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Global impacts of a Foreshock Bubble: Magnetosheath, magnetopause and ground-based observations

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Using multipoint observations we show, for the first time, that Foreshock Bubbles (FBs) have a global impact on Earth's magnetosphere. We show that an FB, a transient kinetic phenomenon due to the interaction of backstreaming suprathermal ions with a discontinuity, modifies the total pressure upstream of the bow shock showing a decrease within the FB's core and sheath regions. Magnetosheath plasma is accelerated towards the intersection of the FB's current sheet with the bow shock resulting in fast, sunward, flows as well as outward motion of the magnetopause. Ground-based magnetometers also show signatures of this magnetopause motion simultaneously across at least 7 h of magnetic local time, corresponding to a distance of $21.5R_E$ transverse to the Sun–Earth line along the magnetopause. These observed global impacts of the FB are in agreement with previous simulations and in stark contrast to the known localised, smaller scale effects of Hot Flow Anomalies (HFAs).

1. Introduction

Although Earth's bow shock primarily mediates the solar wind flow forming the magnetosheath, it is also an effective accelerator of energetic particles allowing a portion of those incident to travel back upstream along magnetic field lines forming Earth's foreshock (e.g. the review of Eastwood et al., 2005). The suprathermal backstreaming particles in this region, which is typically spatially extended upstream of the quasi-parallel shock (where the acute shock normal – magnetic field angle $\theta_{Bn} \lesssim 45^\circ$), cause kinetic instabilities within the incident solar wind plasma that can generate ultra-low frequency (ULF) waves (e.g. Hoppe et al., 1981) and in turn scatter particles. The foreshock is highly dynamic, due to variations in the interplanetary magnetic field (IMF) and solar wind conditions, and a number of kinetic phenomena resulting from the interaction of such changes with the quasi-parallel bow shock have been both simulated and observed. These foreshock transients, which include hot flow anomalies (Schwartz et al., 1985), foreshock cavities (Thomas and Brecht, 1988) and the recently discovered Foreshock Bubbles (Omidi et al., 2010), can have significant magnetospheric impacts such as perturbing the magnetopause (Sibeck et al., 1999; Turner et al., 2011) and generating magnetospheric ULF waves (Fairfield et al., 1990; Eastwood et al., 2011; Hartinger et al., 2013).

Foreshock Bubbles (FBs), first predicted by 2D kinetic hybrid simulations (Omidi et al., 2010, 2013; Karimabadi et al., 2014), are transient phenomena caused by the interaction of suprathermal backstreaming ions with a (rotational) discontinuity. Fig. 1 shows an example of schematic of how FBs are thought to form, following Turner et al. (2013). The motion of backstreaming ions, moving along the magnetic field and originating from the quasi-parallel bow shock, may be altered upon encountering a rotational discontinuity (RD). If the IMF cone angle θ_{Bx} (the angle between the IMF and the Sun–Earth line) is increased on the upstream side of this discontinuity, then the motional electric field $\mathbf{E} = -\mathbf{v}_{sw} \times \mathbf{B}$ will be greater and the backstreaming particles will experience increased $\mathbf{E} \times \mathbf{B}$ guiding centre drift $\mathbf{v}_E$ equal to the component of the solar wind velocity perpendicular to the magnetic field (Greenstadt, 1976) i.e. with a component back towards the RD. In addition, the IMF change also results in the backstreaming ions' pitch angles increasing thereby converting some of the ions' motion parallel to the magnetic field into gyromotion. It can be shown (see Appendix A) in the deHoffmann–Teller rest frame of the RD (de Hoffmann and Teller, 1950), where the motional electric field is zero on both sides and thus particle energies are conserved, that the increase in particle pitch angle results in a concentration of suprathermal ion density upstream of the RD. Together with the increase in gyrospeed, the temperature and thermal pressure of the plasma increase upstream of the RD, thereby causing the

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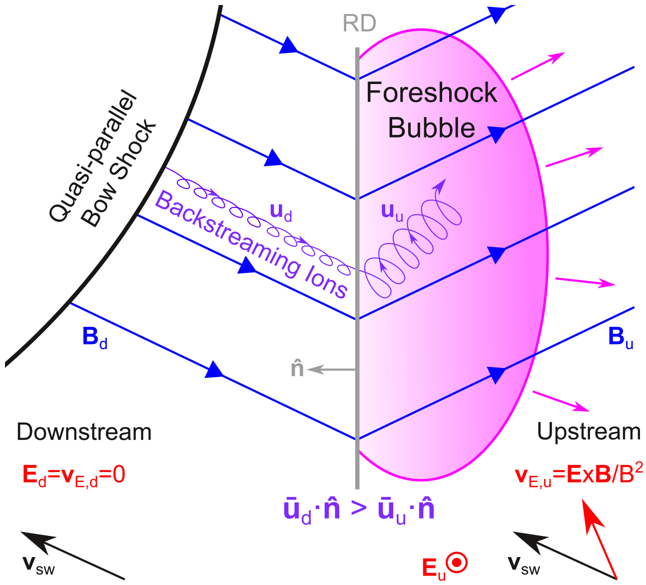

Fig. 1. Example of schematic of Foreshock Bubble formation. A rotational discontinuity (RD, grey) which increases the angle between the IMF (blue) and the Sun–Earth line on its upstream side results in an greater upstream motional electric field $\mathbf{E} = -\mathbf{v}_{sw} \times \mathbf{B}$ (red, out of the page). The motion of backstreaming ions in the foreshock on the downstream side of the RD is altered upstream, with a larger guiding centre drift $\mathbf{v}_E$ (red arrow) back towards the RD as well as increased pitch angle due to the IMF change, resulting in an increase in the suprathermal density and temperature upstream of the RD. This increase in thermal pressure causes a local expansion, forming a Foreshock Bubble. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

thermal plasma to expand. Due to this expansion against the solar wind, a hot core region of depleted density and magnetic field with significant flow deflections forms immediately upstream of the RD followed by a compressed "sheath" region and possibly a shock. This whole structure, which convects with the RD whilst also growing, is what is known as a Foreshock Bubble.

The signatures of an FB in spacecraft observations, however, exhibit many similarities with Hot Flow Anomalies (HFAs): a transient phenomenon in the vicinity of the intersection of the bow shock with a (tangential) discontinuity due to kinetic shock processes (Schwartz et al., 1985, 1988; Thomsen et al., 1988; Paschmann et al., 1988). An HFA consists of a hot depleted core, usually on the side of the current sheet with quasi-parallel bow shock conditions (Omidi and Sibeck, 2007; Zhang et al., 2010; Wang et al., 2013b), sandwiched by compressions and sometimes shocks on both sides due to the lateral expansion of the plasma (Fuselier et al., 1987; Lucek et al., 2004). This structure tracks across the bow shock with a transit velocity given by (Schwartz et al., 2000)

$$\mathbf{v}_{trans} = \frac{\mathbf{v}_{sw} \cdot \mathbf{n}_{DD}}{\sin^2 \theta_{bs,DD}} (\mathbf{n}_{DD} - \cos \theta_{bs,DD} \mathbf{n}_{bs}) \quad (1)$$

where $\mathbf{n}_{bs}$ and $\mathbf{n}_{DD}$ are the normals to the bow shock and directional discontinuity (DD) respectively, $\theta_{bs,DD}$ is the angle between these and $\mathbf{v}_{sw}$ is the solar wind velocity. Schwartz et al. (2000) summarised a set of conditions for the formation of HFAs, which required that the motional electric field points into the discontinuity on at least one side and that the transit speed of the discontinuity $\mathbf{v}_{trans}$ is much slower than the gyrospeed of ions reflected at the bow shock. Furthermore, they showed that HFAs preferentially occur if the discontinuity is tangential in nature (with no magnetic flux threading the current sheet), exhibits a small jump in magnetic field strength and quasi-perpendicular bow shock conditions are present on at least one side (with the upstream/trailing edge being favourable).

Turner et al. (2013) presented the first observational evidence of FBs upstream of Earth's bow shock, comparing and constrasting their signatures to HFAs. They developed a set of identification criteria to distinguish between the two phenomena:

1. HFA formation requires the discontinuity intersects with the bow shock; FB formation does not.
2. HFA cores form on the quasi-parallel side of the discontinuity or centred on the discontinuity if perpendicular/parallel on both sides (Omidi and Sibeck, 2007; Zhang et al., 2010; Wang et al., 2013b); FB cores should only form upstream of the discontinuity.
3. HFAs tend to be bounded on both sides by compression regions except theoretically when the ratio of incident suprathermal to solar wind ions $\gtrsim 65\%$ (Thomsen et al., 1988), though the strength of the compressions is often asymmetric with the upstream one typically being much larger (e.g. Paschmann et al., 1988); FBs observed from within the foreshock should be bounded by a compression region or shock on the upstream side only.
4. HFAs require the electric field point into the discontinuity on at least one side; FBs do not.
5. HFA boundaries can exhibit a range of orientations (Paschmann et al., 1988) though are often close to that of the discontinuity due to the lateral expansion of plasma; FB boundary normals observed from within the foreshock should be oriented predominantly sunwards.
6. HFAs move along the bow shock with the discontinuity intersection; FBs should convect with the solar wind.
7. HFAs have transverse sizes up to $\sim 4R_E$ (Facskó et al., 2009) and their features are thought to diminish within $\sim 5R_E$ of the bow shock (Wang et al., 2013a; Archer et al., 2014); FBs might have transverse scales comparable with the size of the quasi-parallel bow shock, $\sim 10R_E$ or more (Omidi et al., 2010).

HFAs are known to have fairly localised impacts which track across the magnetosphere, including flow deflections in the magnetosheath, distortions of the magnetopause over $\sim 5R_E$, and travelling convection vortices in the ionosphere (Sibeck et al., 1999; Eastwood et al., 2008; Jacobsen et al., 2009; Archer et al., 2014). In contrast, the impacts of FBs are predicted by simulations to be global in scale (Omidi et al., 2010): the arrival of the structure at the bow shock causes reversal of the magnetosheath flow back towards the FB core due to its reduced pressure compared to the magnetosheath plasma, in turn resulting in large scale outward motion of the magnetopause. Hartinger et al. (2013) presented observations of the magnetospheric response to an FB at a single spacecraft location, consisting of a rarefaction (due to the reduced dynamic pressure of the FB core) and then compression (due to the enhanced dynamic pressure of the FB sheath and shock) of the magnetospheric magnetic field and accompanied by Pc5 (2–7 mHz) ULF wave activity in the perpendicular components. However, the scale size of the magnetospheric impact of FBs has yet to be determined observationally. Since Pc5 ULF waves play a role in the mass, energy and momentum transport within the Earth's magnetosphere e.g. accelerating electrons in auroral regions (Lotko et al., 1998) and the radiation belts (Claudepierre et al., 2013; Mann et al., 2013), it is important to understand the impacts of drivers of magnetospheric dynamics such as FBs. In this paper we present observationally, for the first time, the response of the magnetosheath and magnetopause to an FB, using multipoint spacecraft observations in conjunction with ground magnetometer measurements. We demonstrate the global nature of the transient's impact, in agreement with the suggestion of previous simulations and in stark contrast to the known localised effects of HFAs.