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Roles of electrons and ions in formation of the current in mirror mode structures in the terrestrial plasma sheet: MMS observations

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Abstract

Currents are believed to exist in mirror mode structures and to be self-consistent with the magnetic field depression. Here, we investigate a train of mirror mode structures in the terrestrial plasma sheet on 11 August 2017 measured by the Magnetospheric Multiscale mission data. We find that a bipolar current exists in the cross-section of two hole-like mirror mode structures, referred to as magnetic dips. The bipolar current in the magnetic dip with a size of ~3 ρ_i (the ion gyro radius) is mainly contributed by an electron bipolar velocity, which is mainly formed by the magnetic gradient-curvature drift. For another magnetic dip with a size of ~6.67 ρ_i, the bipolar current is mainly caused by an ion bipolar velocity, which can be explained by the ion diamagnetic drift. These observations suggest that the electrons and ions play different roles in the formation of currents in magnetic dips with different sizes.

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1 Introduction

Mirror modes are pressure-balanced and compressional magnetic structures (Hasegawa, 1969; Tsurutani et al., 2011; Wang et al., 2016; Zhang et al., 2018). They widely exist in many space plasma regions, such as solar wind (Zhang et al., 2008, 2009; Russell et al., 2009), planetary magnetosheath (Volwerk et al., 2008; Schmid et al., 2014), planetary magnetosphere (Vaivads et al., 2001; Rae et al., 2007), and comets (Glassmeier et al., 1993; Volwerk et al., 2016). These structures are believed to be generated by the mirror instability excited in the mirror unstable environment (Hasegawa, 1969; Southwood and Kivelson, 1993). The plasma perpendicular temperature anisotropy provides free energy to excite the mirror instability (Kivelson and Southwood, 1996). Once the mirror mode structures are generated, they will convected with the ambient flow since they are non-propagating relative to the ambient flow (Tsurutani et al., 2011). It is expected that they will stop to grow or decay when they move to the mirror stable region. Actually, they are reported to be able to survive in the mirror stable region in the solar wind and magnetosheath (Balikhin et al., 2009; Russell et al., 2009).

Mirror mode structures appears as not only quasi-periodic sinusoidal oscillations, but also local enhancements or decrease of the magnetic field intensity, referred to as magnetic peaks or dips (Tsurutani et al., 2011). Magnetic peaks can only exist in the mirror unstable environments, while magnetic dips are able to survive in the mirror stable region (Kuznetsov et al., 2007; Soucek et al., 2008). The typical scales of the mirror mode structures are 10s ρ_i in the magnetosheath (Tsurutani et al., 1982; Horbury and Lucek, 2009), where ρ_i is the ion gyro radius. Based on observations of the four Cluster satellites, the longest scales of the mirror mode structures in the magnetosheath is found to be 2 – 6 times length of their shortest scales, and their shapes are approximately cigar-like (Horbury and Lucek, 2009).

In the terrestrial plasma sheet, there also exist mirror mode structures with several ion gyro radii (Vaivads et al., 2001; Zieger et al., 2011; Li et al., 2014; Wang et al., 2016). The earthward fast flows can result in a magnetic pileup in its leading area, and the ion perpendicular temperature anisotropy in the pileup region is able to make the local plasma conditions mirror-unstable to generate mirror mode structures (Zieger et al., 2011). Mirror mode structures accompanied by electron dynamics and whistler waves are also reported to occur during the dipolarization processes in the plasma sheet (Li et al., 2014). Dipolarization fronts (DFs), characterized by a sharp enhancement in B_Z in GSM, are formed ahead of the earthward fast flows (Ge et al., 2012; Wu et al., 2013; Schmid et al., 2016; Xiao et al., 2017). They create a magnetic pileup region ahead of the DF when moving earthward (Schmid et al., 2011; Fu et al., 2012; Liu et al., 2013). Mirror mode structures with a scale of ~4 ρ_i are reported to occur in the magnetic pileup region ahead of a DF, and the mirror instability is suggested to be a potential mechanism to generate these structures since local environments are mirror-unstable (Wang et al., 2016). Within a mirror mode structure there should be an electric current driven by the magnetic gradient and curvature drifts of the ions and/or electrons in order to sustain their stability (Constantinescu, 2002).

In this study, we investigate a train of mirror mode structures in the terrestrial plasma sheet on 11 August 2017 using the Magnetospheric Multiscale (MMS) mission data. The aim of this study is to figure out the roles of electrons and ions in the current inside the mirror mode structure based on the high-resolution MMS data.

2 Observation

The MMS spacecraft consist of four identical satellites, which constitute a tetrahedron with inter-spacecraft distances of tens km (Burch et al., 2015). In the present study, we use the survey (a resolution of 16 Hz) and burst (128 Hz) magnetic field data obtained by the Fluxgate Magnetometer (Russell et al., 2014), and the survey (4.5 s) and burst (150 ms for ions, 30 ms for electrons) plasma data recorded by the Fast Plasma Instrument (Pollock et al., 2016). Since the burst magnetic and plasma data are

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only available in parts of the interval in Figure 1, the survey data are used throughout the paper unless stated otherwise.

Figure 1 shows that B_Z sharply increases ~8 nT within 7 seconds at ~20:38 UT on 11 August 2017 accompanied by a fast earthward flow with a maximum velocity ~300 km/s. Also, the local ion beta, the ratio of the ion thermal pressure to the magnetic pressure is ~4, and the elevation angle ($\theta = \arctan\left(\frac{B_Z}{\sqrt{B_X^2+B_Y^2}}\right)$) changes ~50° with a maximum angle of 64° (not shown). These observations satisfy the criteria of the DF from Fu et al. (2012), indicating that it is a DF event shown as the vertical dotted line in Figure 1. At 20:40 UT, the MMS spacecraft are located near (-18, 14.6, 2) R_E in GSM (Geocentric Solar Magnetospheric coordinates, used everywhere unless otherwise stated). The normal direction of the DF is (0.34, 0.82, -0.46) determined by the minimum variance analysis (MVA) (Sonnerup and Scheible, 1998) using the data in the interval between 20:37:33 and 20:37:42 UT. The ratio of the intermediate to minimum eigenvalues (λ_2/λ_3) is ~15, indicating that the estimated normal direction is reliable (Volwerk, 2006; Wang et al., 2014). The estimated normal direction suggests that the MMS spacecraft are located at the duskward side of the DF based on the semi-circle assumption of the DF (Huang et al., 2015).

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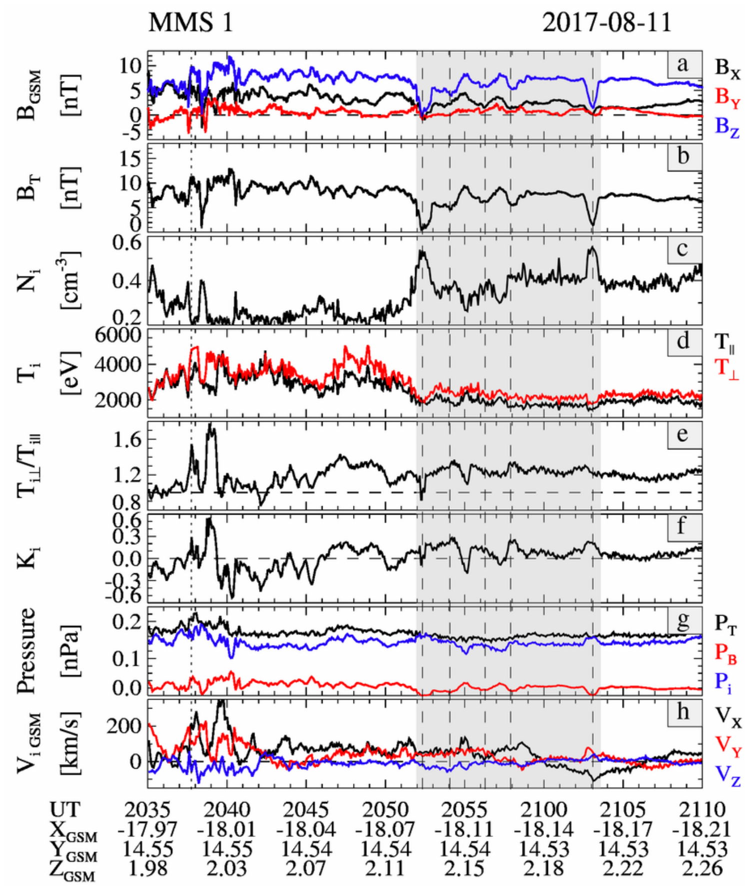

Figure 1. Observations of a DF event by MMS 1 on 11 August 2017. From top to bottom: three components of the magnetic field in GSM (a), the total magnetic field (b), ion density (c), ion perpendicular (red) and parallel (black) temperatures (d), ion perpendicular temperature anisotropy (e), the threshold of the mirror instability (f), the magnetic, ion thermal and total pressures (g), and three components of the ion velocity in GSM (h). The vertical dotted line indicates the DF, and the dashed lines indicates the trough of each compressional structure. The gray shadows indicate the mirror mode structures.

Several quasi-periodic compressional magnetic oscillations with a period of ~2 min are observed in the interval between 20:51 and 21:04 UT shown as the gray region in Figure 1. Since waves with a period of ~20 s are superimposed on the compressional oscillations, and only burst magnetic field data are available before 20:53 UT for this interval, we estimate the velocities of these compressional oscillations by timing

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analysis (Harvey, 1998) using the burst magnetic field data low-pass filtered with a cutoff period of 30 s between 20:51:55 and 20:53 UT. The estimated velocity is (61.6, 12.7, -33.5) km/s, which is close to the average ion velocity (49.3, 38.2, -35.2) km/s in this interval, suggesting that these oscillations are approximately stationary in the ambient flow. The ion number density tends to be larger in the trough of the oscillations as the dashed lines shown in Figure 1. Figure 1g shows that the magnetic and ion thermal pressures vary in anti-phase during the compressional oscillations, in addition, the total pressure is almost constant, indicating that the oscillations are pressure-balanced. The above properties of the compressional oscillations indicate that they are mirror mode structures (Tsurutani et al., 2011).

We mark these mirror mode structures as MM1 to MM5, and their time intervals and scales are listed in Table 1. The scales are estimated by

$$\sqrt{\left(\int_{t_1}^{t_2} V_X dt\right)^2 + \left(\int_{t_1}^{t_2} V_Y dt\right)^2 + \left(\int_{t_1}^{t_2} V_Z dt\right)^2}$$

where V_X, V_Y and V_Z are three components of the ion velocity, while t_1 and t_2 are the start and end time of each structure (Ge et al., 2011). And the local ion gyro radius ρ_i is estimated by the average ion temperature and average total magnetic field low-pass filtered with a cutoff period of 20 s. The scales of these structures vary between ~3 ρ_i and 14.38 ρ_i. The rotation angle of the magnetic field over each structure varies between ~2.5° and 12.4°.

The threshold of the ion mirror instability K_i is shown in Figure 1f, where $K = \frac{T_\perp}{T_\parallel} - 1 - \frac{1}{\beta_\perp}$, and $T_\perp$, $T_{/\!/}$, and $\beta_\perp$ are perpendicular and parallel ion temperatures and perpendicular ion beta, respectively (Southwood, and Kivelson, 1993). Local plasma environments become mirror unstable and can excite ion mirror instabilities when $K_i >$ 0. The maximum K_i in each mirror mode structure reaches over 0.2, and it tends to decrease to near or below 0 from the center of each structure to its edge. Before 20:51

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UT or after 21:04 UT, K_i is near or below 0, i.e. the background environment for these structures is mirror marginal stable.

Table 1. The time interval, angle of the magnetic field at two edges, scale, and maxima threshold of the ion mirror instability for each mirror mode structure.

	Time interval (HH:MM:SS)	θ (°)	ρ_i	Scale (km)	$K_{i\_}max$
MM1	20:51:55 – 20:53:06 UT	13.3	3	4.83×10^3	0.2
MM2	20:53:06 – 20:55:00 UT	6.3	14.41	11.32×10^3	0.28
MM3	20:55:00 – 20:57:14 UT	4.6	12.36	8.25×10^3	0.17
MM4	20:57:14 – 20:58:56 UT	6.3	12.93	8.39×10^3	0.25
MM5	21:02:26 – 21:03:34 UT	2.9	6.67	6.42×10^3	0.23

MM1 and MM5 appear as hole-like structure, which are referred to as magnetic dips (Tsurutani et al., 2011). To further look at the plasma properties in the magnetic dips, we transform the ion and electron velocities as well as the magnetic field and current density into the principal axis (LMN) coordinate system. The principal axes vectors are calculated by the minimum variance analysis (MVA, Sonnerup and Scheible, 1998) in the interval between 20:51:55 and 20:53:06 UT. The **L**, **M** and **N** directions are (0.44, 0.17, 0.88), (0.33, 0.88, -0.34) and (-0.84, 0.44, 0.33) in GSM, respectively. The ratio of the intermediate to minimum eigenvalues is ~4.7, indicating that the MVA results are reliable (Sergeev et al., 2003). The current density is calculated by $\mathbf{j} = qn_e(\mathbf{V}_i - \mathbf{V}_e)$, where n_e, V_i, and V_e are electron number density, ion velocity and electron velocity, respectively. To reduce the effect of the high-frequency oscillations, the magnetic field, electron velocity and current density in Figure 2 (also in Figure 3) have been smoothed within a 20-second window.

Figure 2 shows that B_L is dominant while B_M and B_N vary around 0, indicating that the cross-section of the structure is approximately parallel to the M-N plane. The ion velocity is mainly in the M-N plane during the whole interval, and there are no significant changes in both V_{i_M} and V_{i_N}. By contrast, the N component of the electron velocity V_{e_N} shows a bipolar variation with a maximum change of ~70 km/s. An enhancement (a decrease) of V_{e_N} occurs in the left (right) side of MM1. One can also

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note that the maximum and minimum of V_{e_N} in MM1 tend to occur near the maximum gradient of B_L. V_{e_M} also shows a bipolar variation in MM1 compared to the ambient value. In addition, the N and M components of the current density show bipolar variations similar to the electron velocity with an opposite trend of change. By comparing the variations in the ion and electron velocities, one can note that the current density in MM1 is mainly determined by the the electron velocity. The bottom panel in Figure 2 shows the electron perpendicular thermal pressure $P_{e\perp}$, and there is no significant change in $P_{e\perp}$ in MM1.

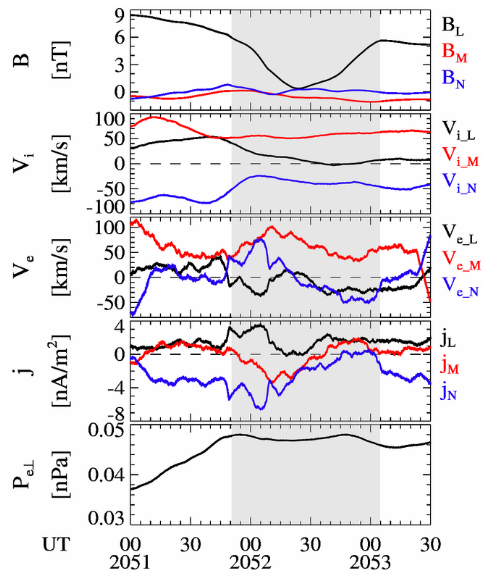

Figure 2. Three components of the magnetic field, ion and electron velocities, current density in the principal axis (LMN) coordinate system, and electron perpendicular thermal pressure between 20:51 and 20:53:30 UT.

Figure 3 shows the magnetic field, ion velocity, electron velocity, current density and ion perpendicular thermal pressure in MM5. The magnetic field data between 21:02:30 and 21:03:30 UT are used to calculate the principal axes vectors by MVA (Sonnerup and Scheible, 1998). The ratio of the intermediate to minimum eigenvalues is ~6.8, and the **L**, **M** and **N** directions are (0.26, 0.09, 0.96), (-0.49, 0.87, 0.05) and (-0.83, -0.49,

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0.27) in GSM, respectively. B_L is dominant during the whole interval, while B_M and B_N are very small. Thus, the cross-section of MM5 is approximately parallel to the M-N plane. The ion velocity V_{i_M} and V_{i_N} are dominant, while V_{i_L} varies around 0. Interestingly, a bipolar feature in V_{i_N} with a variation up to 73 km/s (peak minus trough) can be distinctly found in the dip, while V_{i_M} tends to increase compared to the ambient flow. V_{i_N} is smaller (larger) than the ambient value in the left (right) side of the dip. J_N also shows a similar bipolar feature with a variation up to 5.4 nA/m^2, while J_L and J_N have no significant changes. The N component of the electron velocity, however, shows no such characteristics, indicating that the bipolar J_N is mainly determined by the bipolar V_{i_N}. The ion perpendicular thermal pressure $P_{i\perp}$ in the structure is obviously larger than the ambient value, and $P_{i\perp}$ tends to be larger from the edge to the center of MM5.

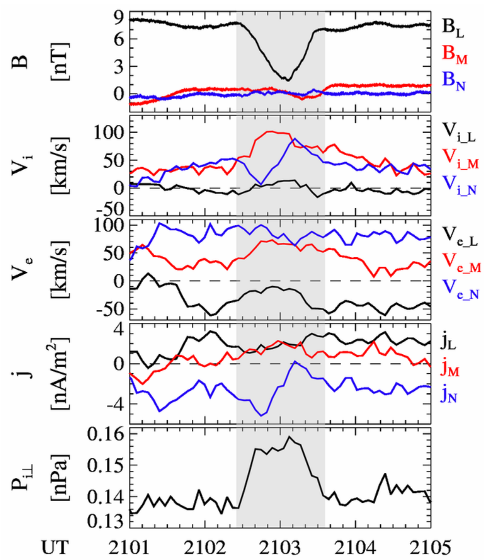

Figure 3. Three components of the magnetic field, ion and electron velocities, current density in the principal axis (LMN) coordinate system, and ion perpendicular thermal pressure between 2101 and 2105 UT.

To look at the variations of the ion flow in MM5, we assume that the ion velocity observed during MM5 consists of $\mathbf{V_{i\_a}}$ and $\mathbf{V_{i\_md}}$, where $\mathbf{V_{i\_a}}$ is the ambient ion velocity, and $\mathbf{V_{i\_md}}$ is the ion velocity in the magnetic dip relative to the ambient flow. The

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average velocity 30 seconds before and after MM5 is selected to be regarded as $\mathbf{V}_{\mathbf{i\_a}}$ with a value of (-2.6, 51.4, 33.4) km/s in LMN. Figure 4 shows the deflection of $\mathbf{V}_{\mathbf{i\_md}}$ in the M-N plane. The arrows indicate the direction of the ion velocity, and their lengths indicate the magnitude of $\mathbf{V}_{\mathbf{i\_md}}$ in the M-N plane. The direction of $\mathbf{V}_{\mathbf{i\_md}}$ gradually changes from around -60° to 50° in the M-N plane. Also, the strength of $\mathbf{V}_{\mathbf{i\_md}}$ in this plane gradually increases and then decreases from the left side of the magnetic dip to the right side. In addition, the N component of $\mathbf{V}_{\mathbf{i\_md}}$ changes from negative to positive at just around the center of the structure.

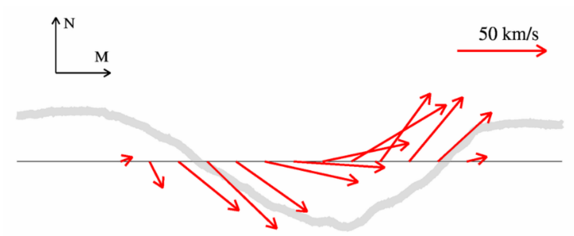

Figure 4. Ion velocities in the M-N plane during MM5. The arrows indicates the direction of the ion velocities, and their lengths indicate the amplitude of the ion velocities. And the gray line indicates the total magnetic field of MM5.

3 Discussion

Figure 1 shows the ambient plasma is marginally mirror stable, indicating that the mirror mode structures are not locally generated. Since they are stationary in the ambient flow, they are estimated to occur dawnside of the MMS spacecraft with a distance of ~4 R_E in the Y direction when the spacecraft are crossing the DF at around 20:38 UT, where the average V_Y ~30 km/s during the structures are used. Compared this distance with the typical size of the DF (~3 R_E) (Huang et al., 2015) and the size of the structures, the mirror mode structures might come from the dawnside flank of the DF. Since the DF is considered to be a tangential discontinuity (Schmid et al., 2019) which pushes the background plasma to its flanks (Fu et al., 2012; Liu et al., 2013), the plasma near the flank is expected to come from the pileup region ahead of DFs. Mirror

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mode structures have been reported to occur in such a pileup region (Wang et al., 2016). The pileup of the magnetic field and the ion reflection ahead of the DF are suggested to provide free energy to excite the ion mirror instability (Zieger et al., 2011; Wang et al., 2016). Thus, the mirror mode structures in Figure 1 might originate from the pileup region ahead of the DF.

Based on Ampère's law, there should exist a current in the magnetic dip to sustain the structure's stability, and the current is determined by the collective behavior of electrons and ions (see Constantinescu, 2002). Figure 2 and 3 shows that a bipolar current density is observed in both MM1 and MM5. B_L changes ~6 nT in MM1, and the estimated length of MM1 is 4.83×10^3 km. Thus, a current density j_B with a value of ~2 nA/m^2 is necessary to be self-consistent with the magnetic field depression. The amplitude of the bipolar j_N in MM1 is ~2 nA/m^2, almost equal to j_B, indicating that MM1 is a stable structure (Constantinescu, 2002). Similarly, MM5 is also a stable structure. The variations of the current density in MM1 is mainly contributed by the variations of the electron velocity. By contrast, no significant changes occur in the electron velocity, while a bipolar ion velocity similar to the current density appears in V_{i_N}. Thus, the bipolar current density in MM5 is mainly contributed by the variations of the ion velocity.

The size of MM1 is ~3 ρ_i, and its central magnetic field strength is almost 0. Thus, the ion gyro radius is expected to significantly change within one orbit, and ions would randomly jump between neighboring magnetic dips (Constantinescu, 2002). These ions are referred to as chaotic particles, which do not contributed to the formation of the current in the mirror mode structure (Constantinescu, 2002). It might be an important reason that the current in MM1 is mainly contributed by electrons. The size of MM1 is ~20 ρ_e, where ρ_e is the local electron gyro radius. Thus, a quasi-hydrodynamic treatment can be used to describe the electrons. Three kind of drifts are expected to form the current in MM1, i.e. the magnetic gradient drift, the magnetic curvature drift, and the electron diamagnetic drift. The electron perpendicular thermal pressure $P_{e\perp}$ changes ~0.002 nPa in MM1, the average electron number density is ~0.4 cm^{-3}, and the average total magnetic field is ~3 nT. Consequently, the estimated electron diamagnetic drift velocity is ~4 km/s, much smaller than the bipolar amplitude ~70 km/s in V_{e_N} in Figure 2. We also calculate the magnetic gradient drift velocity with an estimated value of 1.13 × 10^2 km/s, where the electron perpendicular temperature is ~800 eV, and B_L changes ~6 nT in a length of 2.45 × 10^2 km. Figure 2 shows that the strength of the bipolar velocity in V_{e_N} is ~70 km/s, smaller than the magnetic gradient drift velocity. The magnetic curvature drift in MM1 is in the opposite direction of the magnetic gradient drift. Figuring out the magnetic field geometry, we can get the exact values of the magnetic gradient and curvature drifts. Due to the small interspacecraft distance among the MMS satellites, it is difficult to get a reasonable magnetic field geometry and a reliable curvature radius of MM1. Nevertheless, it is expected that both the magnetic gradient and curvature drifts contribute significantly to the formation of the current in MM1.

The size of MM5 is ~6.67 ρ_i, larger than that of MM1. The ion bipolar velocity in MM5 indicates a local ion flow, suggesting there exists some magnetohydrodynamic properties in this structure. The ion perpendicular thermal pressure tends to be larger from the edge of MM5 towards its center (see Figure 3), therefore, an ion diamagnetic drift is expected to be formed (Baumjohann and Treumann, 1996). The ion perpendicular thermal pressure changes by ~0.013 nPa for intervals 21:02:31 – 21:02:40 UT and 21:03:07 – 21:03:29 UT (see Figure 3). Using the average ion density and magnetic field strength, the estimated velocities of the diamagnetic drift are 40.4 km/s and 19.2 km/s for these two intervals, which is comparable with the amplitude of the bipolar V_{i_N} in Figure 3. Therefore, the ion bipolar velocity as well as the bipolar current in MM5 is mainly contributed by the ion diamagnetic drift. It is expected that the magnetic gradient and curvature drifts of ions move in opposite directions in MM5. We speculate that the difference of the magnetic gradient and curvature drift velocities

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are small possibly resulting from the magnetic field geometry of MM5. The larger scale of MM5 compared to MM1 could reduce the magnetic gradient and electron thermal pressure gradient resulting in slower magnetic gradient drift and electron diamagnetic drift velocities. That's could be the reason why no significant bipolar occurs in the electron velocity in MM5. Another possible reason might the magnetic field geometry which might reduce the difference of the magnetic gradient and curvature drift velocities of electrons.

One can note that there is an enhancement of V_{i_M} in MM5. To figure out the variations of V_{i_M} and V_{i_N} in MM5, we analyze the possible trajectory of the MMS spacecraft crossing MM5. Mirror mode structures in the magnetosheath are found to be cigar-like structures instead of sheets or tubes (Constantinescu et al., 2003; Horbury and Lucek, 2009). To simplify our analysis, we assume that the cross-section of the MM5 structure is a circle. To be self-consistent with the magnetic field depression, the ion flow as well as the current is supposed to be clockwise as the black arrows shown in Figure 5. We calculate the normal directions of the two sides of the magnetic dip by MVA, and the values are (0.03, 0.79, 0.61) and (-0.05, -0.65 0.76) in LMN for the intervals 21:02:30 – 21:03 and 21:03:10 – 21:03:25 UT, respectively. The ratios of the intermediate to minimum eigenvalues λ_2/λ_3 are 6.4 and 8.5, respectively. Thus, we can get a possible trajectory of MMS in the M-N plane based on the ambient flow and the above normal directions as the red arrow shown in Figure 5. Along the trajectory, one can note that the N component of the ion velocity changes from negative to positive from one to another side of MM5, while the M component is positive, which is in agreement with the deflection of the ion flow shown in Figure 4. Thus, the variations of V_{i_M} and V_{i_N} indicates a ring-like flow in the cross-section of MM5. Such a ring-like flow might play an important role in the evolution of the mirror mode structure or maintaining the stability of the magnetic dip.

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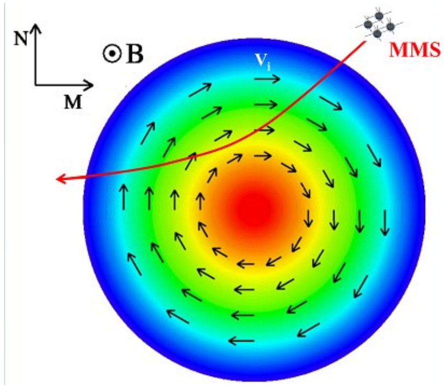

Figure 5. Schematic of MMS crossing the magnetic dip in the M-N plane. The colors changing from center (red) of the magnetic dip to its edge (blue) indicate the decrease of the ion perpendicular thermal pressure. The back arrows in the magnetic dip indicate the direction of the ion velocity. The red arrow indicates a possible trajectory of MMS.

4 Summary

We have studied the mirror mode structures with a size of several to 14.41 ρ_i in the plasma sheet on 11 August 2017. Current is expected to exist in the magnetic dip contributed by the collective behavior of electrons and ions. Our observations show a bipolar current in two magnetic dips, and the electrons and ions play different roles in each dip. The bipolar current in the magnetic dip with a size of ~3 ρ_i is mainly contributed by an electron bipolar velocity. The bipolar electron velocity could mainly result from the magnetic and curvature drifts of electrons. The chaotic motion of ions might be one significant reason that ions have almost no contribution to the formation of the current in this magnetic dip. For another magnetic dip with a size of 6.67 ρ_i, the bipolar current is mainly contributed by the ion bipolar velocity, which can be explained by the ion diamagnetic drift velocity. We suggest that both the scale and magnetic geometry of magnetic dips are significant to determine the roles of electrons and ions in the formation of the current in dips.

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Author contribution

Guoqiang Wang and Tielong Zhang designed the main idea of this study, and and the data analysis was mainly performed by Guoqiang Wang. Guoqiang Wang prepared the manuscript with contributions from all co-authors.

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Code/Data availability

The data of the MMS spacecraft are publicly available at https://lasp.colorado.edu/mms/sdc/public/.

Competing interests

The authors declare that they have no conflict of interest.