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EVIDENCE FOR A SHOCK IN INTERSTELLAR PLASMA: *VOYAGER 1*

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ABSTRACT

Voyager 1 (*V1*) observed electron plasma oscillations preceding a jump by a factor of 1.4 in the magnetic field intensity B near the end of 2012. The frequency of the electron plasma oscillations gives an electron density $n_e = 0.05\ \mathrm{cm}^{-3}$, which implies that *V1* was immersed in plasma from the interstellar medium. The last day on which plasma oscillations were observed is day 332, 2012, and the jump in the B was centered on day 335, 2012 after a data gap in the wave data. The close association between the electron plasma oscillations and the jump in B suggests a causal connection, such as that frequently observed between electron plasma oscillations and interplanetary shocks at 1 AU. Based on the observed parameters and the smooth profile of $B(t)$, the jump in B appears to be associated with a weak, subcritical, laminar, low beta, quasi-perpendicular, resistive, collisionless shock. However, the width of the jump is of the order of 10^4 times that expected for such a stationary shock at 1 AU. The large width of the jump in B might be the result of differences between the structure of shocks in the interstellar medium and the plasma near 1 AU. Alternatively, the subcritical resistive shock might have decayed during a few days after producing the plasma waves, leaving a broad profile in $B(t)$ without significantly changing ambient parameters. Another possibility is that the jump in B is a pressure wave.

Key words: local interstellar matter – magnetic fields – Sun: heliosphere

1. INTRODUCTION

During 2012 *Voyager 1* (*V1*) entered a new region characterized by a depletion of the anomalous cosmic rays and termination shock particles as well as a strong, very uniform strong magnetic field $\boldsymbol{B}$ (Stone et al. 2013; Krimigis et al. 2013; Webber & McDonald 2013; Burlaga et al. 2013). Gurnett et al. (2013) observed electron plasma oscillations in the new region, with the direction of the wave vector $\mathbf{k}$ parallel to the electric field vector $\boldsymbol{E}$ directed along $\boldsymbol{B}$, as expected if the oscillations were excited by a magnetic field aligned electron beam. From the frequency of the waves, Gurnett et al. (2013) derived the ambient density, $n_e = 0.08\ \mathrm{cm}^{-3}$, which is much higher than one expects to observe in the heliosheath (Richardson & Wang 2012) but comparable to expected interstellar densities, indicating that *V1* was in interstellar plasma.

The interstellar plasma is disturbed by its interaction with the nearby heliosheath, which can drape the magnetic field lines along the heliopause and possibly produce gradients in the nearby interstellar plasma density (Cranfill 1971). Based on remote radio wave observations, Gurnett et al. (1993) suggested that a ramp of increasing density exists in the interstellar medium just ahead of the heliopause, and Gurnett et al. (2013) confirmed the existence of this ramp. Fuselier & Cairns (2013) suggested a depletion layer adjacent to the heliopause, which is consistent with the density ramp. Model 2 in Figure 4 of Zank et al. (2013) shows a ramp of increasing density in the range of the observed densities. This model predicts a smooth transition in which a marginally super-fast magnetosonic flow far beyond the heliopause decelerates to a sub-fast flow without a bow shock.

Observations in the solar wind at 1 AU have shown that electron plasma oscillations often occur ahead of interplanetary shocks (e.g., Gurnett et al. 1979; Kennel et al. 1982). The oscillations are produced by an electron beam accelerated at the shock (Scarf et al. 1971; Filbert & Kellogg 1979). Electron plasma oscillations have also been observed ahead of bow shocks, at Jupiter (Scarf et al. 1979), Saturn (Gurnett et al. 1981; Scarf et al. 1982), Uranus (Gurnett et al. 1986), and Neptune (Gurnett et al. 1989). Electron plasma oscillations were also detected in situ and upstream of an interplanetary shock at 46 AU (Kurth & Gurnett 1993) at the termination shock (Gurnett & Kurth 2005, 2008).

Radio waves from beyond the termination shock were observed remotely by Gurnett et al. (1993), who suggested that they were produced by a shock associated with a Global Merged Interaction Region (GMIR) propagating at ≈ 40 km s^{-1}. Whang & Burlaga (1994) discussed how a GMIR shock interacts with the termination shock, propagates through the heliosheath, and interacts with the heliopause to produce a shock in the interstellar medium. Such shocks were described more by the global time-dependent models of Zank & Müller (2003), and Washimi et al. (2011), who found that they were weak shocks.

The aim of this Letter is to discuss a jump in B and a corresponding small change in the direction of $\boldsymbol{B}$ that was observed by the magnetometer experiment on *V1* in the new region during 2012 and its relationship to the electron plasma oscillations observed by the Plasma Wave Science (PWS) instrument prior to the arrival of the jump in B. We present evidence that the jump in B might be associated with a subcritical shock, and we consider other interpretations of the data.

2. RELATIONSHIP BETWEEN THE JUMP IN MAGNETIC FIELD STRENGTH AND ELECTRON PLASMA OSCILLATIONS

A relationship between the magnetic field and electron plasma oscillations was observed by *V1* between day 290 and 350, 2012 (Figure 1). A jump by a factor of 1.4 in B was observed between ≈day 330 and ≈day 340 (Figure 1(b)), and it was associated with a small change in the azimuthal direction of $\boldsymbol{B}$ (Figure 1(c)). The PWS instrument on *V1* observed electron plasma oscillations near 2.2 kHz before the arrival of the jump in B, from

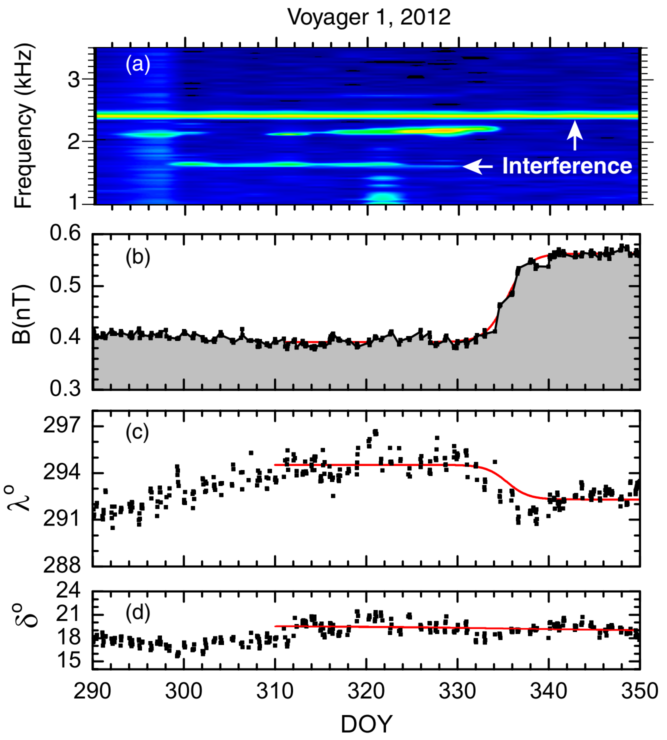

Figure 1. Observations of electron plasma oscillations by the PWS experiment on *Voyager 1* during 2012 (a). These oscillations were observed just ahead of the jump in hour averages in the magnetic field intensity B (b), and an associated change in the azimuthal angle λ (c). There was no significant change in the elevation angle δ across the jump in B (d).

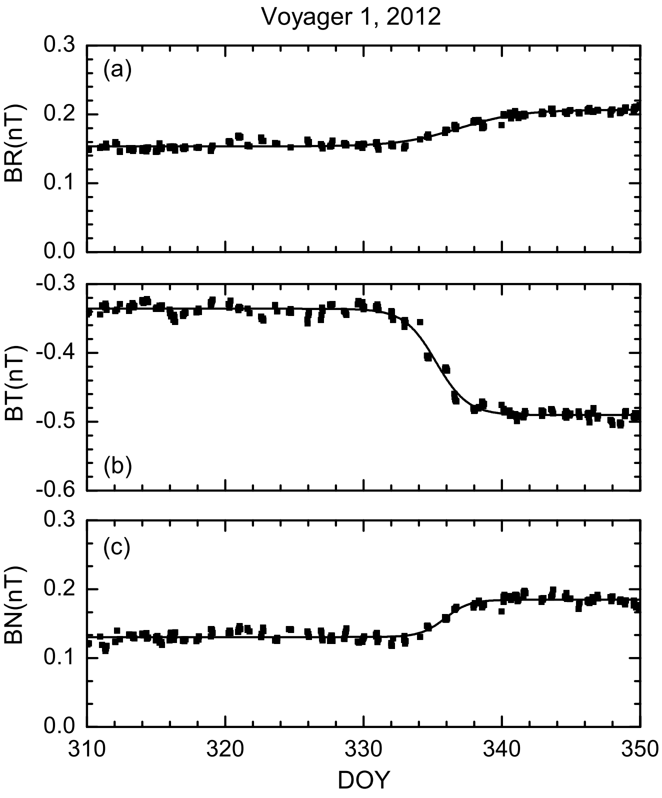

Figure 2. R, T, and N components of hour averages of the magnetic field B from the 310 to day 350, 2012 are plotted in (a), (b), and (c), respectively.

day 297 to day 332 (Figure 1(a)). The plasma oscillations were acquired observed at the rate of one 48 s average approximately twice a week. The frequency and amplitude characteristics of this emission are such that they are not reliably detected in the PWS spectrum analyzer data that are acquired every 16 s. This emission falls between the peak response frequencies of the 1.78 and 3.11 kHz channels. The last frame containing electron plasma oscillations was observed at 07:54 on day 332, and the next frame (which contained no electron plasma oscillations) was observed on day 335, which is in the middle of the jump in B. Thus, there is a close temporal relationship between the electron plasma oscillations and the jump in B, suggesting a causal relationship between the two features.

Since the group speed of electron plasma oscillations is zero, the waves are observed locally, where they are produced. The frequency of these oscillations is $f = 8980\ n_e{}^{1/2}$ Hz, where n_e is the local electron density in cm^{-3}. Since the frequency of the electron plasma oscillations in Figure 1 is 2.2 kHz just ahead of the jump in B, the electron density there is $n_e = 0.05\ \mathrm{cm}^{-3}$, and charge neutrality of the plasma implies that the proton density is also approximately $0.05\ \mathrm{cm}^{-3}$.

Electron plasma oscillations similar to those in Figure 1 but corresponding to a density of $\sim 0.08\ \mathrm{cm}^{-3}$ were observed by Gurnett et al. (2013) in 2012 April–May, with the PWS on *V1*. These authors noted that densities in the range 0.05–0.01 cm^{-3} are representative of densities in the interstellar medium, and much larger than the densities observed in the heliosheath at 101 AU by the plasma instrument on *Voyager 2* (Richardson & Wang 2012). Gurnett et al. (2013) concluded that *V1* was observing plasma of interstellar origin. Model 2 of Zank et al. (2013) produces densities 0.05–0.01 cm^{-3} in the interstellar plasma near the heliopause.

3. PHYSICAL NATURE OF THE MAGNETIC JUMP

Let us consider the possibility that the jump in B observed by *V1* from day ≈330 to ≈day 350, 2012 is associated with a shock. This interpretation implies that the temperature, density, and entropy should increase across the jump in B, and the fluid parameters before and after the shock should satisfy the Rankine–Hugoniot equations. Since we have no observations of the fluid parameters during the jump, we cannot unambiguously identify the nature of the jump. Instead, we shall consider whether the magnetic field and electron plasma wave observations are consistent with the passage of some kind of a shock.

A fit of the magnetic field intensity $B(t)$ in Figure 1 to the sigmoidal (Boltzmann) curve $B(t) = B2 + (B1 - B2)/(1 + \exp\ [(t - t_0)/\tau)]$ (where $B1$ and $B2$ are the magnetic field intensities before and after the jump, t is the time in days and t_0 is the center time of the symmetric distribution) gives an excellent fit ($R^2 = 0.99$) with the parameters $B1 = 0.392 \pm 0.001$ nT, $B2 = 0.562 \pm 0.002$ nT, $t_0 = 335.43 \pm 0.07$ days, and $\tau = 1.18 \pm 0.06$ days. Note that the center of the jump is on day $t_0 = 335.43$, when no plasma oscillations were observed. Another view of the magnetic field profile is shown in Figure 2, which is a plot of the components of the magnetic field $\boldsymbol{B}$ in the *RTN* coordinate system, in which the R-component is radially away from the sun, the N-component is directed northward in the direction of the solar rotation axis, and the T-component completes the orthogonal triad.

A striking characteristic of the curves in Figures 1 and 2 is their very smooth nature, which is quite unlike the magnetic field at termination shock observed by *Voyager 2* (Burlaga et al. 2005). Such a smooth profile is observed for a subcritical resistive laminar shock in the solar wind near 1 AU (Mellott &

Greenstadt 1984). Let us consider such a shock for the parameters appropriate for interstellar plasma just beyond the heliopause, assuming that it is a simple proton–electron plasma. The density obtained from the observed electron plasma oscillations is 0.05 cm^{-3}. Since the ratio $B2/B1 = 1.4$, the jump in B is consistent with a weak, magnetically dominated shock. Although the temperature of the interstellar medium is approximately 6000°, the temperature near the heliopause is higher. For example, the three models considered by Zank et al. (2013; an extension of Zank et al. 1996) give a temperature of ≈20,000° for interstellar plasma near the heliopause. For this temperature, the upstream plasma β is $0.23 < 1$, and the upstream sound speed is $V_S = 17$ km s^{-1}. Since the upstream Alfvén speed is $V_A = 38$ km s^{-1}, $V_A > V_S$ and $(V_A/V_S)^2 = 5 \gg 1$, which is further evidence of a subcritical resistive shock (Kennel et al. 1985). The magnetoacoustic speed of the ambient medium is 42 km s^{-1}. The estimated speed of ≈40 km s^{-1} by Gurnett et al. (2013) is consistent with a weak shock. Since a shock at 1 AU is subcritical when its magnetoacoustic Mach number is less than ≈2, the speed of the shock that we are considering is $V_{\rm sh} < 84$ km s^{-1}. A subcritical resistive shock with ${V_S}^2/{V_A}^2 = 5$ is a quasi-perpendicular shock (see the Fredericks diagram in Kennel et al. 1985, p 17). Pickup protons should be included explicitly, and the corresponding Fredericks diagram should be calculated for problems related to shocks in the interstellar plasma as well as for shocks beyond ≈ 20 AU, where pickup protons provide the dominant contribution to the pressure (Burlaga et al. 1996). To some extent, their presence is implicit in the temperature computed from MHD models that include pickup protons.

A fit of the sigmoidal function to each of the curves in Figure 2 gives the components of $\boldsymbol{B}$ before the shock ($BR1 = 0.896$ nT, $BT1 = 0.040$ nT, and $BN1 = 0.243$ nT) and the components after the shock ($BR2 = 0.207$ nT, $BT2 = -0.490$ nT, $BN2 = 0.185$ nT). The shock normal can be obtained from the co-planarity theorem, which states that $\boldsymbol{B1}$, $\boldsymbol{B2}$, and $\boldsymbol{n}$ are in the same plane (Colburn & Sonett, 1966). The co-planarity theorem gives the shock normal $\boldsymbol{n} = (\boldsymbol{B1} \times \boldsymbol{B2}) \times (\boldsymbol{B1} - \boldsymbol{B2})/|(\boldsymbol{B1} \times \boldsymbol{B2}) \times (\boldsymbol{B1} - \boldsymbol{B2})|$, where $\boldsymbol{B1}$ and $\boldsymbol{B2}$ are vectors before and after the shock, respectively, with the components given above; × is the vector product. The components of these vectors derived from the fits to the curves in Figure 1 give $\boldsymbol{n} = (0.89, 0.40, 0.24)$. The angle between the shock normal $\boldsymbol{n}$ and the radial direction (1, 0, 0) is ≈28°, indicating that the shock is propagating close to the radial direction. The angle between $\boldsymbol{n}$ and the upstream magnetic field direction $\boldsymbol{B1}$ is ≈85°, showing that the shock is a quasi-perpendicular shock. Such a shock is well within the resistive (as opposed to dispersive) shock region of the Fredericks diagram in Kennel et al. (1985) when ${V_S}^2 \approx 0.1 \times {V_A}^2$, which is the case for the observations we have been discussing. For a perpendicular shock $N2/N1 = B2/B1 = 1.4$, consistent with a weak shock.

The fits of the smoothly varying Boltzmann distributions to the hour averages of the magnetic field strength profile $B(t)$ in Figure 1 and the BR, BT, and BN components of B in Figure 2 are very good fits to the data, with R^2 equal to 0.99, 0.96, 0.99, and 0.93, respectively, indicating that the shock is laminar on the scale of the shock itself. Let us now consider the variations of the 0.48 s averages on the smallest scales for which we have continuous high-quality (i.e., carefully edited) observations. The number of successive 0.48 s averages in each interval, varies from 548 to 18,057, as shown in Figure 3(d). The corresponding durations of the intervals with continuous data range from 363 s = 0.07 hr to 8667 s = 2.41 hr, as can be seen in Figure 3(e). Clearly, there are many data gaps on various scales, which is why we choose to look at the intervals of continuous data. Initially, the intent was to compute power spectra for each interval. However, it turns out that the fluctuations are very close to the noise level (0.003 nT) and digitization level (0.004 nT) of the instrument (Behannon et al. 1977). The standard deviation SD, skewness S, and excess kurtosis K for each of these intervals are shown in Figures 3(a)–(c). The average value of the standard deviation $\langle {\rm SD} \rangle = 0.103 \pm 0.001$ from day 236 to day 350. The average skewness $\langle S \rangle = 0.04 \pm 0.11$ and the average kurtosis $\langle K \rangle = 0.07 \pm 0.14$ are consistent with zero, i.e., consistent with Gaussian noise. Thus, the fluctuations are very small even at the smallest scales, and the shock is nearly laminar at these scales as well, within the uncertainties of the measurements. These results suggest that turbulence is not the dominant dissipation mechanism in this shock, assuming it a shock.

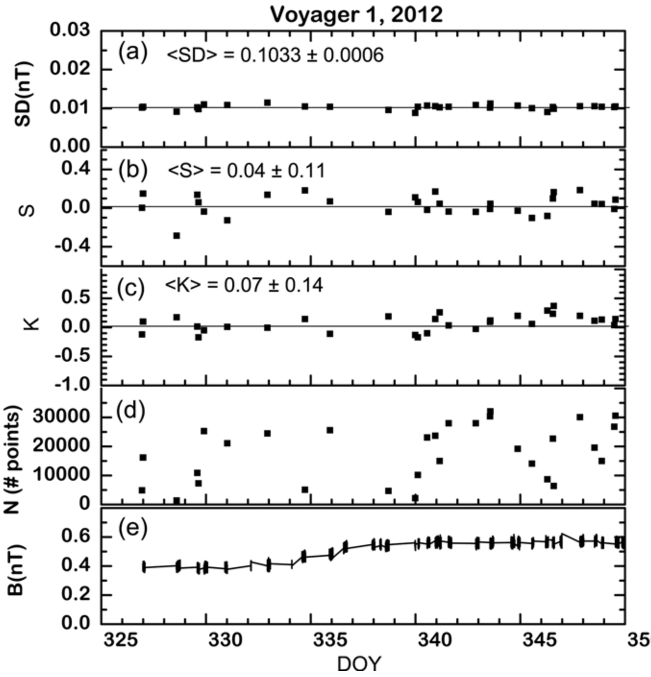

Figure 3. Observations of the 0.48 s averages of B connected by straight lines across the data gaps (d). The data were divided into a number of intervals, each containing nearly continuous observations of 0.48 s averages of B. The number of 0.48 s averages in each of these intervals is plotted as a point in (d). The skewness and kurtosis of the points in each interval are plotted in panels (b) and (c), respectively. The average value of the skewness and kurtosis is zero, consistent with a Gaussian distribution on average in these intervals. The standard deviation for each of these intervals from day 326 to day 350 is plotted panel (a). The fluctuations of the 0.48 s averages is comparable to the level of the instrument noise.

The *V1* observations discussed in the paragraphs above are consistent with a subcritical, low β, laminar, resistive, quasi-perpendicular shock at 1 AU (Kennel et al. 1985; Mellott 1985; Parks 2004). Although these results are very suggestive, a generalization of the calculations describing the internal structure of such a shock at 1 AU to a shock in the interstellar medium, where interactions between pickup protons and a complex mixture of charged and neutral particles are present, is needed.

The results and references of the preceding paragraphs indicate that our observations are analogous to those of a subcritical, resistive shock at 1 AU. Such shocks have been observed in 2% of Earth's bow shock crossings (Formisano et al.

1971). The shock thickness is of the order of two to four times the ion inertial length at 1 AU (Greenstadt et al. 1975). Since the ion inertial length in the plasma that we have been considering is ≈1000 km, we might expect that the magnetic jump that we identified would have a scale of the order of 2000–4000 km. Such a thin shock, with a speed of approximately 80 km s^{-1} and propagating through a stationary medium, would move past *V1* (which is moving relative to the Sun at 17 km s^{-1}) in 30–60 s.

The estimated shock thickness of resistive subcritical shocks, based on observations made near 1 AU and a particular mechanism for producing resistivity, presents a problem with the interpretation of our observations as a shock. Since the sigmoidal fit to the shock profile $B(t)$ has no well-defined beginning and end time, the jump in B (width of the shock) may be defined as the interval containing 80% of the jump in B, which is $w = 4.4\,\tau = 5.1$ days. Alternatively, inspection of the graph of $B(t)$ shows the first and last points of the jump occurred near ≈day 331.5 and ≈day 340.2, respectively, which means that it moved past *V1* in ≈8.7 days. In either case, the jump in B moved past *V1* during an interval of the order of five days, 4×10^5 s, which is $\approx 7 \times 10^3$ times greater than the time for a shock with thickness 4000 km to move past *V1* (≈60 s). If the ambient medium were moving toward the sun at 20 km s^{-1} (Krimigis et al. 2011), the passage time would be slightly less than ≈60 s. Similarly, a shock propagating at a large angle with respect to the radial direction (which is unlikely, given the normal that we computed) would move past *V1* in slightly greater time. Such kinematic effects cannot explain why the passage time of the jump in B is $\approx 10^4$ times larger than that expected for a shock at in the solar wind 1 AU.

There are at least three ways to explain why the jump in B is so broad.

1. The jump observed by *V1* might be a manifestation of the passage of a kind of shock that is analogous to a stationary subcritical low-beta quasi-perpendicular shock at 1 AU, where resistivity generated by the ion sound instability gives a thin shock (Galeev 1976). The broad width of the jump might indicate that the dissipation mechanism in the interstellar medium is different from that at 1 AU. One should use a Fredericks diagram specifically calculated for interstellar plasma. At the current location of *V1*, where interstellar electrons are observed, the plasma is complex, containing pickup protons and neutral particles with a density exceeding that of the protons. Pickup protons significantly alter the structure of shocks beyond 20 AU, including planetary bow shocks, the termination shock, and interstellar shocks. The role of ambipolar diffusion and the associated drag force acting on ions and neutrals should be assessed in interstellar plasma. Pickup protons and interstellar neutrals might produce a thicker shock. Cairns & Zank (2002) suggested that superthermal electrons can be produced by lower-hybrid waves generated by pickup ions created from hot secondary neutrals in the inner heliosheath as they propagate into the outer heliosheath and charge exchange with shocked plasma
2. The jump in B might be a pressure wave. For example, Burlaga (1983) showed that that corotating pressure waves exist between 2 AU and 4 AU. These waves form by the kinematic steepening of corotating streams near 1 AU, and persist as an independent entity when the streams have decayed. In this case, the qualitative agreement between the observed parameters and the magnetic field strength profile with those predicted for a subcritical resistive shock would be a coincidence.
3. The shock might have decayed into a pressure wave, resulting in a structure that is considerably broader than the shock. The decay of the shock must have occurred on a timescale of the order of a day, since plasma waves (which were presumably formed by a beam driven by shock) were observed just before the jump in B, but not after it.

4. SUMMARY AND DISCUSSION

Electron plasma oscillations were observed by PWS experiment on *V1* from ≈day 297, 2012 to ≈day 332, 2012, just before an increase in B by a factor of 1.4. The large jump in B that we have described occurs in a medium containing interstellar electrons. We find that the density derived from the frequency of the electron plasma oscillations just ahead of the jump in B is 0.05 cm^{-3}, similar to that observed by Gurnett et al. (2013), 0.08 cm^{-3}, a few months later in the same region. Such densities are much larger than expected for heliosheath plasma, but they are comparable to estimates of the interstellar plasma density, indicating that *V1* is immersed in nearby interstellar plasma.

Our measurements are consistent with the jump in B corresponding to a subcritical, low β, quasi-perpendicular, laminar, resistive shock. However, the width of the shock is much larger than the shocks observed at 1 AU. It is possible that the mechanism that produces dissipation in the interstellar shock that we have considered might be different than that in the shocks observed at 1 AU. Alternatively, the shock might not be stationary, and we might be observing it in a relaxed, non-stationary state. The jump in B is might be a pressure wave, but this leaves open the question of what caused the electron plasma oscillations observed just ahead of the jump in B.

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