Foreshock bubbles (FBs) are large (up to 10 RE), explosive (expansion speeds of >100 km/s) events upstream of the bow shock. FBs form under a usual range of solar wind conditions between 3 and 20 RE upstream of Earth’s bow shock. FB cores often include deep, localized magnetic holes where the B field drops to <1 nT.

Abstract
This work presents the first detailed analysis of foreshock bubbles (FBs) using high-resolution Magnetospheric Multiscale (MMS) data. Between October 2017 and January 2019, MMS captured 10 foreshock transient events with burst resolution data that we show are consistent with FBs. One “textbook” event is examined and described in detail. Employing the multipoint nature of MMS, we demonstrate how the size and orientation, expansion speed, and distance since formation can be estimated. From all 10 events, FB sizes ranged from 1.1 to 9.9 RE (average of 4.4 RE), and expansion speeds ranged from 139 to 377 km/s (average of 257 km/s). FBs formed under a usual range of solar wind conditions between 3 and 20 RE upstream of Earth’s bow shock. We also report on new features of FBs: deep and localized magnetic “holes” within the cores of FBs, where the total field strength drops to <1 nT.

1. Introduction
Near-Earth space provides a dynamic and varied natural laboratory to study the physics of collisionless plasmas. For example, a spacecraft traveling in orbit from a perigee at 300 km altitude (i.e., 1.05 Earth radii, Re, geocentric distance) to an apogee at 20 Re geocentric distance on the dayside (i.e., toward the Sun from Earth) has the opportunity to sample the dense, low-beta, multispecies plasmas of the ionosphere, the tenuous, hot plasma in the magnetosphere, the turbulent magnetosheath, the collisionless bow shock, and the supersonic solar wind upstream (i.e., sunward) of the bow shock. At Earth’s bow shock, the solar wind slows, heats, and diverts around the magnetospheric obstacle. Being a supercritical shock under most solar wind conditions, a fraction of incident solar wind particles can be reflected at the bow shock and propagate into the upstream flow. This region of near-Earth space is the ion foreshock, where ions accelerated and reflected by the bow shock stream sunward into the incident solar wind resulting in a variety of instabilities, wave activity, and the development of large-scale transient phenomena (see reviews by Eastwood et al., 2005 and Wilson, 2016). Here we focus on new observations of one particular type of transient ion foreshock phenomena known as “foreshock bubbles.”

Foreshock bubbles (FBs) were first identified using global hybrid simulation results reported by Omidi et al. (2010), and since then have been reproduced using two other independent global hybrid models (Karimabadi et al., 2014; Liu et al., 2018). Archer et al. (2014) and Liu et al. (2015) developed a theoretical framework for FB formation, with the latter showing that both rotational and tangential discontinuities in the interplanetary magnetic field (IMF) can be responsible for FB formation. FBs form as superthermal ions in the foreshock are concentrated by discontinuities in the IMF. As an IMF discontinuity moves Earthward and more foreshock ions are concentrated by it, a “bubble” of superheated plasma forms into the core region of an FB, distinguished by hot, tenuous ion populations, low magnetic field strengths, and strongly deflected ion velocities. As the responsible IMF discontinuity approaches the bow shock, the FB core intensifies and expands into the surrounding solar wind plasma, resulting in the formation of a compression region and ultimately a fast magnetosonic shock along the upstream edge of the FB. The FB shock slows and deflects part of the incident solar wind stream around the FB core, resulting in a sheath between the FB core and the upstream shock. Despite multiple similarities to hot flow anomalies (HFAs) (e.g., Schwartz et al., 1985, 2000; Thomsen et al., 1988, 1993; Wang et al., 2013), there are key differences between HFAs and FBs, as discussed in Omidi et al. (2010) and Turner et al. (2013). In simulations, FBs form shocks with strong sunward components on their upstream sides and do not form any compression region or shocks on their downstream legs.
sides, while HFAs often have compression regions of various orientations on both sides. From a satellite's perspective, an FB passes over a spacecraft moving primarily in the same sense as the solar wind, that is, largely in the $-X$ direction in Geocentric Solar Ecliptic (GSE) coordinates; HFAs, however, move along the bow shock concentrated along the intersection line between an IMF discontinuity and the bow shock surface (e.g., Omidi & Sibeck, 2007). Because they can start forming far upstream of the bow shock, FBs can grow to large sizes $>10$ RE (e.g., Karimabadi et al., 2014; Liu et al., 2018; Omidi et al., 2010), while HFAs are typically no larger than a few RE (e.g., Omidi & Sibeck, 2007).

Using the Omidi et al. (2010) simulations and results as guidance, Turner et al. (2013) reported the first observational evidence of FBs using NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission and defined a set of classification criteria to distinguish FBs from HFAs. Since then, observations of FBs have also been reported by Archer et al. (2014), Liu et al. (2015), and Liu, Hietala et al. (2016), Liu, Turner, et al. (2016), Liu et al. (2018). Liu, Hietala, et al. (2016) used multipoint THEMIS observations to estimate the sizes and expansion speeds of six FBs; they estimated that the six FBs ranged in size from $-2$ to $15$ RE and were expanding in the solar wind frame at speeds of $-140$ to $470$ km/s, and none had compression regions or shocks on their downstream edges. Hartinger et al. (2013) and Archer et al. (2014) presented observational evidence that when FBs impact the magnetosphere, they result in global magnetospheric disturbances including large-scale motion of the magnetopause and enhanced ultralow-frequency wave activity throughout the dayside magnetosphere. Other recent works (e.g., Liu et al., 2017, 2018; Wilson et al., 2016) have shown that FBs are efficient accelerators of energetic particles.

In this study, we report new results of multipoint observations of FBs using NASA's Magnetospheric Multiscale (MMS) mission. This paper is structured as follows: MMS data used for this study are briefly introduced in section 2. Section 3 contains a detailed case study of an FB observed by MMS, while section 4 contains results of a multicase study consisting of 10 FBs. The results and conclusions are summarized in section 5.

2. Data

The MMS mission was launched into Earth orbit on an Atlas V rocket in March 2015. The mission consists of four identically instrumented spacecraft in low inclination, highly elliptical orbits. Throughout most of each orbit, the four spacecraft are put into tetrahedron formation, allowing for accurate disambiguation of spatiotemporal features using a variety of multispacecraft analysis techniques (e.g., Paschmann & Daly, 2008). After an initial science phase to study dayside reconnection, the MMS apogees were raised in early 2017 from $-12$ RE up to $-25$ RE geocentric distance. Each year, the MMS orbits’ line of apsides traverse all 24 hr in magnetic local time (MLT) around Earth, with the spacecraft spending the Northern Hemisphere winter months (approximately November to March) on the dayside of the system while near apogee. For this study, we used short periods of burst resolution data selected from the “regions of interest” that are a predesignated subset of each orbit determined by the mission’s science leadership. We only examined data after the apogees were raised in 2017. For all details on the MMS mission, data selection, and instrumentation, see Burch et al. (2016, and references therein). Instrumentation used for this study include the Fast Plasma Investigation (FPI), consisting of a few eV to $-20$ keV ion distributions and moments at 150 ms resolution and electron distributions and moments at 30 ms resolution; fluxgate magnetometers (FGM) providing three-axis magnetic field vectors at 8 ms resolution; and energetic particle telescopes Fly’s Eye Energetic Particle Spectrometer (FEEPS) providing distributions of $-50$ to $-550$ keV ions and electrons. The MMS data are of exceptional quality, but there are still minor caveats to consider, particularly when analyzing solar wind data. The FPI ion instruments do not have the energy and angular resolution to fully resolve the cold and narrow solar wind ion beam, which manifests itself especially in the ion temperature moment that ends up artificially high in the solar wind and in the density moment, which sometimes exhibits spin tone harmonic artifacts. However, the ion velocity moment is still very accurate, and the ion density can be compared to electron density, invoking the quasi-neutrality assumption, to determine its accuracy. These known effects have no impact on the results presented here nor the conclusions of this study. Data from NASA’s Acceleration, Reconnection, Turbulence, and Electrodynamics of Moon’s Interaction with the Sun (ARTEMIS) mission (Angelopoulos, 2010) and the OMNI data set were also included here for estimates of
the upstream solar wind. All data for this study were accessed and analyzed using SPEDAS V3.1; see Angelopoulos et al. (2019) for details.

3. Analysis: Case Study

On 18 December 2017, MMS observed two FBs within 20 min of each other. We focus in detail on the second of these two events, which occurred around 12:56 UT, since it is a textbook case based on our understanding from numerical simulations and previous studies. Figure 1 shows an overview of the MMS observations from 18 December 2017 around 12:56 UT. All data are shown from MMS-1 with the exception of the FEEPS data, which are combined from the FEEPS instruments on all four MMS spacecraft. (a) Magnetic field vector components in GSE coordinates ($X$, $Y$, $Z$ in blue, green, and red, respectively) and magnitude (black). (b) Magnetic field magnitude plotted on a logarithmic scale to detail the deep magnetic “holes” in the core of this FB. (c) Ion omnidirectional-averaged energy distributions from the FPI and FEEPS instruments with the gap in energy coverage between the two filled using an exponential interpolation in energy. (d) Ion (red) and electron (blue) densities from the FPI instruments. (e) Ion velocity vector in GSE coordinates ($X$, $Y$, $Z$ in blue, green, and red, respectively) and magnitude (black). (f) Ion (magenta) and electron (teal) temperatures from the FPI instruments. Note that the magnitude of the ion temperature is not accurate in the solar wind at the start and end of the period shown; however, the moment is likely accurate within the core of the FB shown here. (g) Electron omnidirectional-averaged energy distributions from the FPI instruments.

Figure 1. MMS observations of a foreshock bubble from 18 December 2017 around 12:56 UT. All data are shown from MMS-1 with the exception of the FEEPS data, which are combined from the FEEPS instruments on all four MMS spacecraft. (a) Magnetic field vector components in GSE coordinates ($X$, $Y$, $Z$ in blue, green, and red, respectively) and magnitude (black). (b) Magnetic field magnitude plotted on a logarithmic scale to detail the deep magnetic “holes” in the core of this FB. (c) Ion omnidirectional-averaged energy distributions from the FPI and FEEPS instruments with the gap in energy coverage between the two filled using an exponential interpolation in energy. (d) Ion (red) and electron (blue) densities from the FPI instruments. (e) Ion velocity vector in GSE coordinates ($X$, $Y$, $Z$ in blue, green, and red, respectively) and magnitude (black). (f) Ion (magenta) and electron (teal) temperatures from the FPI instruments. Note that the magnitude of the ion temperature is not accurate in the solar wind at the start and end of the period shown; however, the moment is likely accurate within the core of the FB shown here. (g) Electron omnidirectional-averaged energy distributions from the FPI instruments.
Table 1

| Event | SW date/time | Duration (s) | M₂ downstream | Vₓ, Vᵧ downstream | Bₓ, Bᵧ downstream | Vₓ, Vᵧ upstream | Bₓ, Bᵧ upstream | Notes |
|-------|--------------|--------------|---------------|------------------|------------------|----------------|----------------|-------|
| 2017-12-18/12:56 | 52 | 15.5 | 7.7 | 2.88 | 5.4 | 6.4 | 3.1 | ARTEMIS MVA |
| 2018-12-18/12:36 | 34 | 14.1 | 7.6 | 6.9 | 5.1 | 7.2 | 1.17 | MMS Bₓ × Bᵧ |
| 2018-03-30/21:01 | 101 | 12.1 | 6.3 | 7.2 | 5.1 | 7.2 | 1.17 | ARTEMIS MVA |
| 2018-03-30/21:14 | 49 | 10.0 | 6.3 | 7.2 | 5.1 | 7.2 | 1.17 | ARTEMIS MVA |
| 2018-12-18/12:56 | 20 | 7.2 | 5.1 | 7.2 | 5.1 | 7.2 | 1.17 | ARTEMIS MVA |
| 2019-01-14/04:39 | 39 | 6.1 | 5.1 | 7.2 | 5.1 | 7.2 | 1.17 | ARTEMIS MVA |

Note. Dates are formatted as YYYY-MM-DD.

Table 1 shows the solar wind driving conditions, and IMF discontinuity estimates for 10 FBs observed by MMS.

This FB, while its observed and derived characteristics are summarized in Tables 1 and 2. MMS first entered the core of the FB around 12:55:57 UT, indicated by the decrease in magnetic field strength and density, deflection of the ion velocity, and increase in electron and ion temperatures. Note that MMS did not observe any significant compression region (i.e., enhanced magnetic field strength and density) when it entered the transient structure; the presence of a significant compression region on the downstream side of a foreshock transient is a telltale feature of most HFAs. MMS remained in the core of the structure for 46 s, from 12:55:57 to 12:56:43 UT. The core was characterized by low magnetic field strength, tenuous (n < 1 cm⁻³), strongly deflected (ion velocity is actually sunward, Vₓ > 0, through parts), and superheated plasma, all of which are evident in Figure 1. Features in the core that have not been reported before include deep, narrow magnetic field “holes,” where the total field strength drops below 1 nT. Based on our multievent survey, these magnetic holes are found within the cores of most FBs and HFAs, including in the HFA observed by MMS reported in Schwartz et al. (2018) and Turner et al. (2018). MMS next entered the shear of the FB after 12:56:43 UT, characterized by shocked plasma exhibiting a high density and magnetic field strength. MMS traversed the shock on the upstream edge of the FB from ~12:56:46 to 12:56:54 UT. The observed shock exhibited complex structure and an extended foot including large-amplitude whistler precursor waves (e.g., Wilson et al., 2012). Note that there were no outstanding levels of energetic particles (>100 keV) (e.g., Turner et al., 2018; Wilson et al., 2016) in or around the core of this foreshock transient.

A necessary condition for the formation of a FB (e.g., Liu et al., 2015; Omidi et al., 2010) is the presence of a discontinuity in the IMF about which the core of the FB forms. Since the FB itself conceals any signatures of an IMF discontinuity, NASA's ARTEMIS spacecraft were used to identify any driver discontinuity. ARTEMIS were in lunar orbit in the solar wind at the time of this event. They observed a series of IMF discontinuities around the period of interest, but one that was observed at 12:46 UT was most likely the discontinuity responsible for the formation of the FB observed at MMS 10 min later. Minimum variance analysis (MVA) (e.g., Schwartz, 1998, and references therein) was performed on the ARTEMIS data to determine a discontinuity normal direction of n = [0.74, 0.67, −0.08] in GSE coordinates. With that orientation, the timing of the discontinuity plane traveling between ARTEMIS and MMS (~9.4 min) is consistent with the time the FB was observed at MMS. Using the velocities and magnetic fields observed by MMS before and after the transient event at 12:56 UT on 18 December 2017, the solar wind convection electric fields were calculated downstream and upstream of the FB; these E fields were [0.0, 1.4, 0.1] mV/m downstream and [0.0, 0.5, 0.8] mV/m upstream. Considering the geometry of the IMF discontinuity plane, the convection electric field was only pointing back into the discontinuity plane on the downstream side.

Employing the multipoint nature of the MMS mission, we were able to calculate multiple critical characteristics of this FB. Using
common (i.e., observed by all four spacecraft) features on the upstream and downstream boundaries of the FB, estimates of the boundary normal (\(\mathbf{n}\)) and speeds (\(U\)) can be estimated using the timing difference observed between all four spacecraft (equation 10.20 from Schwartz, 1998). Using the dip in \(|B|\) around 12:56:48 UT on the upstream shock, the following normal direction and speed were estimated: \(\mathbf{n}_{shk} = [−0.99, 0.08, 0.15]\) in GSE at \(U_{shk} = 299\) km/s. This result was consistent with the coplanarity estimate of the shock normal (equation 10.17 from Schwartz, 1998) to within 20° (\(\mathbf{n}_{cop} = [−0.87, 0.39, 0.29]\)) and the conservation of mass flux (equation 10.29 from Schwartz, 1998), which estimated \(U_{shk} = 306\) km/s.

Based on our understanding from hybrid simulations of FBs (e.g., Karimabadi et al., 2014; Omidi et al., 2010) and unlike HFAs (e.g., Schwartz et al., 2000, 2018), the downstream boundaries of FBs are the IMF discontinuity plane about which they form, generally moving with the solar wind. In reality, an IMF discontinuity is often Alfvénic and propagating at the Alfvén speed oblique to the solar wind. However, it is impossible to calculate this for these cases since the FBs conceal the discontinuity signal. Taking the assumption that the downstream velocity represents the motion of the downstream boundary, the difference between the downstream velocity and the upstream shock velocity provides a best estimate of the expansion/compression speed of the FB along MMS’s track through it. For the 18 December 2017 at 12:56 event, the expansion speed is estimated as \(V_{exp} = 307\) km/s, which is \textit{expansion into the surrounding solar wind plasma}. This speed estimate is entirely consistent with the formation of a shock on the upstream edge of this FB, since the fast magnetosonic speed (from OMNI) in the solar wind was approximately 77 km/s at 12:56 UT. The observed duration and geometry and motion of the FB can also be used to estimate its size, \(S = |V_{dn}|\Delta t = |V_{shk} + V_{exp}|\Delta t\), where \(V_{dn}\) is the downstream solar wind velocity, \(V_{shk} = U_{shk}/n_{shk}\), and \(\Delta t\) is the duration in seconds of the observed event. The FB at 12:56 UT on 18 December 2017 was observed by MMS for 52 s, which resulted in a size estimate of 4.9 RE. Assuming the expansion speed was constant, the size and expansion speed can be used to estimate the age, \(A = S/|V_{exp}|\), and the upstream distance where the FB initially formed, \(X_0 = A^*|V_{dn}|\); for this event, our best estimate is that the FB started to form ~9.6 RE upstream approximately 102 s before it was observed at MMS.

### Table 2

| Event date/time | Downstream shock/compression region? | Upstream shock/compression region? | Upstream boundary normal in GSE and speed (km/s) | Magnetic holes in core? (Y/N and #) | Expansion speed (km/s) | Size (RE) | Age (s) | Distance since formation (RE) |
|-----------------|---------------------------------------|-------------------------------------|-----------------------------------------------|-----------------------------------|------------------------|----------|--------|-------------------------------|
| 2017-12-18/12:56 | No                                    | Shock                               | \([-0.99, 0.08, 0.15]\)                         | Y                                 | 306                    | 4.9                  | 102                | 9.6                           |
| 2017-12-18/12:36 | No                                    | Shock                               | \([-0.91, 0.36, -0.21]\)                      | Y                                 | 332                    | 3.3                  | 64                 | 6.2                           |
| 2018-02-04/10:38 | No                                    | Shock                               | \([-0.97, -0.23, 0.00]\)                      | Y                                 | 139                    | 2.1                  | 96                 | 4.7                           |
| 2018-03-30/08:41 | No                                    | Shock                               | \([-0.86, 0.14, -0.48]\)                      | Y                                 | 222                    | 6.0                  | 172                | 10.3                          |
| 2018-12-14/03:32 | No                                    | Shock                               | \([-0.91, -0.11, 0.41]\)                      | N                                 | 244                    | 2.6                  | 68                 | 3.7                           |
| 2018-12-14/03:45 | No                                    | Shock                               | \([-0.94, -0.19, 0.28]\)                      | Y                                 | 141                    | 1.1                  | 51                 | 2.9                           |
| 2018-12-19/15:57 | No                                    | Shock                               | \([-0.82, -0.44, 0.37]\)                      | N                                 | 327                    | 3.1                  | 61                 | 4.1                           |
| 2019-01-05/17:39 | No                                    | Shock                               | \([-0.70, 0.66, 0.27]\)                      | Y                                 | 377                    | 9.9                  | 167                | 13.3                          |
| 2019-01-08/11:47 | No                                    | Shock                               | \([-0.87, 0.43, -0.23]\)                      | Y                                 | 221                    | 9.5                  | 275                | 18.0                          |
| 2019-01-30/04:39 | No                                    | Shock                               | \([0.75, -0.32, 0.58]\)                       | Y                                 | a                      | 1.7                  | a                  | a                             |

*aMMS was in a string-of-pearls configuration at ion scales, so multispacecraft analysis was not used for this event: Shock normal was calculated using \(B\) and \(V\) coplanarity; shock speed was calculated using mass flow conservation.

Note: Dates are formatted as YYYY-MM-DD.
Figure 2. Key characteristics of 10 FBs observed by MMS. Each event is color coded, with the dates and times of observation listed in the legend along with the corresponding solar wind velocity and IMF strength for each. Each event is plotted with an “x” at the location where MMS observed it projected onto the X-Y plane in GSE coordinates. Circles around each event represent the size estimate of each FB, with the diameter of each circle equal to the calculated size in $R_E$. The dashed lines indicate the estimates of the formation location (small horizontal lines on the upstream edges of each dashed vertical line) and distance since formation of each event (length of the dashed vertical lines). The vectors shown for each event capture the calculated expansion speeds (vector length) and upstream normal direction (vector direction); for the expansion speeds, a reference vector of 400 km/s is shown in black below the legend. Note that for the March 2019 event, the expansion speed and distance since formation could not be calculated due to the MMS configuration, but the calculated shock normal direction is shown on the plot using an expansion speed of 100 km/s. The average bow shock location from Jelínek et al. (2012) is shown in red.

### 4. Analysis: Other Events

MMS burst data were surveyed during two dayside seasons spanning approximately November 2017 to April 2018 and October 2018 to January 2019. From these periods, more than 100 foreshock transient events were captured in MMS’ highest resolution data. Of those events, 10 clearly satisfy the identification criteria for FBs as outlined in Turner et al. (2013), Archer et al. (2014), and Liu et al. (2015), including the event at 12:56 UT on 18 December 2017. Key identifying features examined included the presence of a solar wind discontinuity around which a foreshock bubble could form, size estimate and motion of the foreshock transients, directionality of the convection electric field on either side of the foreshock transient with respect to the solar wind discontinuity orientation, reflected-to-incident ion density ratios, and orientation of the shock on the upstream edge of the foreshock transients. All 10 of these events had no compression region on their downstream boundaries but strong fast magnetosonic shocks on their upstream sides and sheath and core structures between the boundaries with superheated and tenuous plasma, weak magnetic fields, and strong flow deflections. IMF discontinuities were identified in ARTEMIS data for 6 of the 10 events, with MVA being used to calculate the discontinuity plane and timing analysis. The timing from the discontinuity geometry and the separation between ARTEMIS and MMS was used to confirm each discontinuity could be responsible for the corresponding FB. For the other four cases where ARTEMIS was either unavailable (i.e., in the sheath or magnetotail) or did not observe any candidate IMF discontinuity, we followed Schwartz et al. (2000) and assumed the discontinuity was a tangential discontinuity, allowing the cross product of the upstream and downstream magnetic fields (i.e., on either side of the FB) to estimate the discontinuity orientation.

From the estimated IMF discontinuity geometries, three of the 10 events revealed convective electric fields on both sides of the IMF discontinuity that did not point back into the discontinuity plane, which is a necessary condition for the formation of an HFA (e.g., Omidi & Sibeck, 2007; Thomsen et al., 1993). Of all 10 FBs, 8 had the deep magnetic holes ($|B| < 1$ nT) in their cores (see Table 2 and more detail on these below), 7 had whistler precursor waves just upstream of their shocks, and 5 (2) events were associated with the presence of significant counts of energetic ions $\geq 100$ keV (electrons $\geq 50$ keV). Whistler precursor waves are a regular feature of collisionless shocks (e.g., Wilson et al., 2017, and references therein), and in these cases, they were identified by in-phase fluctuations in the ion density and total magnetic field strength (evident in Figure 1 but not shown in further detail here). The orientation of the upstream shock for all of the events was consistent with FBs (e.g., Liu, Turner et al., 2016; Turner et al., 2013) in that they all had a strong X-GSE component.

Multipoint analysis using MMS was carried out on all 10 FB cases, with key results detailed in Table 2 and Figure 2. However, the 30 January 2019 case was unlike the rest since MMS was not in its typical electron-scale tetrahedron formation for this event due to a solar wind turbulence campaign during this period. For that event, MMS instead was separated approximately as a “string of pearls” along the orbit with separations in the hundreds of kilometer range. Considering the spacecraft configuration for that 30 January 2019 event, there was high uncertainty in multispacecraft analysis results for the shock orientation, expansion speed, age, and distance since formation for this FB, but the size estimate was likely accurate since the downstream velocity can be used for that calculation. Coplanarity with B and V (equation 10.17 from Schwartz, 1998) was used to determine the shock orientation listed in Table 2 for the 30 January 2019 event, while conservation of mass flux estimated a shock speed of 33 km/s. From the other nine events, the FBs were expanding at speeds ranging from 139 to 377 km/s, with an average of 257 km/s, consistent with the presence of strong shocks on the upstream boundaries.
Size estimates ranged from 1.1 to 9.9 R_E, with an average size of 4.4 R_E, and the sizes were well correlated with the estimates for the FBs' ages (average age, 117 s; correlation coefficient with size, R = 0.88) and distances since formation (average X_in, 8.1 R_E; R = 0.95). The correlation was expected from the models used to calculate age and distance since formation but also from a fundamental viewpoint of FBs as explosive structures. The observed expansion speeds did not correlate with the observation durations (R = 0.23), ages (R = 0.01) or distances since formation (R = 0.26) and only weakly correlated with the size estimates (R = 0.44), which lends further credit to the assumption that |V_\text{exp}| was approximately constant over the life of the FB. The expansion speeds of the FBs correlate strongly with the corresponding solar wind speeds (R = 0.81), which is consistent with Liu, Turner et al. (2016), and the Alfvénic Mach number (M_A) of the shocks on the upstream edges of the FBs was also weakly correlated with the bow shock M_A in the solar wind (R = 0.50).

From Figure 2, all of the FBs were observed between magnetic local times (MLT) of 06:00 and 14:00, which coincides with the location of the ion foreshock under typical Parker spiral solar wind (e.g., Eastwood et al., 2005). The FBs were clustered in the postnoon MLT sector, but there was some observational bias included in that since MMS has not yet completed its 2018/2019 dayside pass, as of the time of writing. All of the FBs were observed within just a few R_E (<5 R_E) of the expected bow shock location; the observations' proximity to the bow shock was somewhat influenced by the selection of the "region of interest" where burst data can be selected along the MMS orbits, which favored coverage near the magnetopause and bow shock. Observational bias in selections of burst data were possibly also a factor in the observations' proximity to the bow shock, since FBs' plasma conditions should be most intense and extreme just before they hit the bow shock. Solar wind speed and IMF strengths for each event are also listed in Figure 2; these 10 FBs formed for a generally average set of solar wind speeds ranging from 207 to 622 km/s with an average of 413 km/s and slightly weaker than average IMF ranging from 2.1 to 6.3 nT with an average of 4.1 nT, the latter of which is consistent with Liu, Angelopoulos et al. (2017). All of these FBs had upstream shock orientations with strong X-GSE components.

Examining the outlier events, the two largest, fastest, and oldest FBs were observed on 5 January 2019 and 8 January 2019, and the two smallest, youngest FBs were observed on 14 December 2018 (03:45 UT) and 30 December 2018. The two largest FBs were both almost 10 R_E in size, consistent with predictions from Omidi et al. (2010). From the estimated ages and distances since formation, these FBs started to form several minutes beforehand between 13 and 18 R_E upstream of their observed locations. Both FBs had similar upstream shock orientations but significantly different expansion speeds, with the younger event (5 January 2019) showcasing a faster expansion speed, 377 km/s, compared to the 221 km/s for the 8 January 2019 event. Contrasting those two largest events, the smallest two events were both less than 2 R_E in size. Both of the smallest events were likely earlier in their formation and evolution process than the rest of the FBs examined here. The 14 December 2018 event was estimated to have formed only less than a minute (51 s) before and 2.9 R_E upstream of its observed location.

Figure 3 shows examples of a large FB (8 January 2019, 9.5 R_E), likely fully developed, and one of the smaller FBs (18 December 2017, 3.3 R_E), likely early in its evolution. The smaller FB was one of the cases where the IMF discontinuity was observed by ARTEMIS and the convection E fields on both sides were not pointed into the discontinuity. Note the differences between these two and the FB from Figure 1 in their durations, core magnetic field intensities and fluctuations, flow deflections, and sheath intensities and durations. Notable similarities include peak temperatures near 1 keV for ions and a few tens of eV for electrons, deep magnetic holes with B < 1 nT in the cores, and flow deflections with a strong Z component in GSE coordinates. The three FBs shown in Figures 1 and 3 offer a good range of characteristics that can be used to identify FBs in future studies.

We closely examined many of the magnetic holes in the cores of 8 of the 10 FBs examined here. These magnetic holes are apparently very small compared to the MMS tetrahedron spacing and/or highly time variable; in several cases, the depth of the hole at the different spacecraft is at very different B or the hole is not even observed by all four spacecraft. From those cases in which the holes are observed clearly by all four spacecraft, we used the minima in |B| with multispacecraft timing analysis to determine the motion of the holes and, with that velocity alongside the time series data, estimate the sizes of the holes. The results of this analysis for 25 of these magnetic holes (|B| < 1 nT) is shown in Table 3. For a typical example of one of these
Table 3
Multispacecraft Timing Analysis of 25 Deep Magnetic Holes (|B| < 1 nT) Observed in 8 of the 10 FBs Examined Here (see Table 1)

| Date YYYY-MM-DD | Time hh:mm:ss.s | Velocity GSE (km/s) | Speed (km/s) | Crossing time (sec) | Size estimate (km) |
|-----------------|-----------------|---------------------|--------------|--------------------|-------------------|
| 2019-01-08      | 11:47:24.6      | [−82.4, 81.2, −89.0] | 146.0        | 0.40               | 58.4              |
| 2019-01-08      | 11:47:36.3      | [−79.7, 154.4, −30.0] | 176.4        | 0.05               | 8.8               |
| 2019-01-05      | 17:39:34.1      | [338.5, 121.6, −89.9] | 370.8        | 0.65               | 241.0             |
| 2019-01-05      | 17:39:35.3      | [40.5, 168.2, 68.7] | 186.1        | 0.41               | 76.3              |
| 2019-01-05      | 17:39:53.5      | [16.4, 113.6, 188.9] | 221.0        | 0.35               | 77.4              |
| 2018-03-30      | 08:41:04.3      | [−72.8, −116.7, 30.4] | 140.9        | 0.40               | 56.4              |
| 2018-03-30      | 08:41:13.2      | [−21.6, −202.1, 73.2] | 216.0        | 0.25               | 54.0              |
| 2018-03-30      | 08:41:18.7      | [−73.8, −151.1, 72.6] | 183.2        | 0.30               | 55.0              |
| 2018-03-30      | 08:41:49.2      | [−152.7, −143.9, −34.4] | 212.6        | 0.65               | 138.2             |
| 2018-03-30      | 08:41:50.0      | [−145.5, −135.7, 49.9] | 205.1        | 0.50               | 102.6             |
| 2018-03-30      | 08:41:52.3      | [−174.0, −177.6, 125.7] | 278.6        | 0.80               | 222.9             |
| 2018-03-30      | 08:41:56.6      | [−325.8, −76.7, −23.0] | 335.5        | 0.32               | 107.4             |
| 2018-03-30      | 08:41:57.3      | [−208.7, −170.0, 149.1] | 307.7        | 0.22               | 67.7              |
| 2018-03-30      | 08:42:09.0      | [−97.8, −143.4, 166.8] | 240.8        | 0.30               | 72.2              |
| 2017-12-18      | 12:35:57.9      | [−242.3, 227.8, 32.7] | 334.2        | 0.35               | 117.0             |
| 2017-12-18      | 12:35:59.8      | [−134.1, −145.0, 138.0] | 240.3        | 0.17               | 40.9              |
| 2017-12-18      | 12:36:03.8      | [−156.0, −48.8, −86.8] | 185.1        | 0.37               | 68.5              |
| 2017-12-18      | 12:36:05.7      | [−207.3, 121.3, −83.3] | 254.3        | 0.40               | 101.7             |
| 2017-12-18      | 12:36:06.5      | [−286.1, −36.4, 30.2] | 290.0        | 0.78               | 226.2             |
| 2017-12-18      | 12:36:08.4      | [−190.4, 256.9, −162.9] | 358.9        | 0.43               | 154.3             |
| 2017-12-18      | 12:55:59.8      | [−253.5, −176.4, 75.9] | 193.7        | 0.90               | 174.3             |
| 2017-12-18      | 12:56:15.7      | [−44.3, −80.9, 225.6] | 243.7        | 0.32               | 78.0              |
| 2017-12-18      | 12:56:38.2      | [−9.5, −100.7, 273.4] | 291.5        | 0.33               | 96.2              |
| 2017-12-18      | 12:56:42.0      | [21.3, 4.9, −9.4] | 23.8         | 0.80               | 19.0              |
| 2017-12-18      | 12:56:15.7      | [−264.6, −180.7, 31.6] | 321.9        | 0.14               | 45.1              |

Note. The magnetic hole from 5 January 2019 at 17:29:25.3 UT is shown as an example in Figure 4.
magnetic holes, see Figure 4; the case shown in Figure 4 has a near-average size and speed compared to the other 24 events but also showcased the deepest minima in field strength (~0.05 nT). Table 2 shows the number of holes observed per FB, with the most having >10 holes in the FB cores and the least revealing only one hole in the FB core. The depths of the deepest minima observed ranged from 0.05 to 0.71 nT. The sizes of the 25 holes examined in detail ranged between 8 and 241 km (average size ~100 km, i.e., subion kinetic scales), and most were moving past the spacecraft at >100 km/s (average speed was ~240 km/s).

5. Summary and Conclusions

This paper reports on the first observations of foreshock bubbles from NASA’s MMS mission. Ten FBs were examined in detail using MMS burst resolution data, which offers the highest resolution yet available to study FBs, and multipoint analysis was employed to establish key characteristics of the events. All 10 events exhibited telltale characteristics of FBs including core plasma with low magnetic field strengths and density, strong flow deflections, superheated plasma, fast magnetosonic shocks on their upstream boundaries, and no compression regions on their downstream boundaries, which is an important characteristic for distinguishing FBs from HFAs. Three of the 10 events did not have convection electric fields pointing back into the IMF discontinuity that was responsible for their formation, which is a necessary condition for the formation of an HFA. These FBs formed under a normal range of solar wind speeds and IMF strengths, and all were observed between 06:00 and 14:00 MLT, consistent with the location of the quasi-parallel foreshock under typical Parker spiral IMF. Considering that two pairs of the 10 events formed within an hour of each other on 2 days, it raises the question as to whether there are certain solar wind conditions that are preferential to FB formation, which should be addressed in future studies.

From multipoint analysis, the sizes of these FBs ranged from 1.1 to 9.9 RE, with an average of 4.4 RE, and the expansion speeds ranged from 139 to 377 km/s, with an average of 257 km/s. These ranges are fully consistent with the sizes and expansion speeds of the six FBs examined by Liu, Turner, et al. (2016) using multipoint THEMIS data, who found sizes ranging from 2 to 15 RE and expansion speeds of 143 to 467 km/s. For the first time, we estimated the age and distance since formation of these FBs, which revealed that they formed between a few (~3) RE and ~20 RE upstream of the bow shock location. That result is consistent with the formation of FBs in global hybrid simulations from Omidi et al. (2010), Karimabadi et al. (2014), and Liu et al. (2018). One new result of this study is that the Alfvénic Mach number of the FB shocks is weakly correlated with the Alfvénic Mach of the bow shock in the solar wind responsible for the formation of the FBs.

Eight of the 10 FBs examined here had deep magnetic holes in their core plasma, where the total magnetic field strength dropped to <1 nT. It is not yet understood what the nature of these magnetic holes is nor whether magnetic reconnection (e.g., Phan et al., 2018; Torbert et al., 2018) might be present in the cores of foreshock transients. An example of one of these magnetic holes is shown in Figure 4, and Table 3 details results from multipoint timing analysis on 25 magnetic holes observed in the cores of several of the FBs examined here. The holes are on electron spatial scales (average size ~100 km) and move past the spacecraft at speeds of ~200 km/s. Five of the foreshock bubbles were associated with significant enhancements of energetic particles (ions ≥100 keV; electrons ≥50 keV), which lends further support to evidence that foreshock transients, such as FBs and HFAs, might be efficient accelerators of energetic particles (e.g., Liu, Angelopoulos et al., 2017; Liu et al., 2017; Liu et al., 2018; Turner et al., 2018; Wilson et al., 2016).
Furthermore, these new results on the nature of FBs also support how particle acceleration in FBs may occur. Each of the 10 FBs presented here involved a large (several Rs) magnetic structure that formed upstream of the bow shock, developed a shock on its upstream edge, and converged upon the bow shock. In those events in which there is magnetic connectivity between the FB (and most importantly the large-amplitude waves and magnetic ramp between the FB’s core and sheath regions) and the bow shock, particles that are “trapped” between the two when the FB forms (or that enter into the trap after formation from either boundary) can enter into a near-ideal system for efficient first-order Fermi acceleration (e.g., Hietala et al., 2012; Liu et al., 2018; Liu, Lu, et al., 2017; Turner et al., 2018).

Over the course of the mission’s two days with apogee ~25 Rs, the four MMS spacecraft have observed hundreds of transient structures in the ion foreshock, many of which have been captured with burst resolution data. From those events, we have presented here 10 cases that were unambiguously consistent with FBs. The multipoint nature of the MMS mission allowed for detailed analysis of the characteristics and geometry of these FBs, which we have shown to be consistent with previous observations and simulations of FBs. Much work remains to develop a full understanding of the 3-D structure, formation, and evolution of FBs, but the MMS observations and cases presented here provide a data set for more detailed observational studies and a baseline against which future simulations can be tested.

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