Magnetospheric Multiscale Observations of Foreshock Transients at Their Very Early Stage

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Abstract

Foreshock transients are ion kinetic structures in the ion foreshock. Due to their dynamic pressure perturbations, they can disturb the bow shock and magnetosphere–ionosphere system. They can also accelerate particles contributing to shock acceleration. However, it is still unclear how exactly they form. Recent particle-in-cell simulations point out the important role of the electric field and Hall current in the formation process. To further examine this, we use data from the Magnetospheric Multiscale (MMS) mission to apply case studies on two small (1000–2000 km) foreshock transient events that just started to form. In event 1 where MMS was in a tetrahedral formation, we show that the current density configuration, which determined the magnetic field profile, was mainly driven by Hall currents generated by demagnetized foreshock ions. The resulting time variation of the magnetic field induced an electric field that drove cold plasma moving outward with magnetic field lines. In event 2 where MMS was in a string-of-pearls formation, we analyze the evolution of field and plasma parameters. We show that the magnetic flux and mass flux were transported outward from the core, resulting in the steepening of the boundary. The steepened boundary, which trapped more foreshock ions and caused stronger demagnetization of foreshock ions, nonlinearly further enhanced the Hall current. Based on our observations, we propose a physical formation process wherein the positive feedback of foreshock ions on the varying magnetic field caused by the foreshock ion Hall current enables an “instability” and the growth of the structure.

Unified Astronomy Thesaurus concepts: Planetary bow shocks (1246); Shocks (2086)

1. Introduction

Upstream of Earth’s quasi-parallel bow shock, the ion foreshock is characterized by backstreaming ions that have been reflected from the shock (e.g., Eastwood et al. 2005; Wilson 2016). In the ion foreshock, many foreshock transients have been observed and simulated, such as hot flow anomalies (HFAs; e.g., Schwartz et al. 1985, 2018; Thomsen et al. 1986, 1988; Thomas et al. 1991; Lin 1997; Omidi & Sibeck 2007; Zhang et al. 2010), spontaneous HFAs (Omidi et al. 2013; Zhang et al. 2013), foreshock bubbles (FBs; e.g., Omidi et al. 2010; Turner et al. 2013, 2020; Liu et al. 2015), foreshock cavities (e.g., Lin 2003; Sibeck et al. 2002), foreshock cavities (e.g., Blanco-Canó et al. 2011), and short large-amplitude magnetic structures (SLAMS; e.g., Schwartz et al. 1992; Wilson 2016). HFAs, SHFAs, and FBs are three of the most significant types of foreshock transients due to their large sizes (e.g., several $R_E$ for HFAs/SHFAs and even larger for FBs), strong perturbations, and plasma heating. They are characterized by a hot, tenuous core associated with plasma deflection bounded by compressional boundaries or shocks on one or both sides. Due to large variation in plasma density and velocity, the dynamic pressure is distinct from the surrounding solar wind and foreshock plasma. As a result, when these foreshock transients encounter the bow shock, the bow shock surface can locally move back and forth. Such perturbation can propagate to the magnetopause, causing magnetospheric and ionospheric disturbances (e.g., Sibeck et al. 1999; Hartinger et al. 2013; Archer et al. 2014, 2015; Zhao et al. 2017; Wang et al. 2018).

Recent observations showed that foreshock transients can also accelerate particles (e.g., Kis et al. 2013; Wilson et al. 2013, 2016; Liu et al. 2017a). When HFAs or FBs expand suprathermospherically, a shock can form. Such shocks can accelerate solar wind particles through shock drift acceleration (Liu et al. 2016a). When the boundary of HFAs/FBs convects toward the bow shock, ions and electrons can bounce between the two regions of strong compressed magnetic fields, resulting in Fermi acceleration (Liu et al. 2017b, 2018; Turner et al. 2018). As magnetic flux is transported toward the boundary during the expansion of an FB, electrons can be accelerated through betatron acceleration (Liu et al. 2019). Recently, magnetic reconnection was observed to heat electrons inside HFAs/SHFAs and SLAMS (Liu et al. 2020; Wang et al. 2020). Shock acceleration is one important acceleration mechanism but is still not fully understood (see review by Treumann 2009). For example, the particle acceleration efficiency is underestimated, and the source of energetic particles that can participate in the acceleration process is unclear. Foreshock transients, which are often present upstream of supercritical shocks, could potentially increase particle acceleration efficiency and provide a particle source (e.g., Turner et al. 2018).

However, how HFAs, SHFAs, and FBs form is still not fully understood. In the simulations by Omidi et al. (2013), SHFAs form from foreshock cavities (the nonlinear evolution of ultralow frequency (ULF) waves), but the mechanism is unknown. For HFAs and FBs, thermal pressure enhancement by foreshock ions is considered to drive their formation and expansion, which, however, is insufficient. Based on simulations (e.g., Burgess 1989; Thomas et al. 1991; Lin 2002; Omidi & Sibeck 2007; Omidi et al. 2010), HFAs and FBs form when foreshock ions are trapped by a solar wind discontinuity. Around certain magnetic field configurations of solar wind
discontinuities (e.g., Archer et al. 2015; Liu et al. 2015), the gyrokinetic motion of foreshock ions can result in their concentration and thermalization, resulting in a thermal pressure increase. The increased thermal pressure can push ambient cold plasma outward, forming a low density core surrounded by compressional boundaries that, depending on the expansion speed into the surrounding plasma, can form into fast mode shocks. However, as the gyroradius (thousands of kilometers) and gyroperiod (10–20 s) of foreshock ions are larger than or comparable to the spatial scale and timescale of field variation around HFAs/FBs, respectively, the concept of thermal pressure of foreshock ions is invalid. Therefore, the kinetic effects of foreshock ions must be considered.

Recent particle-in-cell (PIC) simulations provide a physical model (An et al. 2020). When foreshock ions encounter a discontinuity, foreshock ions are demagnetized whereas electrons are magnetized, resulting in a Hall current that shapes the magnetic profile of a foreshock transient. The associated electric field transfers energy from foreshock ions to cold plasma and the field. To confirm and further investigate these, it is important to observe those foreshock transients that just start to form. During their very early stage, they must be very small (e.g., less than or comparable to one foreshock ion gyroradius) and may evolve very fast. Only recently have we had the sufficient time resolution of particle measurements to resolve them using NASA’s Magnetospheric Multiscale (MMS).

Using MMS, we study two very small foreshock transients (around 5 s in duration; 1000–2000 km in size). We do not distinguish among HFAs, HFAs, or FBs in this study because their driver discontinuities are difficult to identify when embedded in the ULF waves and their distinctive characteristics (e.g., size and upstream shock) are not available when they have just formed. At the end of this paper, however, we discuss possible differences in their formation process. In event 1 (Section 3.1), with MMS in a tetrahedral formation, we analyze how foreshock ions contributed to the current density configuration that determined the magnetic field geometry of the event. In event 2 (Section 3.2) with MMS in a string-of-pearls formation, we analyze how plasma and field parameters evolved. In Section 4, we summarize our results and propose a formation mechanism.

2. Data and Methods

We used data from NASA’s MMS mission (Burch et al. 2016). We analyzed plasma data from the Fast Plasma Investigation instrument (FPI; Pollock et al. 2016), DC magnetic field data from the fluxgate magnetometer (Russell et al. 2016), magnetic field wave data from the search coil magnetometer (le Contel et al. 2016), and electric field data from axial and spin-plane double-probe electric field sensors (Ergun et al. 2016; Lindqvist et al. 2016).

During daytime seasons with apogees from 12 $R_E$ to 25 $R_E$, MMS observed many HFAs, HFAs, and FBs. We searched for events that have very short duration (a few seconds) observed in burst mode with very high resolution (30 ms for electrons and 150 ms for ions). Here we present case studies on two representative events with spatial scale $\sim$1000–2000 km (comparable to around one foreshock ion gyroradius or 10–25 ion inertial length). In event 1, the four identical MMS spacecraft were in a tetrahedron formation with a very small separation of $\sim$20–30 km. Such a formation allows the availability of the four-spacecraft timing method (Schwartz 1998) and the curlometer method (Robert et al. 1998). In event 2, MMS spacecraft were in a string-of-pearls formation with separation from 200 to 400 km. Such a formation can capture the fast evolution of event 2 within 1 s.

3. Results

3.1. Event 1: Current and Field Configuration

In Figure 1, MMS observed a foreshock transient at the flank of the bow shock ($\phi$, $\sim$147°, 41°) $RE$ in GSE. It had the common characteristics of typical SHFAs/HFAs/FBs except for the very small size (1000–2000 km along the GSE-X direction comparable to one foreshock ion gyroradius). The transient had a core with low field strength (Figure 1(a), low density (Figure 1(b)), and plasma deflection (Figure 1(c)) associated with electron heating (Figure 1(f); ion temperature is not shown as it is inaccurate in the foreshock). Upstream of the core, there was a compressional boundary with enhanced field strength and density (vertical dotted line). Using the four-spacecraft timing method (Schwartz 1998), the boundary normal was $[0.95, -0.29, -0.03]$ in GSE and the normal speed was $930 \text{ km s}^{-1}$, nearly the same as the local ion bulk velocity along the normal direction in the spacecraft frame. At the boundary (vertical dotted line), the electron perpendicular temperature shows an increase profile similar to that of the field strength, suggesting the betatron acceleration consistent with Liu et al. (2019). The interplanetary magnetic field (IMF) variation across the event was not significant. Before the event, the IMF was dominated by $B_x$ in GSE. After the event, $B_y$ became slightly weaker and other two components became slightly stronger. If we assume there was a tangential discontinuity (TD), its magnetic shear angle was only $\sim$25° and its normal was $[0.56, -0.17, 0.81]$ in GSE calculated from the cross-product method (Schwartz 1998) using the time interval between the vertical dashed lines before and after the event. (Unfortunately, neither ARTEMIS, Cluster, nor Geotail was available in the upstream solar wind, and it is difficult to identify a discontinuity with a small shear angle at the L1 point.) This event could be either a foreshock caviton-driven SHFA or a solar wind discontinuity-driven HFA/FB. The geometry of the event is sketched in Figure 2(a), and the magnetic field configuration is sketched in Figure 2(b), which shows curved field lines corresponding to two $B_y$ reversals in Figure 1(a).

As the magnetic field structure of the foreshock transient was determined by the current density configuration, to understand how the foreshock transient formed, it is important to examine the current density and how motions of ions and electrons contributed to it. Figures 3(b) and (c) show the current density calculated from the curlometer method (Robert et al. 1998) and from plasma data, respectively. They are qualitatively consistent except for the upstream region (gray shaded region). We see that there was overall a negative $J_y$ in the core with two peaks at two edges of the core (second and fourth vertical dotted line at 16:30:01 UT and 16:30:03.5 UT, respectively; note that the fluctuation at the second vertical dotted line in Figure 3(b) was whistler waves). Such a negative $J_y$ (purple out-of-plane symbol in Figure 2) was likely the reason for the $B_y$ reversal from negative to positive in the core. There were also other currents. At the leading edge (downstream) of the core (16:30:01 UT), there were finite $J_x$ and $J_z$ likely responsible for the $B_y$.
depletion in the core. At the trailing (upstream) edge of the compressional boundary (16:30:04 UT), there was a positive $J_y$ peak, which caused the $B_z$ reversal from positive to negative. The positive $J_y$ peak could close a current loop with the negative $J_y$ peak at the fourth vertical dotted line and together enhanced the positive $B_z$ at the compressional boundary. Inside the compressional boundary (16:30:03.5–16:30:04 UT; fifth vertical dotted line), there was negative $J_z$, which was likely responsible for the reversal of $B_x$ and $B_y$.

Next, we determine what caused such current density configuration by examining the velocity of foreshock ions, solar wind ions, and electrons inside the event (16:30:01–16:30:04 UT). Figures 3(d) and (e) show the total ion bulk velocity and electron bulk velocity, respectively. They were similar overall, but in the core, the ion $V_{iGSE}$ was negative whereas the electron $V_{eGSE}$ was around zero or positive, resulting in the negative $J_y$. To examine the reason for this velocity difference, we calculated the velocity of solar wind ions and foreshock ions separately by confining the energy and direction from ion distributions (Figures 3(f) and (g)). Unlike the total ion bulk velocity, the solar wind ion velocity in the core was very similar to the electron bulk velocity. To see it more clearly, Figure 3(h) shows their comparison in the perpendicular velocity. We see that the electron and solar wind ion perpendicular velocities almost overlap (solid and dashed lines; except in the upstream region). The total ion perpendicular velocity (dotted line in Figure 3(h)), on the other hand, clearly shows a smaller GSE-$Y$ component in the core compared to that of the electrons. The reason is that foreshock ions were moving mainly in the negative GSE-$Y$ direction (Figure 3(g)). Therefore, the differences between the total ion bulk velocity and electron bulk velocity, and thus the current density was mainly due to the motion of foreshock ions.
To further examine the motion of foreshock ions, we plot ion distributions in Figure 4. In the background foreshock (1st vertical dotted line in Figure 3), Figure 4(a) shows that in the GSE-XZ slice, foreshock ions were mainly moving in the negative GSE-X and GSE-Y directions. Figure 4(c) shows that in the BV slice (horizontal axis is along the magnetic field and the plane contains the electron bulk velocity vector), the center of the foreshock ion distribution shows an \( E \times B \) drift the same as the solar wind ions and a parallel component opposite the solar wind ions. In the perpendicular slice (Figure 4(d); cut through the vertical dotted line in Figure 4(c)), foreshock ions show a complete gyration. Therefore, the background foreshock ions were moving along the field lines with large thermal speed. Because the IMF was dominated by negative \( B_z \), the foreshock ion bulk velocity therefore was dominated by a negative GSE-Y component and had a GSE-X component similar to the solar wind ions (\( E \times B \) drift) consistent with Figure 3(g). Such foreshock ion motion cannot cause a strong current in the background foreshock because electrons can move freely along the field lines (Figure 3(b)).

In the core (second and third vertical dotted lines in Figure 3), foreshock ions were still mainly moving in the negative GSE-X and GSE-Y directions (Figures 3(g), 4(e) and (i)). This is because the ion gyroperiod was very long (~10–20 s) compared to the timescale of the field variation (e.g., within 1 s in event 2), and thus foreshock ions cannot immediately change their velocity, i.e., foreshock ions were demagnetized. Furthermore, because the magnetic field direction varied from being \( B_z \), dominant to \( B_x \) dominant (Figure 3(a)), the foreshock ion bulk velocity, which was initially field aligned, projected onto the perpendicular direction. As a result, in the perpendicular slices (Figures 4(h) and (l)), foreshock ions changed from a complete gyration to partial gyration in the direction opposite to the convection electric field (i.e., in the negative GSE-Y direction; see Figure 3(k)). Such perpendicular velocity caused the negative \( J_y \) (Figures 3(b) and (c)) as electrons were nearly always magnetized. In other words, it was the Hall current driven by the demagnetized foreshock ions.

Because the gyroradius of foreshock ions was comparable to the spatial scale of the event, the initial gyration of foreshock ions can also contribute to the Hall current in the GSE-XZ plane. In the BV slices (Figures 4(g) and (k)), we see that foreshock ion velocity had a sunward component diffuse in the field-aligned direction, because some of the (sunward) gyrovelocity of foreshock ions projected to the new field-aligned direction (orange arrow in Figure 2(b)). We also see that there was less Earthward gyration in Figures 4(g) and (k) compared to Figure 4(c), which can also be seen in the perpendicular slices by comparing with the gyrocenter (red dots in Figures 4(h) and (l)), in the XZ slices (Figures 4(t) and (j)), and in Figure 3(g) (weaker GSE-X component). The possible reason is that the event had a compressional boundary on its upstream side and no compressional boundary on its downstream side, fewer foreshock ions from the upstream side can enter the core and contribute Earthward gyration than those from the downstream side that contributed sunward gyration. This preference in gyrophase caused a velocity difference in the GSE-X direction between foreshock ions and electrons (Figure 3(h)) and thus a small Hall current \( J_y \) (around the second vertical dotted line in Figure 3(b)). (There was also a small \( J_y \) right before \( J_x \) (Figure 3(b)), probably because there were more foreshock ions entering the core than leaving the core from the downstream side.) Additionally, at the third vertical dotted line, the calculated foreshock ion density dropped from 0.5 to 0.35 cm\(^{-3}\) (Figure 3(j)), possibly for the same reason as the \( V_y \) variation (foreshock ions from the upstream side were obstructed by the compressional boundary).

Next, we examine the \( J_y \) peak at the edge of the compressional boundary (fourth vertical dotted line in Figure 3). We see that the foreshock ion velocity was still in the negative GSE-X and \( Y \) directions except that more Earthward gyration appeared (Figures 4(m)–(p)) likely because more foreshock ions from the upstream side can reach here. Note that the reversal of the foreshock ion distribution in the perpendicular slice (Figure 4(p)) was simply caused by the reversal of \( B_z \) (and thus \( B \times V \)). This

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**Figure 2.** Sketch of event 1. (a) The overall geometry of the event. The event was observed at the flank of the bow shock with IMF (blue arrows) dominant in the negative GSE-Y direction. The convection electric field (green arrows) upstream of the possible TD pointed toward the TD. The TD normal was mainly in the GSE-Z direction, and the upstream compressional boundary (gray box) was mainly sunward. (b) The zoom-in sketch in the XZ plane corresponding to the pink box in panel (a). In the solar wind rest frame, as MMS crossed the event (gray dashed arrow), it observed curved magnetic field lines (blue) caused by the Hall current (purple) and the corresponding outward plasma flow speed (red arrows) driven by the electric field (green). Foreshock ions were mainly moving in the negative GSE-Y direction (orange out-of-plane symbol) with gyration in the GSE-XZ plane (orange arrow).
temperature anisotropy interpolated to the magnetic drift; (the electric)

region likely due to the large measurement uncertainty of the narrow solar wind

time of ion distributions in Figure 4.

Figure 3. Current density configuration of event 1. From top to bottom are the
(a) magnetic field; (b) current density calculated from the curlometer method;
(c) current density calculated from plasma data (inaccurate in the gray shaded
region likely due to the large measurement uncertainty of the narrow solar wind
ion beam); (d) total ion bulk velocity; (e) electron bulk velocity; (f) solar wind
ion bulk velocity; (g) foreshock ion bulk velocity; (h) perpendicular velocity of
electrons (solid), solar wind ions (dashed), and total ions (dotted); and
(i) $E \times B$ drift velocity in comparison with the electron perpendicular velocity
(dotted), and their differences may be due to the measurement uncertainty of
the electric field in the spin axis direction and other drifts, such as diamagnetic
drift; (j) total plasma density and foreshock ion density; (k) electric field
interpolated to the magnetic field resolution (to better examine the DC electric
field). The large-amplitude fluctuations of the electric field in the compressional
boundary were very likely whistlers triggered by electron perpendicular
temperature anisotropy (Shi et al. 2020). The vertical dotted lines indicate the
time of ion distributions in Figure 4.

$J_x$ peak was due to at least two reasons. One reason is the
enhancement of foreshock ion density (Figure 3(j)), which was
likely because the field strength enhancement can help trap
foreshock ions by preventing them from gyrating away. This is
the same reason that caused the foreshock ion density depletion
in the core (fewer foreshock ions from the upstream side can
gyrate further downstream into the core). The other reason is the
electron $E \times B$ drift in the positive GSE-$Y$ direction
(Figures 3(e) and (h)). At the edge of the boundary with a
strong magnetic field gradient, there was an enhancement in the
electric field $E_x$ (Figure 3(k)). As the boundary normal was
mainly in the sunward direction, the enhanced negative $E_x$ was
pointing from the boundary into the core. Our calculation shows
that the $-E_x B_z$ component dominates the $(E \times B)_x$. The
possible process is that as ions (especially foreshock ions) from
the core can penetrate farther into the field strength enhancement
region than electrons due to their different gyroradii, a static
electric field arose pointing from the boundary into the core
(sketched in Figure 2(b)). Such electric field can drive the
electrons’ $E \times B$ drift in the GSE-$Y$ direction but had nearly no
effects on foreshock ions, resulting in the Hall current along the
boundary surface (this electric field component corresponded to
the Hall electric field). This process is similar to that at shock
surfaces (see review in Treumann 2009) and can also explain the
positive $J_x$ peak at the upstream edge of the compressional
boundary (Figure 3(b); although we do not have accurate plasma
data to confirm this current). Such a scenario is consistent with
recent PIC simulations by An et al. (2020).

As for the negative $J_x$ in the middle of the boundary (fifth
vertical dotted line in Figure 3), although electrons show a clear
enhancement in $V_{de}$, and ions do not (Figures 3(d)–(g)),
their perpendicular velocities match very well in the GSE-Z direction
(Figure 3(h)). Therefore, their velocity difference in the GSE-$Z$
direction was dominant in the field-aligned direction. The
reason is likely that as the magnetic field and electric field evolved rapidly at the compressional boundary (see event 2),
electrons can immediately respond and change their drift
velocity (electron bulk velocity at the compressional boundary
was almost the same as the perpendicular velocity), but ions
cannot. The varied magnetic field projected some ion velocity
to the parallel direction resulting in field-aligned current. The
effect of this field-aligned current was to twist the magnetic
field lines and make them look like a flux rope but cut in half
(see sketch in Figure 2(b)). (As the boundary continued to
steepen, the open part of the “half flux rope” might have a
chance of closing, i.e., magnetic reconnection might occur and
form a real flux rope. This is a possible explanation of the
observations of a small-scale flux rope at an HFA’s compro-
sional boundary by Bai et al. 2020.)

Here we summarize a possible formation process based on
our observations: initially, when foreshock ions encountered a
$B$-field discontinuity (e.g., a solar wind discontinuity or a
steepened ULF wave/foreshock cavitation), they cannot imme-
diately change their bulk velocity and cannot complete a
gyration. In other words, as the timescale of field variation
was shorter than the ion gyroperiod and the discontinuity
thickness-field variation spatial scale was less than or
comparable to a foreshock ion gyroradius, foreshock ions were
demagnetized whereas electrons were nearly always magne-
tized, resulting in the establishment of a Hall current (purple
vectors in Figure 2(b)). Such Hall current varied the magnetic
field around the discontinuity. We propose that if such field variation favors a stronger Hall current, the stronger Hall current can in return further vary the magnetic field. This completes a feedback loop resulting in a kind of instability and thus the nonlinear growth of a foreshock transient (SHFA, HFA, and FB). We will examine this process in event 2.

The field variation (or field line motion) during this process induced an additional electric field (e.g., enhanced $E_y$ shown in Figure 3(k)). The effect of this electric field was to self-consistently drive frozen-in cold plasma moving outward together with the magnetic field lines (red arrows in Figure 2(b)). Such outward motion corresponded to the expansion of the foreshock transient consistent with PIC simulations by An et al. (2020). As sketched in Figure 2(b) (in the solar wind rest frame), as MMS transited (gray dashed arrow), solar wind ion and electron perpendicular velocity (Figure 3(h)) and $E \times B$ drift velocity (Figure 3(i)) first had a large negative GSE-Z component corresponding to the deformation toward the downstream side (red arrows; also see the supporting information in Appendix B showing the electron bulk velocity in the solar wind rest frame). Later, the field line direction rotated, and the cold plasma motion became mainly sunward (in the solar wind rest frame), resulting in the compression at the upstream boundary.

Finally, we discuss the energy budget as both the cold plasma outward motion and magnetic field deformation require energy input. As the process started from the Hall current driven by the demagnetized foreshock ions, foreshock ions must be the energy source. This can be seen from the enhanced $+E_y$ around the leading edge of the event and foreshock ion $-V_x$, i.e., the partial gyration of foreshock ions was against the induced electric field in the core. At the compressional boundary, however, the enhanced $E_y$ was negative, meaning that foreshock ions were gaining energy. This is simply because the observation was in the spacecraft frame where foreshock ions were pushed back by the Earthward moving compressional boundary (Liu et al. 2018). To consider the energy conversion between the foreshock ions and the field, we need to exclude the effect of the background convection electric field. In the solar wind rest frame (see the supporting information in Appendix B showing $E + V_{cw} \times B$), $E_y$ was positive (and cold plasma $V_x$ became sunward), and foreshock ions were losing energy by pushing the compressional boundary sunward, consistent with PIC simulations by An et al. (2020).

### 3.2. Event 2: Evolution

Figure 5 shows observations of event 2 by four MMS spacecraft. In this event, MMS was in a string-of-pearls formation (see geometry in Figure 6). MMS2 was the first spacecraft that observed the event (Figure 5.1). Similar to event 1, it was a very small (∼2000 km along the GSE-X direction) foreshock transient with a hot, tenuous core associated with plasma deflection bounded by a compressional boundary on the upstream side. Inside the core, the foreshock ion energy flux shows energy dispersion (Figure 5.1(d)). Because the foreshock magnetic field was fluctuating significantly, we cannot determine the driver discontinuity in this event. MMS1, which
the compressional boundary steepened, and a wave train the corresponding 
strong radial component. The compressional boundary was mainly sunward 5.2 was ∼ the compressional boundary further steepened, and the foreshock ion energy became smaller, corresponding to the energy dispersion observed in Figure 5(d). This scenario is consistent with previous THEMIS observations (Liu et al. 2018) that sunward foreshock ions were reflected by the Earthward moving compressional boundary and gained speed in the spacecraft frame (in the solar wind rest frame, foreshock ions lost energy as discussed in event 1; also see the supporting

Figure 5. Observations of event 2 in the sequence of MMS2 (Figure 5.1), MMS1 (Figure 5.2), MMS4 (Figure 5.3), and MMS3 (Figure 5.4). From top to bottom are the (a) magnetic field, (b) density, (c) ion bulk velocity, (d) ion energy flux spectrum, (e) electron energy flux spectrum, and (f) electron parallel (blue) and perpendicular (green) temperature. MMS4 FPI electron data were not available here. Vertical dotted lines in Figures 5.1–5.3 indicate the moments of ion distributions in Figure 8.

Figure 6. Geometry and spacecraft position in event 2. The IMF (blue) had a strong radial component. The compressional boundary was mainly sunward (based on MVA results) with a strong Bz; inside it (blue) and a bipolar current configuration (purple) on two sides. This compressional boundary reflected some sunward foreshock ions to be Earthward (orange arrow). The position of the B-field directional discontinuity (DD) was inferred from the Bz reversal and the corresponding Jz, observed at ∼05:22:09 UT (Figure 9(b)).

was ∼200 km farther downstream than MMS2, observed the event around 0.4 s later (Figure 5.2). In MMS1 observations, the compressional boundary steepened, and a wave train appeared right upstream of the compressional boundary (Figure 5.2(a)), which was very likely a whistler precursor often observed upstream of shocks and SLAMS (e.g., Wilson 2016). Inside the core, the foreshock ion energy flux enhanced (from yellow to red), whereas the solar wind ion energy flux depleted (less red), and the solar wind ion energy decreased a little (Figure 5.2(d)). The electron temperature in the core further increased (Figure 5.2(f)). When MMS4 (∼100 km downstream than MMS1) observed the event (Figure 5.3) around 0.2 s later, the compressional boundary further steepened, and the amplitude of the wave train increased. The foreshock ion energy flux further enhanced, while the solar wind ion energy flux further depleted, and the solar wind energy further decreased (Figure 5.4(d)). (Unfortunately, MMS4 FPI electron measurement became unavailable beginning mid-2018.) Using minimum variance analysis (Sonnerup & Scheible 1998), MMS2, MMS1, and MMS4 observed similar compressional boundary normals of [0.81, −0.55, 0.19], [0.80, −0.36, 0.47], and [0.83, −0.27, 0.47] in GSE, respectively (minimum-to-intermediate eigenvalue ratio less than 0.1). Using the coplanarity method (Schwartz 1998), we also obtained a similar normal of [0.77, −0.23, 0.58], [0.75, −0.21, 0.63], and [0.74, −0.18, 0.65] in GSE, respectively. Such normal direction was roughly along the spacecraft train (less than ∼25°; Figure 6). Therefore, the observation differences among three spacecraft were mainly due to the evolution rather than the spatial difference. MMS3, which was ∼400 km downstream than MMS4, observed the magnetosheath part of the event.

To see the evolution more clearly, we time-shifted MMS1 and MMS4 observations by −0.4 s and −0.6 s, respectively, to match the downstream boundary observed by MMS2 (see their superposed plots in Figure 7). By comparing their magnetic field strength and electron density (ion density had large uncertainties) shown in Figures 7(a) and (c), we see that there was a clear magnetic flux and mass flux transport from the core toward the upstream boundary, consistent with the outward motion of plasma along with the field lines discussed in event 1. Such sunward magnetic flux transport can result in betatron acceleration, which increased the electron perpendicular temperature at the inner edge of the compressional boundary (Figure 5.2(f)). As a result, Figure 7(d) shows enhanced perpendicular anisotropy at the compressional boundary corresponding to the field strength increase, consistent with Liu et al. (2019). Figures 7(e) and (f) show that the ion and electron deflection became more and more significant.

Figure 8 shows the ion distribution evolution from MMS2 to MMS4 (the time differences between them are roughly the same as the time shift in Figure 7; corresponding to the vertical dotted lines in Figure 5). In the background foreshock, sunward foreshock ions can be seen (Figures 8(a)–(f)), as the IMF had a strong radial component unlike event 1. Inside the core (Figures 8(g)–(l)), three MMS spacecraft observed Earthward foreshock ions with speed faster than the sunward component. Farther in the core (Figures 8(m)–(r)), the Earthward foreshock ion energy became smaller, corresponding to the energy dispersion observed in Figure 5(d). This scenario is consistent with previous THEMIS observations (Liu et al. 2018) that sunward foreshock ions were reflected by the Earthward moving compressional boundary and gained speed in the spacecraft frame (in the solar wind rest frame, foreshock ions lost energy as discussed in event 1; also see the supporting
information in Appendix B showing the ion distribution in the local flow rest frame where the foreshock ion energy does not change). The energy dispersion was due to the time-of-flight effect (faster ions reached the spacecraft earlier). Comparing distributions measured by the three spacecraft in the core, we see that the solar wind phase space density becomes lower and lower from MMS2 to MMS4, consistent with Figures 5.1–5.3(d). The calculated solar wind ion density decreased from MMS2 to MMS1 in Figure 9(h). The decrease in solar wind ion density was due to the sunward mass flux transport from the core. Figure 9(h) also shows an increase in the foreshock ion density consistent with Figures 5.1(d) and 5.2(d), likely because the steepened compressional boundary can reflect and trap more foreshock ions in the core. If we compare the calculated solar wind velocity measured by MMS2, MMS1, and MMS4 (Figures 8(m)–(r)) \([-283.2, -58.9, -28.5]\) km s\(^{-1}\), \([-232.8, -100.3, -25.0]\) km s\(^{-1}\), and \([-224.1, -118.5, -25.0]\) km s\(^{-1}\), respectively, we see that MMS1 observed slower and more deflected solar wind ions than MMS2 by \(-50\) km s\(^{-1}\) in both GSE-X and Y directions and MMS4 observed further deceleration/deflection by another 20 km s\(^{-1}\) (also see vertical dotted lines which indicate the solar wind speed observed by MMS2 in Figure 8), consistent with Figures 5.1–5.3(d) (solar wind ion energy decreased). Therefore, the stronger ion bulk velocity deflection observed by MMS1 and MMS4 than by MMS2 (Figure 7(e)) was due to increasing foreshock ion density, decreasing solar wind ion density, and deceleration/deflection of the solar wind ions in the spacecraft frame (acceleration in the solar wind rest frame).

Next, we examine the evolution of the current density configuration. Limited by the uncertainty of the velocity measurement, only the current density in the GSE-X direction was high enough to be seen in Figure 9.1(b). This can also be seen from the ion (Figure 9.1(d)) and electron bulk velocity (Figure 9.1(e)). Their perpendicular velocities, on the other hand, only show small differences in the GSE-X direction (Figure 9.1(f)), indicating that the positive \(J_x\) was mainly field aligned. One possibility is that as the background IMF had a strong radial component, the background solar wind ions and electrons had a large field-aligned speed. As the field direction varied in the core, electrons could maintain the field-aligned speed whereas ions projected the field-aligned speed onto the perpendicular direction. Meanwhile, foreshock ions also contributed sunward velocity. At MMS1 (Figure 9.2), a bipolar \(J_x\) signature on two edges of the compressional boundary similar to event 1 was enhanced enough to be seen (Figure 9.2(a)), responsible for the steepening of the compressional boundary (see sketch in Figure 6). Like event 1, the enhancement of the positive \(J_x\) was caused by at least two processes. One process is the density enhancement of foreshock ions (Figure 9(h)) that were moving in the positive GSE-Y direction (Figure 8). Another process is that electrons can respond to the field evolution (Figures 9(a) and (c)) much faster than ions. As a result, the electron \(V_{e}\) varied more significantly than the ion \(V_{i}\) (Figures 9(d) and (e)). A possible process could be that the steepened compressional boundary can cause foreshock ions to be more demagnetized and have a stronger static electric field pointing from the boundary to the core (difficult to see from Figure 9(c) as the convection electric field was dominant). The enhanced Earthward static electric field can drive a stronger electric \(E \times B\) drift along the boundary surface but cause no effects on foreshock ions, contributing to the stronger Hall current. This process is similar to the shock-steepening process, which can also explain the enhancement of negative \(J_x\) at the trailing edge of the compressional boundary.

Here we summarize our results. The Hall current between the demagnetized foreshock ions and magnetized electrons deformed the magnetic field configuration, which transported the magnetic flux from the core to steepen the compressional boundary (Figure 7(a)). The enhancing field strength at the compressional boundary reflected and trapped more foreshock ions (Figures 5(d), 8 and 9(h)), and the sharper field variation caused foreshock ions to be more demagnetized and have a stronger static electric field, resulting in a larger velocity difference between ions and electrons (i.e., a feedback loop; Figures 9(d) and (e)). Increases in both foreshock ion density and velocity difference can cause a stronger Hall current (Figure 9(h)). The stronger Hall current can further steepen the compressional boundary (Figure 7(a)), which can in return cause an even stronger Hall current. This is the same nonlinear feedback growth process as was already outlined for event 1.

The variation in the magnetic-field-induced convection electric field drove cold plasma outward and caused sunward mass flux transport (Figure 7(c)). The outward moving speed must increase from 0 to a certain value in the solar wind rest frame, meaning that there should be acceleration (or deceleration in the spacecraft frame) as shown in Figures 5(d) and 8. The physical process of this acceleration could be as follows: as it was a kind of instability, the growth in the Hall current was
Figure 8. Ion distributions of MMS2, MMS1, and MMS4 in the GSE-XY and XZ slices at the moments corresponding to the vertical dotted lines in Figures 5.1–5.3. There is a ∼0.4 s and a 0.6 s time difference between distributions by MMS2 and MMS1 and by MMS2 and MMS4 in each column, respectively. The vertical dotted lines indicate the solar wind ion velocity measured by MMS2 to compare with MMS1 and MMS4 measurements.
nonlinear ($\partial \mathbf{E}/\partial t \neq 0$), resulting in a faster magnetic field variation ($\partial \mathbf{B}/\partial t \neq 0$) and consequently the increasing electric field (Figure 9(c); $\frac{\partial}{\partial t} \mathbf{E} + \mathbf{J} \times \mathbf{B} = 0$). The increasing electric field can be responsible for the acceleration of the frozen-in cold plasma, e.g., through a process similar to the acceleration of pickup ions, self-consistently corresponding to the faster magnetic field line motion.

4. Conclusions and Discussion

Using MMS, we analyzed two very small foreshock transients in their earliest stages of development to understand how they formed. We used a tetrahedron formation to study the current density configuration inside one foreshock transient to show how motions of foreshock ions and electrons contributed to it. Then, we used a string-of-pearls formation to study the temporal evolution of plasma and field parameters in another foreshock transient. Based on our observational results, we summarize a formation model as follows: when suprathermal foreshock ions encounter a $B$-field discontinuity (e.g., a solar wind discontinuity for HFAs/FBs or a steepened ULF wave/foreshock caviton for SHFAs), they cannot immediately change their bulk velocity (the ion gyroperiod is typically much longer than the timescale of early foreshock transient formation as shown in event 2) and cannot complete a gyration (the foreshock ion gyroradius is larger than or comparable to the spatial scale of field variation and the thickness of the $B$-field discontinuity), so the foreshock ions become demagnetized. As electrons are nearly always magnetized, a Hall current is established, which varies the magnetic field profile around Figure 9. Evolution of the current density from MMS2 (Figure 9.1) to MMS1 (Figure 9.2). From top to bottom are the (a) magnetic field; (b) current density calculated from plasma data; (c) electric field interpolated to the magnetic field resolution; (d) total ion bulk velocity; (e) electron bulk velocity; (f) perpendicular velocity of electrons (solid) and total ions (dotted); (g) $E \times B$ velocity in comparison with electron perpendicular velocity; and (h) density of electrons (blue), solar wind ions (black), and foreshock ions (red). At MMS1, because the ion distribution was rather diffuse in the compressional boundary, the density of foreshock ions may be overestimated, so this part is shaded in gray.
the discontinuity. If such a magnetic field variation then further enhances the Hall current (Figure 9(b)), e.g., by trapping more foreshock ions (Figure 9(h)) and causing a larger velocity difference between ions and electrons (Figures 9(d) and (e)), the enhanced Hall current can in return further steepen the magnetic field profile. This feedback loop forms a kind of nonlinear instability (see a simple derivation in Appendix A) that enables the growth and development of the foreshock transients. During the growth of the magnetic field profile, an induced electric field is established, which self-consistently drives frozen-in cold plasma to move outward (e.g., Figure 2(b)) together with the field lines (mass and magnetic flux outward transport in Figure 7(a)). The outward moving speed must increase from zero, meaning acceleration in the solar wind rest frame (Figures 5(d) and 8) driven by the enhancing electric field (Figure 9(c)) because the growth of the Hall current, and thus the time variation of the magnetic field, is nonlinear (instability). The energy source is the foreshock ions that partially gyrate against the induced electric field in the solar wind rest frame.

Based on this model, a critical point of foreshock transient formation is the initiation of the “instability.” For example, if the field variation by the Hall current cannot trap more foreshock ions to enhance the Hall current, a stable solution can be reached (see the derivation in Appendix A). In this case, there is only static modification of the magnetic field profile around the discontinuity, and no foreshock transient will form and grow. Here we consider two examples (Figure 10) with a $B$-field discontinuity that varies the IMF direction by positive and negative $90^\circ$, respectively. For simplicity, we ignore the thermal speed of foreshock ions so that the Hall current is only driven by the bulk velocity. Based on our model, when foreshock ions encounter the discontinuity, the Hall current can form in the direction mainly along the purple arrow. Such Hall current causes $+\Delta B_z$ near the discontinuity and $-\Delta B_z$ away from the discontinuity. In example 1 with $-B_z$ upstream of the discontinuity (Figure 10(a)), the Hall current decreases the field strength at the discontinuity, meaning that foreshock ions can cross the discontinuity more easily, resulting in a stronger Hall current (instability). In example 2 with $+B_z$ upstream of the discontinuity (Figure 10(b)), the Hall current increases the field strength at the discontinuity, meaning that fewer foreshock ions can cross the discontinuity, resulting in a weaker Hall current (stable solution). Interestingly, if the $B$-field discontinuity is a solar wind TD, the convection electric field points toward the TD in example 1 and points away in example 2 (green arrow). The convection electric field pointing toward the TD is one important characteristic of HFAs (e.g., Thomsen et al. 1993; Schwartz et al. 2000). Our model could at least partially explain this characteristic. As solar wind velocity is always Earthward, the convection electric field direction indicates the magnetic field configuration relative to the TD. Such magnetic field configuration could determine whether the Hall current from foreshock ions can trigger the “instability.”

Besides HFAs, SHFAs, and FBs, our model may also help explain the formation of other types of foreshock transients. For example, when a solar wind discontinuity separates the foreshock and the pristine solar wind and the discontinuity cannot trigger the “instability,” a stable solution could be a local field strength enhancement at the discontinuity due to the foreshock ion Hall current (e.g., Figure 10(b)). Such kind of structure could be identified as a foreshock compressional boundary. Additionally, in event 2, the steepening process of the compressional boundary may also contribute to the steepening process of SLAMS. In the future, more case studies in comparison with simulations are needed to further investigate the formation and development process of various types of foreshock transients.

Our model only considers background foreshock ions as a beam based on observations (Figures 4 and 8). Due to the specular reflection at the bow shock, however, foreshock ions can also be gyrating ions with a certain gyrophase (e.g., Fuselier 1995). Previous models (e.g., Burgess & Schwartz 1988; Burgess 1989) show that specularly reflected ions can more easily channel along a TD when the convection electric field
points toward it, which favors the formation of HFAs. In our model, what we are concerned with is how specularly reflected ions contribute to the Hall current when they gyrate across a TD. Compared to a field-aligned beam, specularly reflected ions also have field-aligned motion and the difference is the large gyration with a certain gyrophase. Based on the model by Liu et al. (2015), when the convection electric field points toward the TD, the corresponding IMF configuration makes a single ion (similar to gyrophase bunched ions) prefer to project its initial velocity onto the perpendicular direction, which favors a strong Hall current. The Hall current direction, however, strongly depends on the initial gyrophase. This significantly complicates our model, which requires further study in the future.

Next, we discuss what may happen after the formation process. Based on our model, the energy source is foreshock ions. If foreshock ions cannot provide enough energy, the foreshock transient structure cannot be maintained and will become dissipated. For example, in the observations of “mature HFAs” (e.g., Zhang et al. 2010), foreshock ions and solar wind ions merged into one diffuse ion population, meaning that there was no longer free energy from foreshock ions. As a result, the Hall current strength decreased, so the magnetic field structure should become more gradual or less steepened. The electric field induced during this process should drive plasma to move inward (back to the core). Indeed, as observed by THEMIS when in a string-of-pearls formation, the density in the core of an FB increased during its late stage (Liu et al. 2016b).

As the energy source is foreshock ions, higher background foreshock ion density and energy must favor the formation process. As shown in PIC simulations (An et al. 2020), the expansion speed of a foreshock transient is proportional to the normalized foreshock ion energy and the density ratio of foreshock ions to the solar wind ions. This density ratio is proportional to the Alfvén Mach number (see review by Lembège et al. 2004). The foreshock ion speed is proportional to the solar wind speed, and the foreshock ion speed normalized to the Alfvén speed is also proportional to the Alfvén Mach number. This is consistent with previous statistical studies (e.g., Chu et al. 2017; Liu et al. 2017a) and multicase studies (Liu et al. 2016b; Turner et al. 2020) that fast solar wind speed and small field strength favor the occurrence of SHFAs/HFAs/FBs, and the expansion speed of FBs is proportional to the solar wind speed and the Alfvén Mach number.

Here we estimate the energy and momentum transfer from foreshock ions to the magnetic field and cold plasma. In event 2, the foreshock ion density at MMS2 \( n_f \approx 0.5 \sim 2 \text{ cm}^{-3} \) (Figure 9.1(h)), and the foreshock ion velocity \( V_f \) was \( \approx 500 \text{ km s}^{-1} \) (Figure 8). The electric field was \( \approx 1 \text{ mV m}^{-1} \) (Figure 9(c)). The energy transfer rate was thus around 0.04-0.16 nW m\(^{-3}\) (Figure 8). The acceleration of cold plasma expansion speed \( V_{exp} \) was from \( 0 \) to \( 50 \text{ km s}^{-1} \) within \( 0.4 \text{ s} \) (Figure 8 from MMS2 to MMS1). The solar wind density at MMS2 \( n_{sw} \) was \( 2 \sim 10 \text{ cm}^{-3} \) (Figure 9.1(h)). The energy increase of cold plasma per unit time was \( m \cdot n_{sw} \cdot V_{exp} \cdot \Delta V_{exp} / \Delta t \sim 0.02 \sim 0.1 \text{ nW m}^{-3} \), comparable to the energy input from foreshock ions. The magnetic energy also redistributed with a rate that varied from \( -0.01 \) to \( +0.1 \text{ nW m}^{-3} \). As for the momentum, the transfer from foreshock ions to cold plasma was not straightforward, because there was no collision. In event 1, for example, the momentum of foreshock ions was mainly in the negative GSE-Y direction, but the outward motion of cold plasma was dominant in the GSE-XZ plane (Figure 3(h)). The momentum transfer was through the electric field and magnetic field \( q n_f (E + V_f \times B) \).

In event 2 at MMS2, \( E_c \approx 0 \) to \( -1 \text{ nV m}^{-1} \) (Figure 9.1(c)) and \( (V_f \times B) \sim 5 \times 10^{-6} - 4 \times 10^{-6} - 4 \times 10^{-6} - 4 \times 10^{-6} - 4 \times 10^{-6} \text{ nV m}^{-1} \), which gives a momentum input around \( 4 \times 10^{-17} \) to \( 1.6 \times 10^{-15} \text{ N m}^{-3} \). The momentum gain of cold plasma per unit time was \( m \cdot n_{sw} \cdot \Delta V_{exp} / \Delta t \sim 4 \times 10^{-16} \) to \( 2 \times 10^{-15} \text{ N m}^{-3} \) (likely overestimated as there was also Earthward expansion at the leading edge seen in Figure 9(f)), which is comparable to the momentum input from foreshock ions to the field. The momentum of the magnetic field also redistributed, which was too complicated to estimate.

In both events, no clear downstream compressional boundary was observed. This could be due to the direction of the Hall current. In event 1, as the initial bulk velocity of downstream foreshock ions was the dominant contribution to the Hall current, the Hall current was roughly along the downstream IMF direction. The field variation by the Hall current was thus roughly perpendicular to the downstream IMF (Figure 2(b)), which hardly increases the field strength but mainly rotates the field direction. Therefore, the direction and strength of the Hall current and IMF configuration determine whether a compressional boundary can appear. Additionally, as there was magnetic flux transporting downstream, although the flux direction was roughly perpendicular to the downstream IMF, betatron acceleration could still occur, which may explain the observed electron temperature increase at the downstream edge of event 1 (especially the perpendicular temperature in Figure 1(f)). This temperature increase was even higher than that at the upstream compressional boundary. A possible reason could be that electrons accelerated at the upstream compressional boundary could move along the same field lines toward the downstream edge (as solar wind electrons had Earthward preference) and experience the second instance of betatron acceleration consistent with Liu et al. (2019). (We do not explain event 2, as we do not have good data to determine the discontinuity orientation and IMF configuration.)

Based on our model, we discuss what might cause the differences between HFAs and FBs that FBs are typically larger than HFAs with a shock at the upstream side. If foreshock ions from the downstream side can cross the discontinuity to the upstream side (rotational discontinuity or if the TD thickness is small enough compared to the foreshock ion gyroradius), and the upstream IMF configuration can trigger the “instability,” a bump can form upstream of a tenuous core. If the energy source from foreshock ions is strong enough, the expansion can be supermagnetosonic and the upstream bump can thus steepen into a shock. Also because of the supermagnetosonic expansion, the size of the core will soon become very large. We will identify such a structure as an FB. In some other cases, for example, if the expansion is very slow, no shocks will form, and the structure size will be small. If both sides could trigger the “instability” or the downstream magnetic flux transport is strong enough to increase the field strength, there could be two compressional boundaries or shocks on two sides of the core. Or if the TD is too thick, a local structure will form. We may identify those structures as HFAs. Although HFAs and FBs share similarities in the formation process and observational characteristics, we still need to distinguish them, because the effects of FBs are more significant. For example, because of the large size, the perturbations on the bow shock and magnetosphere/ionosphere by an FB can be global compared to typical HFAs (e.g., Archer et al. 2015). Because of the upstream shock and no significant downstream compression region, FBs can
accelerate particles more significantly than many HFAs that do not have shocks, e.g., through shock drift acceleration and Fermi acceleration (Liu et al. 2016a; 2017b, 2018).

Foreshock transients have been shown to contribute to particle acceleration at Earth’s bow shock. Foreshock transients potentially contribute to the energy budget at other astrophysical shocks, like supernova-driven shocks, but direct observations are unavailable for those more exotic systems. Our model sheds light on the quantification of the formation of foreshock transients to infer whether they can form at other shock environments to include them in general shock models. For example, our results imply that at shocks with an Alfvén Mach number larger than Earth’s bow shock, foreshock transients could be more significant and occur more frequently. In the future, theoretical work and simulations can be applied to improve and refine our model.

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Appendix A
A Simple Derivation

Here we derive the growth rate of the “instability” based on our model. Considering a 1D magnetic profile based on event 1, the magnetic field is in the Z direction with a profile varying in the X direction. The Hall current from the projected perpendicular velocity of magnetized foreshock ions is in the Y direction. We ignore the motion of cold plasma in the solar wind rest frame (and thus the background convection electric field). For linearization, we have the foreshock ion density $n_f = n_0 + n_1$, foreshock ion velocity $V_f = V_{f0} + V_{f1}$, magnetic field $B = B_0 + B_1$, electric field $E = E_0 + \frac{\partial E_1}{\partial t}$ $\approx \rightarrow -i\omega$, and $\nabla \rightarrow ik\hat{x}$.

The foreshock ion density continuity equation is

$$\frac{\partial n_f}{\partial t} + \nabla \cdot (n_f V_f) = \frac{\partial n_1}{\partial t} + \hat{\beta}n_1,$$

where $\hat{\beta}n_1$ indicates the particle source from the background foreshock. In events 1 and 2, we show that stronger compressional boundary can trap more foreshock ions at the magnetic gradient by limiting their gyration (Figures 3(j) and 9(h)). We thus assume that $\frac{\partial n_1}{\partial t} = i\alpha \frac{\partial n_f}{\partial \xi}$, where $\alpha$ is a parameter in a scale of 1 simplifying how the magnetic profile variation traps foreshock ions. The sign of $\alpha$ indicates whether the magnetic profile variation traps more foreshock ions. If the magnetic profile variation increases the field strength at the compressional boundary (Figure 10(a)) to trap more foreshock ions, $\alpha$ will be positive. If the magnetic profile variation increases the field strength at the discontinuity (Figure 10(b)), which causes fewer foreshock ions to pass through the discontinuity and contribute to the Hall current, $\alpha$ will be negative. At the end of this appendix, we show that the sign of $\alpha$ is critical to determine whether the “instability” can occur. From Figures 3(j) and 9(h), we see that the foreshock ions were accumulated at the magnetic gradient, and we thus include $i\alpha$ to indicate the 90° phase difference in $k$ between the peak of the foreshock ion density and magnetic field strength. To linearize the continuity equation, we have $-i\omega n_f = k V_{f1} + V_{f0} \frac{\partial n_0}{\partial \xi}$, and thus

$$n_f = \frac{k}{\omega} V_{f0} V_{f1} + \frac{\partial n_0}{\partial \xi} V_{f0}.$$  \hspace{1cm} (A1)

Next, the foreshock ion momentum equation is $mV_{f1} = eE + eV_f \times B$, $V_f = V_{f0} + V_{f1}$ and $V_f \rightarrow 0$, implies that $V_{f1} = eE_0 / \omega_0 m (1 - \frac{\Omega^2}{\omega^2})$ and $V_{f0} = eE_0 / \omega_0 m (1 - \frac{\Omega^2}{\omega^2})$ and $V_0 = eE_0 / \omega_0 m (1 - \frac{\Omega^2}{\omega^2})$, where $\omega$ is the ion gyrofrequency. Because as seen from event 2 the field variation is much faster than the ion gyrofrequency ($\Omega^2 \ll 1$), we simplify them as

$$V_{f1} = -eV_{f0} / \omega_0 m$$

and

$$V_{f0} = -eE_0 / \omega_0 m.$$  \hspace{1cm} (A3)

From Ampere’s law, $i\alpha B_0 = \mu_0 J_1$. As we only consider field strength variation, we have $i\alpha B_0 = \mu_0 J_1$. The current density variation $J_1 = e\gamma_1 V_{f0} e\gamma_2 V_{f1}$. Using Equations (A1) and (A3), we have $J_1 = e\gamma_1 \left(\frac{\partial n_0}{\partial \xi} V_{f0} + \frac{\partial n_1}{\partial \xi} V_{f0} + eE_0 / \omega_0 m \right)$. Therefore, we have

$$\omega^2 = -\left(\gamma_1 V_{f0}^2 / (1 + \gamma_2 V_{f1}^2 / \omega_0^2 + \omega_0^2)\right).$$  \hspace{1cm} (A4)

We modify the foreshock ion beam instability by involving a particle source that is modulated by the magnetic variation. We see that if $\alpha > 0$, $\omega^2$ is always negative, meaning instability. Based on observations, we estimate $k \sim 2\pi / 2000$ km$^{-1}$, $c \sim 300$ km/s, $V_{f0} \sim 500$ km/s$^2$, and $\Omega \sim 2\pi / 15$ s$^{-1}$. Therefore, $\omega^2 \sim -14 / (1.9 + 3.8 \times c^2)$. If $\alpha \sim 1$, we obtain a growth rate of $\sim 2.4$ s$^{-1}$. Such a growth rate is consistent with the timescale of field variation in event 2. If the magnetic field variation traps fewer foreshock ions (Figure 10(b)) and $\alpha \sim -1$, $\omega^2 > 0$ meaning no instability. In this simplified derivation, many processes are ignored, such as the static electric field, electron Hall current, and diамagnetic current. In the future, more comprehensive theoretical work is needed.
Appendix B
Supporting Information

The electron bulk velocity $V_e$ and electric field in the solar wind rest frame of event 1 is given in Figure B1. Figure B2 shows the ion distribution in the local solar wind rest frame in the perpendicular cut of event 2.

**Figure B1.** Electron bulk velocity $V_e$ in the solar wind rest frame calculated by subtracting the electron bulk velocity in the downstream background value. The electric field in the solar wind rest frame is calculated through $E + V_{sw} \times B$.

**Figure B2.** MMS1 observations of the ion distribution in the perpendicular cut (the horizontal axis is the foreshock ion bulk velocity projected direction) at the time corresponding to the third vertical dotted line in Figure 5.2. The distribution was in the local solar wind rest frame, so the solar wind beam was at the origin. The foreshock ions were gyrating around the origin with a certain gyrophase corresponding to the orange curved arrow in Figure 6, i.e., reflection at the compressional boundary. In this frame, the local solar wind ions were not moving, so the convection electric field was zero and foreshock ions did not change energy during the gyration as seen from the distribution. In other reference frames, however, the shifted origin can cause energy variation during the gyration. In the solar wind rest frame, the local solar wind ions were moving sunward due to the expansion. The foreshock ions before the partial gyration or reflection (sunward) had higher energy than those after the reflection (Earthward), i.e., foreshock ions lost energy through partial gyration against the convection electric field. In the spacecraft frame, the local solar wind ions were moving Earthward. The foreshock ions before the reflection (sunward) had lower energy than those after the reflection (Earthward), i.e., foreshock ions gained energy through partial gyration along the convection electric field.
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