Ion-Scale Flux Rope Observed inside a Hot Flow Anomaly

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Abstract We report an earthward moving ion-scale flux rope embedded within the trailing edge of a hot flow anomaly (HFA) observed by the Magnetospheric Multiscale satellite constellation on 17 December 2016 upstream of Earth’s quasi-parallel bow shock. The driver of the HFA, a tangential discontinuity, was observed by the Wind spacecraft without flux rope signatures around it in the solar wind. This suggests that the earthward moving flux rope was generated inside the HFA. This ion-scale flux rope is not a force free structure and expands due to a strong magnetic pressure gradient force. Solar wind ions are decelerated inside the flux rope by the static electric field likely caused by the charge separation of solar wind particles. Our observations imply that magnetic reconnection may have occurred inside the HFA. Reconnection and flux ropes may play a role in particle acceleration/heating inside foreshock transients.

Plain Language Summary Energetic particles are often observed inside the foreshock transients or in the foreshock region. The acceleration mechanisms of these energetic particles remain an open question. Possible candidates responsible for the acceleration have been put forward, such as Fermi acceleration, electron firehose, and lower hybrid drift instabilities and magnetic reconnection. However, to date, magnetic reconnection is only found in hybrid simulations during the generation of foreshock transients, but never reported by in situ observations. In this paper, we report an ion-scale flux rope observed at the trailing edge of a hot flow anomaly, which could be generated during the magnetic reconnection. Our observations indicate that reconnection could occur locally within foreshock transients and contribute to their particle acceleration.

1. Introduction

Hot flow anomalies (HFAs) are frequently observed near Earth’s bow shock, which are characterized by a superheated, tenuous, low-field-strength core region (Schwartz et al., 1985; Schwartz et al., 2000; Zhang et al., 2010; Chu et al., 2017; Wang et al., 2013a, 2013b, 2013c; Zhao et al., 2015, 2017). The streaming energy of the solar wind ion beams and reflected ion beams is converted into the thermal energy inside HFAs, which leads to the expansion of HFAs. Because of the expansion, a strong deflection of the plasma velocity is exhibited within the structure, and the magnetic field and plasma compression regions or secondary shock is presented on one or both sides of the core (Thomsen et al., 1988; Omidi & Sibeck, 2007; Zhang et al., 2010).

Energetic particles up to hundreds of keV have been observed inside the cores of foreshock transients and most of foreshock transients can accelerate/heat particles (Wilson et al., 2016; Liu, Angelopoulos, Hietala, et al., 2017), which raises the question of how particles are accelerated and heated inside the structure. The Fermi acceleration through particle bouncing between the bow shock and the earthward moving boundary of foreshock transients is one possible candidate, which has been carefully investigated recently (Liu, Lu, et al., 2017; Liu et al., 2018; Turner et al., 2018). Recent observations also showed that the betatron acceleration can explain hundreds of keV electrons inside foreshock transients (Liu et al., 2019). The electron firehose and lower hybrid drift instabilities are also possible candidates for the isotropization and heating processes within HFAs (Eastwood et al., 2008; Zhang et al., 2010). Magnetic reconnection during the
development of HFA might be another possible mechanism for the particle acceleration inside HFAs (Lin, 1997). A particle-in-cell simulation shows that suprathermal electrons were accelerated by the magnetic islands generated by magnetic reconnection in the quasi-perpendicular shock (Matsumoto et al., 2015). Reconnection is also shown to occur in the quasi-parallel shock transition region through the Weibel instability (Gingell et al., 2017). If magnetic reconnection occurs inside foreshock transients, Fermi acceleration during the coalescence of magnetic islands could be another potential mechanism.

Recently, features of current sheet structures consistent with magnetic reconnection were found in the transition region of a quasi-parallel shock (Gingell et al., 2019; Hamrin et al., 2019) and quasi-perpendicular shock (Wang et al., 2019) with Magnetospheric Multiscale (MMS) high cadence plasma measurements. Signatures of magnetic reconnection such as small-scale flux ropes, which formed due to the tearing mode instability (Daughton et al., 2006; Drake, Swisdak, & Che, et al., 2006) or electron Kelvin-Helmholtz instability (Fermo et al., 2012) during the reconnection, might be found inside foreshock transients. To date, only a magnetic flux rope event in the magnetosheath part of an HFA has been reported (Hasegawa et al., 2012), which probably originates from magnetic reconnection in the magnetosheath part of the HFA. However, there is no clear observation of flux ropes formed locally inside foreshock transients.

In this study, we report an ion-scale flux rope observed at the trailing edge of an HFA in the ion foreshock, which is expanding and moving earthward with the HFA. The paper is organized as follows. In section 2.1, we introduce the data used in this study. In section 2.2, an overview of the HFA observed by MMS is given, in which the ion-scale flux rope is encountered. The solar wind condition observed by ACE and Wind is also provided in this section. Detailed analysis of the flux rope embedded in the HFA is presented in section 2.3. The expansion of the flux rope is investigated in section 2.4. Section 3 briefly discusses the mechanism of the expansion of the ion-scale flux rope and the energy transfer around the flux rope.

2. Observations

2.1. Data

In this paper, the solar wind magnetic field is measured by the magnetometer onboard the Wind satellite (Lepping et al., 1995) and ACE satellite (Smith et al., 1998). The foreshock observation comes from the fluxgate magnetometer (Russell et al., 2016), the fast plasma investigation (FPI; Pollock et al., 2016), and the electric field double probes (EDP; Lindqvist et al., 2016; Ergun et al., 2014) onboard the MMS satellite constellation (Burch et al., 2016).

2.2. MMS Observation of an HFA

The time scale of the observed HFA is only 16 s, extending from 12:55:12 UT to 12:55:28 UT, located upstream of a quasi-parallel shock ($\hat{B}_{\text{in}} = 43^\circ$, determined by using the bow shock model (Slavin & Holzer, 1981) shown in the black dashed box in Figure 1. The magnitude of the magnetic field and the electron density increased at both edges and decreased in the core region of the HFA (Figures 1(a) and 1(b)), which is caused by the expansion of the HFA (Thomsen et al., 1988; Omidi & Sibeck, 2007). The electron temperature increases continuously inside the HFA (Figure 1(c)); this might be related to the earthward motion of the HFA and the Fermi acceleration of electrons (Liu, Lu, et al., 2017). The electron velocity decreases inside the HFA (Figure 1(d)). Energetic foreshock ions (Figure 1(e)) get thermalized inside the HFA, which provides the energy for the expansion of the HFA (Onsager et al., 1990). All of these are typical observational features of HFAs. The HFA was expanding and moving toward the bow shock based on timing analysis (Schwartz, 1998). The velocities of the leading and trailing edges of the HFA are $165.8 \pm 7.6 \times [0.96, 0.01, 0.24]$ km/s and $91.9 \pm 3.6 \times [0.90, -0.29, 0.31]$ km/s in GSM coordinates, respectively.

The prevailing solar wind parameters, observed by ACE and Wind, are shifted to the MMS location (Figures 1(g) and 1(h)). Because of the large disturbance in the magnetic field, the comparison of cone/clock angle between MMS and Wind/ACE was not used when MMS was in the foreshock region and not shown in Figures 1(i)–1(j). Using only the time interval when MMS was in the solar wind before and after the event, the comparison of the cone angle and clock angle of the interplanetary magnetic field (IMF) observed by ACE, Wind, and MMS are shown in Figures 1(i) and 1(j) and the lag time between ACE/Wind and MMS is determined by the highest correlation coefficient of the cone angle ($r > 0.9$). Within this time interval, there is only one possible discontinuity observed by Wind at ~12:55:04 UT (blue
shaded region; only a weak variation is observed by ACE) that might trigger the generation of the HFA. It is a tangential discontinuity (TD) identified by a near-zero normal component and a discontinuity in the tangential component of the magnetic field around it. The normal of the TD is \([-0.543, -0.830, 0.122]\) in GSM coordinates determined by the minimum variance analysis (Sonnerup & Cahill, 1967; MVAB), and a similar normal is obtained through the cross product method (Schwartz, 1998) at Wind. The propagation of the TD is consistent with the time delay from Wind to MMS. The motional electric field \(E = -V \times B\) points toward the TD on both sides, consistent with the preferred condition for the HFA generation (Thomsen et al., 1993). During the entire time interval around the discontinuity, no flux rope signature, such as the unipolar component and bipolar component of magnetic field, is shown. A schematic illustration of the TD, the HFA, and the relative trajectory of MMS is shown in Figure 1(k).

2.3. Ion-Scale Flux Rope

At the trailing edge of the HFA (Figures 1–3 shaded region; 12:55:23 UT to 12:55:28 UT), the magnetic field strength and the electron density enhancement at the trailing edge are very significant. The electron density increased from 11.35 cm\(^{-3}\) in the solar wind to 80.98 cm\(^{-3}\) at the trailing edge of the HFA and the magnetic field strength also increased from 4.5 nT in the solar wind to 34.0 nT at the trailing edge of the HFA with a compression ratio much larger than 4. This means that it is not a typical compressional boundary. The
bipolar $B_z$ and unipolar $B_y$ suggest that it could be a small-scale flux rope. Using the timing analysis (Schwartz, 1998), the velocities of the leading and trailing edges of the flux rope are $113.5 \pm 5.9 \times [-0.84, -0.32, -0.43] \text{ km/s}$ and $91.93 \pm 3.6 \times [-0.90, -0.29, -0.31] \text{ km/s}$ in GSM coordinate, respectively. This suggests that the flux rope is expanding at ~20 km/s toward the sun in the solar wind reference frame.

The spatial scale of the flux rope is $6.10 \sim 7.51$ ion inertial lengths. The ion inertial length here is $75.5 \text{ km}$ determined by the ion density in the solar wind (12:55:30–12:55:40 UT). The expansion of the flux rope will be carefully investigated in the next section.

To better investigate this case, we use the L-M-N coordinate system, which is determined by MVAB (Sonnerup & Cahill, 1967). We found that $L \sim [-0.18, 0.98, -0.07]$, $M \sim [-0.46, -0.02, 0.88]$, $N \sim [0.86, 0.19, 0.45]$ are the maximum, intermediate, and minimum variation directions in GSM coordinates, respectively. The core field of the flux rope is in the $L$ direction, and the bipolar signature is shown in the $M$ direction. $B_N$ is negative and decreased inside the flux rope. Field-aligned current, which is calculated using the culometer
technique (Dunlop et al., 1988, 2002), was observed at the center of the flux rope (Figure 2(b)). Due to the presence of helical structure inside the flux rope, the local radius of curvature of the magnetic field lines increases from 300 to 1,000 km inside the flux rope (Figure 2(c)), which is obtained by magnetic field rotation analysis (Shen et al., 2007). The observational features of the magnetic field, current density, and radius of curvature of the magnetic field lines listed above are consistent with the previous work on flux ropes (e.g., Russell & Elphic, 1979; Slavin et al., 2003; Shen et al., 2007; Zong et al., 2004; Sun et al., 2019).

The electric field is shown in Figure 2(d), and we focus on the component in the normal direction. Two ion populations were observed inside the flux rope, one comes from the solar wind from 10 to 1,000 eV and the other from the foreshock ions from 1 to 3 keV (see Figure 1(e)). The $\mathbf{V} \times \mathbf{B}$ of these two ion populations are

![Image](https://example.com/image.png)
quite different. The $\mathbf{V}_{i,\text{solarwind}} \times \mathbf{B}$ agrees well with the $\mathbf{V}_e \times \mathbf{B}$. For foreshock ions, on the other hand, the $\mathbf{V}_{i,\text{foreshock}} \times \mathbf{B}$ does not match the $\mathbf{V}_e \times \mathbf{B}$ at all. There is also disagreement between the $\mathbf{V}_e \times \mathbf{B}$ and the electric field measured by EDP from 12:55:26 to 12:55:27.5 UT. One possible reason is that when the solar wind penetrates the flux rope, the gyroradii difference between the solar wind ions and electrons generates the electrostatic field in normal direction, which could decelerate the solar wind ions. Considering the velocity of the trailing edge of the HFA, the spatial scale of this disagreement electric field is 133.56 km, which is close to the gyroradii difference between the solar wind ions and electrons (142.03 km for 1-keV solar wind particles). To further confirm this, we calculated this static electric field in +N direction through the disagreement between EDP measurement and $\mathbf{V}_e \times \mathbf{B}$ and compared it with the energy decrease of solar wind ions. Here we used the average value of the disagreement between the $\mathbf{V}_e \times \mathbf{B}$ and the measured electric field from 12:55:26 to 12:55:27.5 UT as the static electric field $E = 1.7$ mV/m. Then we calculated the solar wind energy decrease as $1.7 \text{ mV/m} \cdot 133.56 \text{ km}$ in the de Hoffmann Teller frame (Sonnerup et al., 1987; $V_{1\text{T}} = 232.5 \times [-0.96, 0.28, 0.07] \text{ km/s}$) and transformed it back to the spacecraft frame shown as the white solid lines in Figure 2(g). It matches the energy where the solar wind ion flux peaks very well, confirming the deceleration of solar wind ions by the static electric field at the trailing edge of flux rope. There is no significant change in the Tpara of the solar wind ions around the trailing edge of the flux rope (red in Figure 2(f)). The Tperp (blue in Figure 2f), on the other hand, increases during the deceleration of solar wind ions at the boundary of the flux rope possibly due to the magnetic field strength enhancement. At the peak of the field strength where $J_f$ reaches the peak, however, the perpendicular temperature decreases, and the parallel motion dominates (Figure 2(h)). This is again inconsistent with typical compressional boundaries or shocks, but more consistent with field-aligned particle motion inside flux ropes.

To see it more clearly, Figure 2(i) show the ion distribution at 12:55:25.24 UT (marked by the vertical dashed line) when the field-aligned current peaked. The white dashed and solid lines overlaid in Figure 2(i) represent the ions with the same parallel velocity, suggesting that the solar wind ions are decelerated and thermalized in the perpendicular plane inside the flux rope than in the solar wind. Figure 2(i) shows the ion distribution in the $M$-$N$ plane (roughly the plane perpendicular to the magnetic field as $B_e$ dominates), the $E \times B$ motion of the solar wind ions is mainly in the $M$ direction, and the thermalization of the solar wind ions is mainly in the $N$ direction. The red dashed line in Figure 2(j) is the velocity of trailing edge of the flux rope in the normal direction. Most of the solar wind ions are faster than that speed ($V_n$).

### 2.4. Force Analysis inside the Flux Rope

To understand why the structure is expanding, Figure 3 shows the pressure and force analysis inside the flux rope. Because the spatial scale of the flux rope is too small compared to the gyroradii ($\sim 710$ km) of foreshock ions and the foreshock ion density is much lower than the solar wind ion density, we ignore the pressure and pressure gradient force caused by the foreshock ions inside the flux rope and separate the solar wind ions (10–1,000 eV) from the total ion distribution. However, foreshock ions still contribute to the current and electrostatic field inside the flux rope. Before we analyze each term on the right side of the MHD momentum equation (equation (1)), we test the reliability of our calculation by comparing the sum of the ion density calculated by two ion populations with the MMS measurement (Figure 3(b)), which shows excellent agreement.

As shown in Figure 3(c), the magnetic pressure is enhanced at the center of the flux rope and the thermal pressure reaches the two peaks at two edges of the flux rope. Each term on the right side of the momentum equation shown below is calculated in $L$-$M$-$N$ coordinates and displayed in Figures 3(d)–3(f). The pressure gradients are calculated based on the pressure tensor.

In the $L$ direction (Figure 3(d)), the ion pressure gradient determines the motion of the flux rope, whereas the other three terms are insignificant inside the flux rope. In the $M$ direction, the motion of the flux rope is determined by the magnetic pressure gradient and ion pressure gradient force. The $M$ component of the magnetic pressure gradient and magnetic tension force (Figure 3(e)) changes direction during the MMS crossing, indicating that the MMS is crossing the center of the flux rope rather than a pressure pulse driven structure; otherwise, the $M$ component should be unidirectional (Sibeck, 1990; Lockwood, 1991). In the $N$ direction (Figure 3(f)), the magnitude of the magnetic pressure gradient force is much larger than the other two terms and determines the expansion of the flux rope. Magnetic tension force in the normal direction is
very weak inside the flux rope, which suggests that the field line might be elongated in the M direction rather than circular in the M-N plane. Another piece of evidence to support this point is that the dimension of this flux rope is quasi-one-dimensional (1-D) rather than two-dimensional (2-D) structure as usual, which is determined by the minimum directional derivative method (Shi et al., 2005; Shi et al., 2019). The structure should be 1-D when \( \sqrt{\lambda_{\text{max}}} \gg \sqrt{\lambda_{\text{mid}}} \gg \sqrt{\lambda_{\text{min}}} \) as shown in Figure 3(g). \( \lambda_{\text{max}}, \lambda_{\text{mid}}, \) and \( \lambda_{\text{min}} \) are three eigenvalues of a symmetrical matrix \( L = G G^T = (\nabla \mathbf{B}) (\nabla \mathbf{B})^T \), which represent the maximum, intermediate, and minimum values of the field directional derivatives, respectively.

### 3. Summary and Discussion

In this paper, we report a small-scale flux rope with the width of 6.1–7.5 ion inertial lengths at the trailing edge of the HFA in the foreshock for the first time, which is characterized by the bipolar signature of the \( B_m \) component, a strong core field, and field-aligned current. Inside the flux rope, the perpendicular temperature decreased, and the M components of the magnetic gradient force changes direction several times. Both features further support that it is a flux rope, rather than a typical compressional boundary at the trailing edge of the HFA. A TD was observed in the solar wind, which may leads to the generation of the HFA. However, no flux rope signature was observed in the solar wind around the discontinuity and the flux rope is moving toward the bow shock, indicating that the ion-scale flux rope is locally generated at the trailing edge of the HFA, rather than being generated in the magnetosheath or in the solar wind and propagating to the core region of the HFA.

Solar wind ions are decelerated at the boundary of the flux rope between 12:55:26 and 12:55:28 UT, which is related to the positive static \( E_N \) pointing toward the solar wind possibly caused by the charge separation of the solar wind particles. The perpendicular temperature of solar wind ions (10–1,000 eV) increased simultaneously, indicating that solar wind ions at the HFA boundary are strongly diffused in the normal direction, and the kinetic energy of solar wind ions is converted into the thermal energy. Inside the flux rope, however, the parallel ion motion dominates. These parallel motion-dominated solar wind ions could be decelerated by the \(-L\) electric field and eventually trapped inside the flux rope, which may lead to the unusual high density observed by MMS. There is no enhancement of the thermal energy inside the flux rope. Instead, the perpendicular temperature decreases although the magnetic field strength continues to increase. The kinetic energy of solar wind ions was probably converted to the magnetic energy with the local J-E’ in the flux rope close to \(-0.9nW/m^3\). These features further indicate that the trailing edge of the HFA is not a typical compressional boundary or shock, but a flux rope.

The \( M \) component of the magnetic pressure gradient and magnetic tension changes directions several times during the flux rope crossing, indicating that the MMS crosses the center of the flux rope. The \( N \) component of the magnetic tension force is close to zero, indicating that the flux rope is a quasi-1-D structure, which is easier to be observed in the magnetic reconnection with small guide field than quasi-2-D flux rope (Sun et al., 2019). This transient quasi-1-D flux rope is not a force free structure and expanding mainly in the normal direction, which is determined by the magnetic pressure gradient force. Therefore, reconnection might be triggered within the HFA at the early stage during the interaction between the discontinuity and the bow shock, which is consistent with the hybrid simulation (Lin, 1997) and MMS observation (Hamrin et al., 2019). Additionally, this provides another way to generate energetic electrons inside foreshock transients that electrons could be accelerated up to hundreds of keV during the coalescence of ion-scale flux ropes (Drake, Swisdak, & Schoeffler et al., 2006; Matsumoto et al., 2015). However, electrons with hundreds of keV were not observed in this case, which might have not been generated yet or have leaked to the foreshock region like energetic ions (Liu, Angelopoulos, & Hietala, 2017). Our observations of the ion-scale flux rope inside the HFA fills in the blank of in situ observation of reconnection signature inside foreshock transients and might shed light on the particle acceleration in the foreshock region.

### References


