dawn and dusk flanks during ortho-Parker spiral and Parker-spiral. As a result of this, the dusk-favored asymmetry remains. It is currently unclear why the asymmetry favors the inward ortho-Parker spiral range of angles. However, what causes the large values is that the dawn flank $\Theta$ does not strongly peak around $-135^\circ$ as opposed to the dusk side resulting in a large relative difference. For the remaining angles, the dawn and dusk flanks follow, closely resulting in relatively steady values of $\sim 1.25$ favoring the dusk side. To determine the exact cause of this trend around $-135^\circ$ one would have to specifically determine the properties of the dawn ($Q_{\parallel}$) shock for these events, and this extends beyond the scope of the present study.

4. Discussion

In the present manuscript we have presented a 6 year survey of dayside magnetosheath temperature anisotropy and MM activity in the magnetosheath using data provided by the THEMIS spacecraft. In line with previous magnetosheath studies [Dimmock and Nykyri, 2013; Dimmock et al., 2014; Nykyri, 2013] and to build on the existing work such as those performed by Soucek et al. [2008] and Génot et al. [2009b, 2009a], we focused our attention on quantifying the dawn-dusk asymmetry of anisotropy, MM occurrence, and their statistical properties as a function of upstream conditions. The statistical maps presented in Figure 2 showed convincing evidence of a dusk-favored asymmetry of $T_{\perp}/T_{\parallel}$ for a range of $M_a$ and as a result should drive similar asymmetries of MM activity. We applied our previous magnetosheath data analysis tool [see Dimmock and Nykyri, 2013; Dimmock et al., 2014] with the addition of an event selection criteria (see section 2.3) to distinguish between MMs and other categories of magnetosheath fluctuations. For each event database, we

<table>
<thead>
<tr>
<th>$F_{\text{mipm}}$ Range</th>
<th>All</th>
<th>$M_a \leq 10$</th>
<th>$M_a \geq 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq F_{\text{mipm}} \leq 1$</td>
<td>$0.17$</td>
<td>$0.11$</td>
<td>$0.25$</td>
</tr>
<tr>
<td>$0 \leq F_{\text{mipm}} \leq 1/3$</td>
<td>$0.18$</td>
<td>$0.09$</td>
<td>$0.27$</td>
</tr>
<tr>
<td>$1/3 \leq F_{\text{mipm}} \leq 2/3$</td>
<td>$0.15$</td>
<td>$0.19$</td>
<td>$0.23$</td>
</tr>
<tr>
<td>$2/3 \leq F_{\text{mipm}} \leq 1$</td>
<td>$0.09$</td>
<td>$0.11$</td>
<td>$0.09$</td>
</tr>
</tbody>
</table>
Figure 10. (a) Mirror mode occurrence rate as a function of IMF spiral angle computed for both flanks and then for the dusk and dawn flanks separately. (b) The relative asymmetry (dusk/dawn) where points >1 represent a dusk-favored asymmetry.

created further subdata sets with respect to the upstream Alfvén Mach number and the IMF spiral angle. Each database was used to determine the statistical properties of MMs for each upstream condition. Furthermore, occurrence rates were calculated on both the dawn and dusk flanks, and their comparison was used to estimate the relative dawn-dusk asymmetry as a function of each upstream condition.

Presented in Figure 2 were statistical maps of the dayside magnetosheath temperature anisotropy. Each map showed a strong and visible dusk-favored asymmetry which appears to be most enhanced during $M_A < 10$. These results are in strong agreement with the recent study by Soucek et al. [2015] in which similar dependencies for temperature anisotropy on shock geometry and $M_A$ were reported. The quasi-perpendicular favored asymmetry and Numerical cuts of these data were shown in Figure 3, providing a quantitative estimate of temperature anisotropy as a function of the angle from the subsolar point. Figure 4 compared the numerical measures of asymmetry with an addition Parker-spiral criterion. This criterion ensures two things; (1) the polarity of the solar wind GSE $B_x$ and $B_y$ components are aligned with a Parker-spiral IMF orientation and (2) the magnitude of the solar wind GSE $B_x$ and $B_y$ are greater than $0.3|B|$. The purpose of this is that although statistically the IMF can be Parker-spiral in terms of $B_x$ and $B_y$, item (2) ensures that the x and y components dominate the IMF vector. This effectively reduces the inclusion of IMF orientations which could be classed as radial, northward or southward. These data suggest that the largest dusk-favored anisotropy was during the Parker-spiral IMF as opposed to the lower $M_A$ dataset. Such a result suggests that the asymmetry of temperature anisotropy is controlled more by the IMF orientation than $M_A$. Although our data sets are arranged by the upstream IMF, the remaining data sets likely contain weakly Parker-spiral intervals, which means that the relative difference in the shock geometry between each flank is less pronounced compared to stronger Parker/ortho-Parker spiral intervals. We conclude that although $M_A$ is a significant driver of $T_\perp/T_\parallel$, our data suggest that the shock geometry plays the largest role in generating the dusk asymmetry.

Ever since the early Explorer 33 mission, it has been shown that the magnetosheath ion temperatures perpendicular to the local magnetic field direction exceed those aligned with it [Crooker et al., 1976]. These anisotropic distributions arise from both the heating associated with the quasi-perpendicular bow shock and also the draping of magnetic field lines in the magnetosheath. Close to the subsolar/stagnation point, the magnetic field lines are compressed and “piled up”. This pileup region extends along the dayside magnetopause and to some extent is dependent on the upstream IMF. During northward IMF when reconnection is absent/weak, the pileup region can increase. Just upstream of the magnetopause lies a plasma depletion layer [Zwan and Wolf, 1976] in which the magnetic field is increased, but density and $\beta$ are significantly reduced [Zwan and Wolf, 1976; Crooker et al., 1979; Song et al., 1990; Fuselier et al., 1991]. In general, the ion temperature anisotropy is visibly enhanced just upstream of the magnetopause compared to the magnetosheath proper [Gary et al., 1993; Phan et al., 1994; Hill et al., 1995]. It was shown, using superimposed epoch analysis by Hill et al. [1995], that the parallel temperatures decrease from the bow shock to the magnetopause whereas the perpendicular temperatures remained relatively constant, creating a buildup of $T_\perp/T_\parallel$ at the magnetopause. In fact, the ion temperature anisotropy generally obeys an inverse correlation to the local $\beta$ which has been studied in detail, e.g., by Gary and Lee [1994] and subsequent studies. This dependence has been shown on both the quasi-parallel and quasi-perpendicular flanks [Fuselier et al., 1994]. As a result, the temperature anisotropy increases from the bow shock toward the magnetopause on the dayside. In the magnetosheath proper, the
anisotropy generally should decrease from the nose as the plasma propagates tailward, squeezed out from the subsolar region and as the compression reduces. Such a spatial distribution is demonstrated in the statistical maps shown in Figure 2. Contrary to this, however, it is logical to assume that the free energy provided by large anisotropies would drive MM activity and thus act to reduce the anisotropy. However, even though the anisotropy is larger in this region, the plasma $\beta$ is low, meaning that the plasma in many occasions should be mirror stable, limiting the growth rate of MMs. In these regions of low $\beta$ and high $T_\|/T_\perp$, the ion cyclotron instability may become important and act to reduce the anisotropy. However, estimates of MM occurrence, in general, do not exceed 30%. When compiling magnetosheath data with and without MMs as shown in our statistical maps, the impact on the temperature anisotropy is not sufficient to create an isotropic magnetosheath from a global perspective. In addition, the nonlinear evolution and the competition between the MM and ion cyclotron instability as a function of upstream conditions and their global impact on the magnetosheath is currently not understood and lies outside the scope of the current study.

Using a different data set, THEMIS, instead of Cluster, we found that our results compare favorably with MM statistical studies using similar methodology [Soucek et al., 2008; Génot et al., 2009b, 2009a]. Soucek et al. [2008] analyzed the relationship between the statistical properties of MMs and the local magnetosheath plasma conditions based on 2 months of Cluster observations. They reported that dips occur for $\beta_\parallel < 5$ whereas peaks favor a higher range of $2 < \beta_\parallel < 15$. We reproduced this relationship in Figure 5 in which we also observed similar ranges of $\beta_\parallel$ for peaks and dips. The reproduction of this statistical dependency provides a means of validation for our MM data set since equivalent methodologies should provide equivalent results for large statistical data sets. It should also be mentioned that both data sets, i.e., the one used by Soucek et al. [2008] and the present one, differ not only by spacecraft but also by orbital parameters, selection window lengths, and instrument resolutions. The orbital coverage of THEMIS favors the equatorial plane whereas Cluster includes more high-latitude polar coverage. The equivalence of our results and those of previous studies [Soucek et al., 2008; Génot, 2008; Génot et al., 2009a] suggests that these particular statistical properties are not dependent on or sensitive to an ecliptic or polar orbital configuration. The agreement of both statistical dependencies therefore indicates that MMs possess robust statistical properties inside the Earth’s magnetosheath. Future studies could utilize both data sets to determine the evolution of MMs during convection as they deviate from the equatorial plane.

We expanded upon the dependency between local $\beta$ and skewness by highlighting each data point with its respective value of $M_A$. Since MMs are driven by temperature anisotropy at the bow shock, the Mach number is indicative of the driving of the instability. Even though an increase in the Mach number can also modify global and local properties of the magnetosheath as a result of enhanced fluctuations [Dimmock et al., 2014] and associated compression, we are herein only using $M_A$ as an indicator of the driving, not the long-term evolution of the instability [e.g., see Génot et al., 2011]. We observed that higher solar wind $M_A$ drives larger values of magnetosheath $\beta_\parallel$, indicating that the magnetosheath should be more favorable to MMs in the form of peaks during these conditions. In Figure 5 (right), we also plotted the skewness as a function of $\beta_\parallel$, again marking each point by $M_A$. The vast majority of our data set were collected during mirror-unstable conditions, but similar to the results by Soucek et al. [2008], we also detected MMs below the threshold. According to Figure 7a, the MMs observed during mirror stable plasma were mostly dips. The important point to take from these results is that as the upstream $M_A$ and forcing increases, the Earth’s magnetosheath becomes statistically more mirror unstable and as a result favors peaks. We investigated this further by plotting the ratio of the number of observed dips with respect to peaks as a function of $M_A$ in Figure 6. It was clearly shown that the ratio between the observed dips and peaks is rather sensitive to the value of $M_A$. In fact, during $M_A > 25$ we identified approximately 3.5 times more peaks than dips as opposed to $M_A < 5$ where 4 times more dips were identified.

This last point also suggests that as $M_A$ increases (as the instability is driven harder), the stabilization is not uniquely achieved by the isotropy of the distribution. It is clear from Figure 7 that for high $M_A > 15$, the cluster of points shifts away from the marginal stability line toward the linearly unstable region. This result, as well as the increase of the occurrence rate of MMs for high driving (see Figure 8), is partly in contradiction with numerical results, i.e., Gary et al. [1996] and Qu et al. [2008], indicating that MM remnants would saturate as a result of wave-particle scattering caused by high- or low-frequency waves. In the simulation of Qu et al. [2008], harder driving in the simulation leads to isotropy in parallel and perpendicular temperature on timescales $T < 500/\Omega_i$. With a typical gyroradius $\rho_i \sim 80$ km and thermal speeds $v_{th} \sim 200$ km/s in the magnetosheath, the timescale of saturation by wave-particle scattering should be of the order 3 min or less. Whereas a
significant portion of MM structures might have been quenched by wave-particle scattering, explaining the lack of points around the marginal stability condition, peak regions with very large skewness might stabilize as a result of additional mechanisms, perhaps in the form of particle trapping or some nonlocal effects due to the inhomogeneity of the plasma near the magnetopause and bow shock boundaries. A strict comparison between current numerical models of MM instability and observations are limited by the fact that numerical techniques do not include the effects of a 2-D or 3-D boundary conditions. These effects are believed to have a nontrivial impact on the transport and evolution of MMs [Johnson and Cheng, 1997b] and could explain the discrepancy between the results of Gary et al. [1996], Qu et al. [2008], numerical results, and our statistical data. Our results therefore indicate the necessity to include boundary effects in numerical studies of MM structures for future comparisons. Having said that, since the present study is primarily statistical, a comparison with single case studies focused on the evolution of MMs is somewhat limited. Therefore, future studies could narrow down particular intervals from our statistical samples for comparison purposes to shed light on the saturation theory and the simulations of Passot et al. [2006] and Kuznetsov et al. [2007].

The next phase of our study was to examine the occurrence of MMs and quantify their dawn-dusk asymmetry. The occurrence rate of magnetic field fluctuations associated with the MM instability was also studied in depth by Génot et al. [2009b, 2009a] using 5 years of Cluster magnetosheath encounters. The authors also suggested that the occurrence of MMs increase with $M_A$ and similar to our results, (see Figure 8) stopped increasing around $M_A \sim 15$. They also commented on the dawn-dusk asymmetry, suggesting that MMs favor the dusk flank, but a numerical estimate of the asymmetry was not provided. In the present study, we have focused on quantifying the dawn-dusk asymmetry by using a larger data set. Figure 8 (right) conveyed convincing evidence that the generation of MMs is more frequent on the dusk flank, i.e., behind a quasi-perpendicular shock. It is worth reiterating that the MIPM frame arranges data points as a function of the IMF vector, and therefore, in our statistical data, dawn and dusk flanks correspond to quasi-parallel and quasi-perpendicular geometries, respectively. In general, the heating of perpendicular temperature [Leroy et al., 1982] across a quasi-perpendicular shock front is nonadiabatic [Lee et al., 1986, 1987] compared to the smaller and more adiabatic parallel temperatures [Biskamp and Welter, 1972]. As a result, a larger temperature anisotropy is present downstream of the quasi-perpendicular shock which is favorable for the growth of MMs. In fact, the ion temperature anisotropy downstream of the shock generally decreases as the shock geometry moves from perpendicular to parallel [Ellacott and Wilkinson, 2007], suggesting a dusk-favored asymmetry of temperature anisotropy during a Parker-spiral IMF. Since MMs grow from the free energy provided by temperature anisotropies, the dusk-favored asymmetry of MMs is believed to originate from the larger temperature anisotropy associated with plasma processed by a quasi-perpendicular, as opposed to a quasi-parallel shock front, as shown in Figure 2.

Our calculation of the dusk-favored asymmetry appeared to decrease with increasing $M_A$. A physical explanation for this could be that as $M_A$ increases, the instability is driven harder resulting in ions that are more isotropic [Gary et al., 1996; Qu et al., 2008] as shown by the decrease in $T_\perp/T_\parallel$ with $M_A$ in Figure 7. We also estimate that as well as the decrease in magnitude of $T_\perp/T_\parallel$, the relative asymmetry also decreases with increasing $M_A$ meaning, the difference in MM favorability between the dawn and dusk sectors is reduced. In addition, $\beta_\perp$ increases with $M_A$ which is also a factor in MM generation. It follows then that for large $M_A$, the $1/\beta_\perp$ term in the threshold condition becomes negligible, meaning the threshold condition will be comfortably satisfied on both flanks. Therefore, during sufficiently high $M_A$, the asymmetry of occurrence of MMs in the dayside magnetosheath is very small. Furthermore, our data suggests that the minimum asymmetry exists close to the magnetopause. It should be mentioned that the turbulent properties of the magnetic field behind the quasi-parallel shock could potentially result in false identifications of MMs. However, if this were the case, it would produce an asymmetry that is dawn favored and not dusk. The most likely scenario is that our estimates in some instances could be more conservative that in reality.

Since $T_\perp/T_\parallel$ increases dramatically toward the magnetopause (see Figure 2), generally, the anisotropy difference on the dawn and dusk flanks decreases. Although the asymmetry reduces, this does not mean that the properties of MMs on both flanks remain the same. On the contrary, the amplitude and spatial scale of the MMs may be different, as it was shown that larger-amplitude MMs favor the dawn flank [Génot et al., 2009a]. To quantify this, one would have to isolate MMs within each window and then determine their individual properties. Such analysis is, however, beyond the scope of this study and would overlap with the work by Génot et al. [2009a].
We also quantified for the first time the relationship between the asymmetry of the occurrence rate of MMs and the spiral angle. Our results suggest that the largest occurrence of MMs and asymmetry were during an atypical inward ortho-Parker spiral IMF orientation (−135°). Such an observation was made previously by Génot et al. [2009a] and our observations are quantitatively equivalent, where the occurrence increases from around 25% to 30% from Parker-spiral to ortho-Parker spiral. In spite of the large error bars, the dusk-favored asymmetry is observed for the majority of spiral angles but appears at a maximum for the inward ortho-Parker spiral IMF. Although our data agree with previous studies, the underlying cause remains unclear. On a statistical basis, this is very difficult to determine, and therefore, future studies should focus on the individual properties of the bow shock during these conditions to identify possible underlying causes.

5. Conclusions

We have used 6 years of THEMIS observations to quantify the spatial distribution and dawn-dusk asymmetry of mirror mode occurrence in the Earth's magnetosheath. The main findings from this study are as follows:

1. $T_\parallel / T_\perp$ is stronger on the dusk flank compared to the dawn.
2. The dusk-favored asymmetry of $T_\parallel / T_\perp$ appears to be dictated more by the IMF orientation as opposed to upstream Alfvén Mach number.
3. The occurrence of mirror modes increases with Alfvén Mach number until $M_A \sim 17.5$. Beyond the break point ($M_A > 17$) the occurrence rate is steady.
4. The dusk-favored asymmetry decreases with increasing solar wind Alfvén Mach number.
5. The largest asymmetry was estimated in the central magnetosheath during low/moderate Alfvén Mach numbers where over twice as many mirror modes were observed on the dusk flank compared to the dawnside.
6. Largest values of occurrence rate and (dusk-favored) asymmetry were observed when the IMF was aligned with an atypical inward ortho-Parker spiral IMF orientation.
7. As the solar wind Alfvén Mach number increases, the magnetosheath mirror modes transition from dips to peaks.

The statistical dependencies above should be compared with the results of kinetic simulations [Karimabadi et al., 2006; Alfthan et al., 2014] to determine their reproducibility. Although mirror modes are relatively well understood, there remain unanswered questions, such as the tendency for mirror modes to favor atypical IMF orientations. Future studies correlating bow shock structure and its parameters to mirror mode statistical properties (including plasma convection) may shed some light on this interesting statistical dependence.

Acknowledgments

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References


