Fast Shocks at the Edges of Hot Diamagnetic Cavities Upstream From the Earth's Bow Shock

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Recently, several interesting events, described as hot expanding diamagnetic cavities, have been observed upstream from the earth's bow shock using the ISEE 1 and 2 spacecraft. It has been suggested that fast shocks may form at the edges of some of these events because of the rapid expansion of the cavities. We have examined plasma density, temperature, velocity, and total field changes across the edges of several events and find these changes to be qualitatively consistent with the presence of shocks there. The presence of flat-topped electron distributions and occasional electron beams at and downstream from the edges provides additional evidence for shocks. Plasma wave observations also show shocklike electrostatic noise at the edges of several events. We conclude that the edges of diamagnetic cavity events are often shocks, with a range of shock strengths similar to that observed in the interplanetary medium. The range of shock strengths may be the result of different convection and/or expansion speeds of the cavities; these convection and/or expansion speeds in turn may ultimately be related to the age of the cavities.

INTRODUCTION

An interesting but apparently rare class of phenomena occurring upstream from the earth's bow shock has recently been reported. The observed structures have been described variously as hot, expanding diamagnetic cavities [Thomsen et al., 1986] or active current sheets in the solar wind [Schwartz et al., 1985]. A survey of data from the first two ISEE 1 and 2 solar wind seasons (October-December 1977 and August-December 1978) produced only eight events [Thomsen et al., 1986], and one event has been reported from the Active Magnetospheric Particle Tracer Explorers (AMPTE) UKS data [Schwartz et al., 1985]. Other possible candidates have been identified in the ISEE data since these studies; nevertheless, these expanding diamagnetic cavities remain relatively rare events.

Some of the typical plasma and magnetic field characteristics of the hot diamagnetic cavity events are illustrated in Figure 1, which displays data from one of the events described by Thomsen et al. [1986]. Plasma observations in the top three panels of Figure 1 and elsewhere in this paper are from the Los Alamos/Garching fast plasma experiments (FPEs) on ISEE 1 and 2 [Bame et al., 1978]. Independent of data rate, the FPE measures a two-dimensional electron and a two-dimensional ion distribution function (16 energies x 16 angles) in 3 s. Since this was a high data rate interval, the data points in Figure 1 are separated by 3 s. The magnetic field observations in the bottom panel of Figure 1 and elsewhere in this paper are from the University of California, Los Angeles (UCLA), triaxial flux gate magnetometers on the ISEE 1 and 2 spacecraft [Russell, 1978]. These instruments make a vector magnetic field measurement 16 times each second in high data rate.

The duration of the event shown in Figure 1 is about 1 min. Two-spacecraft timing between ISEE 1 and 2 indicates that this structure convected past the spacecraft more or less with the solar wind; thus the 1-min duration corresponds to a scale size of a few earth radii. The central region (diamagnetic cavity) shows a reduction in the total magnetic field below the ambient solar wind value. Magnetic enhancements occur on both sides of the diamagnetic cavity (between the two sets of vertical dashed lines) as well as within the interior of the cavity (from 0609:45 to 0610:10 UT). The plasma density profile across the event is similar to the magnetic profile except there is no interior density enhancement. Inside the diamagnetic cavity the bulk velocity is depressed, and the electron temperature is very high when compared to the ambient solar wind. Other interesting features of the event, but not show in Figure 1, are a large azimuthal flow deflection (φ ~ 40°) and a large ion temperature inside the cavity (T_i = 10^7 K).

The other events reported by Thomsen et al. [1986] for the most part have features similar to those in Figure 1. However, some events show plasma and magnetic field enhancements only on their trailing (sunward) side. Primarily because of the large ion temperature inside the cavity, these hot diamagnetic cavities are not in pressure balance with the surrounding solar wind plasma and are thus believed to be expanding [Thomsen et al., 1986]. The estimated expansion velocity of the event studied by Schwartz et al. [1985] was ~50-75 km/s. This expansion speed is comparable to the typical value of the fast magnetosonic speed in...
Two-spacecraft timing between ISEE 1 and 2 indicates that in Figure 1 should thus contain shocked solar wind plasma. The event in Figure 1 is convecting more or less with the solar high-field regions between the two sets of vertical dashed lines (0610:48 UT) which we tentatively identify as fast shocks. The plasma within these high-field regions is quite different from that in the solar wind that fast shocks form at the edges of the events [Schwartz et al., 1985; Amata et al., 1985; Lepine et al., 1985].

The purpose of this paper is to present evidence supporting the suggestion that fast shocks occur at the edges of at least some of the expanding diamagnetic cavities observed by ISEE 1 and 2. This evidence consists of plasma and total magnetic field changes across the edges, detailed examination of ion and electron velocity distributions, and plasma wave observations at the edges of the events. Apparent differences in shock strengths at the edges of the different events further suggest that the relative convection and/or expansion speeds may vary from event to event and these different convection and/or expansion speeds may in turn be related to the age of the cavities.

**Observations**

**Plasma Moments and Magnetic Field**

The diamagnetic cavity in Figure 1 is flanked on both sides by high-field regions. The plasma within these regions is quite distinct from that within the diamagnetic cavity itself; it appears to be ambient solar wind which has been compressed by the expanding high-pressure cavity [Thomsen et al., 1986]. It is the outer edges of these high-field regions (0609:30 and 0610:48 UT) which we tentatively identify as fast shocks. The high-field regions between the two sets of vertical dashed lines in Figure 1 should thus contain shocked solar wind plasma. Two-spacecraft timing between ISEE 1 and 2 indicates that the event in Figure 1 is convecting more or less with the solar wind. Thus the transition from upstream to downstream across the leading (earthward) edge of the event (0609:30 UT) should have the characteristics of a fast forward shock, and the transition from downstream to upstream across the trailing (sunward) edge should have the characteristics of a fast reverse shock.

Across the earthward edge of the event in Figure 1 (0609:30 UT), both the magnetic field and the electron density increase abruptly by a factor of 3. A similar but opposite change in the magnetic field and electron density is seen across the sunward edge (0610:48 UT). The spatial scales for the magnetic field increases along the direction of convection of the event are ~260 km for the earthward edge and ~160 km for the sunward edge, assuming that these edges convect past the spacecraft with the upstream solar wind speed.

On the other hand, the electron bulk velocity and temperature do not appear to change very significantly across the edges of the event in Figure 1. One would expect certain changes in these parameters if the edges are indeed shocks (i.e., the velocity and temperature should both rise across the earthward edge, while the temperature should decrease and the velocity increase across the sunward edge). However, if the shocks are quite weak, as we argue on the basis of additional evidence to be presented below, then it is very possible that those changes would be very small. For example, electron temperature increases at weak interplanetary shocks are sometimes not detectable [Feldman et al., 1983b]. The temperature and velocity changes at these events might thus be smaller than the uncertainties associated with the measurements shown in Figure 1. In particular, there is an inherent uncertainty in determining bulk flow velocities in the solar wind using electron measurements. (A rough estimate of the uncertainty in the bulk velocities so derived is about ±30 km/s and is reflected in the error bar on the first velocity point in Figure 1.) In addition, both the bulk velocity and temperature measurements across the edges may be time aliased. Hence we regard the electron temperature and velocity estimates recorded in Figure 1 to be rather neutral evidence regarding the question of the nature of the edges of the diamagnetic cavity event.

The ion moments, on the other hand, clearly change across at least the sunward edge of the event. These changes in the ion moments are not distinguishable in the FPE ion data because this instrument does not accurately resolve relatively cold ion distributions such as those in the solar wind and within the high-field regions at the edges of the event. Fortunately, however, ISEE 1 remained in the sunward high-field region long enough to obtain an ion distribution with the separate solar wind ion experiment [Bame et al., 1978]. That experiment measures a two-dimensional ion velocity distribution (4 × 14 energies at eight angles in a 21° area centered on the sun direction) in ~3 spacecraft spins (~9 s) in high data rate.

Ion velocity distributions obtained by this instrument in the sunward high-field region and in the solar wind after the event are compared in Figure 2. Angular information has been removed from each distribution in Figure 2 by averaging over the eight angles measured in each spacecraft spin. Since the averaging was done over a small azimuthal range, the distributions in Figure 2 are similar to one-dimensional cuts along the earth-sun line.

The spectrum starting at 0611:57.6 UT shows the nominal solar wind ion distribution. (The plasma parameters did not
The plasma and field changes in Table 1 with the presence of shocks at the edges of the event in Figure 1. The electron and ion density and temperature and the total magnetic field must increase from upstream to downstream across a fast shock. For weak shocks, the scale length of the magnetic field increase along the normal to the shock is of the order of $c/\omega_{pe}$, where $c$ is the speed of light and $\omega_{pe}$ is the ion plasma frequency [Russell et al., 1982]. In the spacecraft frame the bulk velocity increases from upstream to downstream across a forward shock, and the bulk velocity decreases from upstream to downstream across a reverse shock.

As shown in Table 1, the changes in the plasma and field quantities across the edges of the event are qualitatively consistent with the presence of fast shocks there. The total magnetic field and electron density increase by a factor of 3 across the edges. The scale lengths of the magnetic field changes across the earthward and sunward edges are 262 and 160 km, respectively, compared to $c/\omega_{pe} = 130$ km for the event. (Note that the scale lengths of the magnetic field increases were determined along the convection direction of the event and not along the shock normal and thus represent upper limits on the actual scale lengths of the shocks.)

The ion temperature increase and the velocity decrease from upstream to downstream across the sunward edge are consistent with the heating and slowing expected across a reverse shock. The electron temperature and velocity changes across both edges are inconclusive for this event because of uncertainties in the measurements. Because three-dimensional velocity measurements were not available, the supersonic to subsonic transition expected across shocks cannot be confirmed. For the same reason, Rankine-Hugoniot relations cannot be tested across the edges.

Electron Velocity Distributions

Further evidence for shocks at the edges of the event in Figure 1 is seen in the character of the electron velocity distributions in the high-field regions. Figure 3 shows cuts through the electron distribution taken approximately parallel and perpendicular to the magnetic field for the event in Figure 1. The circles connected by solid lines in this figure show the one-dimensional electron distribution measured by the FPE in the sunward high field region, while the circles connected by dashed lines show a reference distribution in the solar wind just after the event. The velocity distribution is not plotted below $|V| < 1500$ km/s because of contamination by photoelectrons from the spacecraft. The parallel electron distribution in Figure 3 in the high-field region shows a field-aligned electron beam at about $-3500$ km/s, whereas the perpendicular distribution shows a

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<td>$V_e$, km/s</td>
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<td>Transition</td>
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slight rounding at lower energies and a slightly broader distribution at higher energies. The field-aligned beam is directed into the high-field region from the upstream solar wind. Because the distributions are broadened only slightly at lower energies where most of the particles reside, the net increase in electron temperature documented in Figure 1 is small. Though not shown here, the parallel and perpendicular distributions in the earthward high-field region of the event in Figure 1 have features similar to those shown in Figure 3, as do cuts through electron velocity distributions from the high-field regions of other diamagnetic cavity events.

As another example, parallel and perpendicular cuts from the high-field regions of another hot diamagnetic cavity event on November 16, 1977, at about 0633 UT are shown in Figure 4 together with cuts taken in the upstream solar wind (see Figure 1 of Thomsen et al. [1986] for the plasma moments for this event, and note there the elevation of $T_e$ within the high-field region on the sunward side). This event exhibits considerably more heating in the high-field region, and the parallel electron distribution in Figure 4 clearly shows a field-aligned beam at about $-4000$ km/s which is directed into the high-field region. A flattening of both the parallel and perpendicular electron distributions is seen at lower speeds ($|V| \leq 4000$ km/s). The distribution is broader in the parallel than in the perpendicular direction at lower speeds, while being broader in the perpendicular direction at higher speeds.

Parallel and perpendicular electron velocity distributions from an event which exhibited relatively strong heating in the high-field regions are shown in Figure 5 (see Figure 3 of Thomsen et al. [1986] for the plasma moments from this event, and again note the clearly elevated $T_e$ in the high-field region on the sunward side). In this event the parallel and perpendicular distributions within the high-field region are clearly "flat-topped" out to $|V| \sim 5000$ km/s. This distribution is broader in the parallel than in the perpendicular direction at all energies, but no field-aligned beam is seen in the parallel distribution.

The electron distributions shown in Figures 3, 4, and 5 have characteristics similar to those seen in electron distributions downstream from the earth's bow shock [Montgomery et al., 1970; Feldman et al., 1983a] and downstream from interplanetary shocks [Feldman et al., 1983b] (see also the recent review by Feldman [1986]). Field-aligned beams (Figures 3 and 4) are often observed at the earth's bow shock [Feldman et al., 1983a]. These beams are believed to be generated by the charge separation electric field within the shock. So-called "flat-topped" electron distributions similar to those in Figures 4 and 5 are characteristic of the shocked plasma downstream from the earth's bow shock [Montgomery et al., 1970] and are seen downstream from the stronger interplanetary shocks as well [Feldman et al., 1983b].

The electron distributions in Figures 3, 4, and 5 are qualitatively similar to one another but show quantitative differences which might be attributable to different shock strengths at the edges of the three events. For shocks in the interplanetary medium, Feldman et al. [1983b] have found that the amount of electron heating increases with increasing shock strength, where shock strength is somewhat loosely defined in terms of either the density compression or the velocity jump, which are themselves well correlated. In addition, the degree of flatness of the parallel distribution is correlated with shock strength. The flatness is estimated by fitting the parallel distribution with a generalized Gaussian function of the form

$$f(V_p) = A \exp \left\{ -\left[ (V_p - V_{th})/V_{th}^2 \right] \right\}$$

(1)
Here, $V_\text{f}$ is the bulk flow velocity, $V_\text{th}$ is related to the thermal velocity, and $s$ determines the degree of flatness. For interplanetary shocks, $s$ ranges from 2 (i.e., Gaussian or no flatness) for very weak shocks to $\sim 5-6$ for fairly strong shocks [Feldman et al., 1983b].

A generalized Gaussian fit to measured values of the parallel distribution at velocities below 4000 km/s (excluding the beam) yields a value of $s = 3.5 \pm 0.25$ for the distribution illustrated in Figure 3. This small value of $s$ is consistent with the small amount of heating observed and suggests that the shock at the sunward edge of this event is weak. Fits to the parallel distributions in Figure 4 and 5 yield values of $s = 4.75 \pm 0.25$ for both distributions, consistent with the greater amount of heating observed for these examples. Thus the shocks at the edges of these latter events appear to be as strong as some of the stronger interplanetary shocks.

(One might argue that the flatness index $s$ is a rather indirect measurement of the strength of the shocks as compared to more direct indicators such as the density ratio or the velocity change. However, for the events we are considering, we feel it is a more reliable indicator than these parameters for two reasons: First, as mentioned earlier, the change in the bulk flow speed across these shocks is of the same order as our measurement uncertainties. Second, for a piston-driven shock, as we interpret these events to be, the density jump across the shock can be meaningfully estimated only if the shock is well separated from the piston, with a readily distinguishable downstream region. Most of our events have relatively thin high-field regions, suggesting that the shocks may not be fully separated. Hence we feel it is very likely that the downstream density is affected by the proximity of the piston. The shape of the electron distributions, on the other hand, should be more directly related to the nature of the shock itself.)

**Plasma Waves**

The presence of electron beams (see Figure 3) and flat-topped distributions in the high-field regions flanking the diamagnetic cavity events indicates the possibility of significant wave-particle interactions in those regions. Plasma wave observations confirm this possibility.

In Figure 6, plasma wave observations of the hot diamagnetic cavity event introduced in Figure 1 are shown along with the electron density and total magnetic field. Plasma wave observations are from the University of Iowa plasma wave instrument on ISEE 2 [Gurnett et al., 1978]. This instrument measures the fluctuating electric fields in 16 logarithmically spaced frequency channels 4 times a second in high data rate. Only those channels of interest here are shown. ISEE 2 plasma wave data are shown because of a 30-s gap in the ISEE 1 data, but throughout the event, when simultaneous ISEE 1 and 2 plasma wave data exist, they show essentially the same features.

On either side of the event (from 0608:30 to 0609:25 UT and from 0610:50 to 0611:30 UT), plasma wave data in Figure 4 show electrostatic emissions common observed in the region upstream from the earth's bow shock (see the recent review by Gurnett [1986]). Electrostatic electron plasma oscillations at the local electron plasma frequency are seen in the 17.8-kHz channel [Fredricks et al., 1968], and Doppler-shifted ion acoustic emissions (for example, from 0609:00 to 0609:15 UT) are seen in the 1 to 10-kHz frequency range [e.g., Fuselier and Gurnett, 1984].
and properties include (for an upstream to downstream passage) magnetic field increase, density increase, ion and electron temperature increases, appropriate velocity change (increase on earthward side, decrease on sunward side), flat-topped downstream electron distributions, ingoing field-aligned electron beams, and characteristic plasma wave emissions.

For the most part we have concentrated our attention so far on a single event, that which occurred at ~0610 on November 16, 1977. This event, particularly the sunward edge, was found to satisfy a number of the above shock indications, although a few of the conditions could not be conclusively established because of measurement difficulties.

Table 2 summarizes the observational situation with regard to these various properties at the edges of all eight diamagnetic cavity events reported by Thomsen et al. [1986]. In this table those properties which appear to be qualitatively consistent with a shock are identified by a Y. Those properties which are inconsistent with a shock are identified by an N. Because the FPE does not always detect field-aligned beams at shocks [Feldman et al., 1983b], the absence of a field-aligned beam is not necessarily inconsistent with a shock and is thus identified by an N*.

Determinations which are subject to some doubt are modified by a question mark, and inconclusive determinations are identified by a question mark alone. Also given in Table 2 is the value of the flatness parameter s for the downstream electron distributions.

**Discussion**

Examination of Table 2 reveals that the plasma and field changes observed at the outer edges of diamagnetic cavity events are often qualitatively consistent with the changes that would be provided by shock transitions. However, some of the individual pieces of evidence in Table 2 are also consistent with other discontinuities besides shocks. For example, the density, temperature, and velocity changes across the edges could be caused by a pressure wave that has not steepened into a shock. It is the combination of all evidence that rules out other discontinuities and leads us to the conclusion that shocks exist at the edges of many of the events listed in Table 2.

If the strength of the shock is related to the degree of flattening of the downstream parallel electron distribution (i.e., to the parameter s) as is true for interplanetary shocks [Feldman et al., 1983b], then Table 2 suggests that the shocks at the edges of the diamagnetic cavity events vary considerably in strength but are generally weak. For example, the degree of flatness, s, for the earthward shock at 0610 UT on November 16, 1977 (Figure 1), was estimated to be 3.0 ± 0.25. This value is typical of weak interplanetary shocks. The small electron velocity and temperature changes across the edges of the event (see Table 1) are also characteristic of weaker interplanetary shocks.

Possible additional evidence that the shock is weak can be seen in the total magnetic field profile in Figure 1. Small, roughly periodic fluctuations in the total magnetic field just prior to the crossing of the earthward edge (from 0609:10 to 0609:28 UT) and also in the high-field regions at the sunward edge (from 0610:40 to 0610:48 UT) may be the signature of damped whistler wave trains which are often seen extending upstream or downstream from weak shocks [Fairfield, 1974; Mellott and Greenstadt, 1984]. Additional two-spacecraft studies would be needed to confirm this suggestion. It is also possible, however, that these upstream fluctuations may be whistler waves generated by electrons reflected off the magnetic field ramp of the shock [Sentman et al., 1983] and are not necessarily an extension of the shock itself.

A summary of our present view of the expanding diamagnetic cavity event in Figure 1 is illustrated by the schematic in Figure 7. The normals n1 and n2 to the edges of this event have been computed from minimum variance analysis of the magnetic field data. These normals are (in GSE coordinates) n1 = (−0.595, 0.754, −0.277) for the earthward edge and n2 = (0.905, 0.754, −0.383) for the sunward edge. The angle between the solar wind magnetic field and the boundary normal at both edges was θ'' = 82°, indicating that the shocks at the edges are probably quasi-perpendicular. The angle between the two normals n1 and n2 is 80°, indicating that the structure has a finite radius of curvature. This is in contrast to an infinite planar current sheet for which the angle between the two normals would be nearly 180°. Thus the schematic in Figure 7 represents a view along the axis of an expanding flux.
The values of $s$ shown in the tenth column of Table 2 range from $s \sim 3$, consistent with weak shocks, to $s = 5-6$, consistent with stronger shocks. Events with stronger shocks at the sunward edges tend not to have shocks at the earthward edges. If shocks exist at both edges, they are both weak, with the weaker of the two on the earthward edge.

The above associations suggest that the various diamagnetic cavity events are coupled differently to the solar wind flow. When the coupling is complete (equal flow speeds), the expansion of the high-pressure cavity into the surrounding solar wind proceeds at equal rates on both the sunward and earthward edges of the cavity. In this case, shocks of nearly equal strengths or no shocks at all (depending upon the intrinsic overpressure associated with the cavity) form on opposite sides of the cavity. On the other hand, when the coupling is poor (unequal flow speeds), the relative expansion speed of the cavity into the solar wind on the sunward edge is considerably greater than in the case of complete coupling, while that on the earthward edge is less than in complete coupling. As a consequence, in the case of poor coupling a strong shock forms on the sunward edge of the cavity, and a weak shock or no shock at all forms on the earthward edge. Since all events show either nearly equal strength shocks on both the sunward and earthward edges or strong shocks on their sunward edges, none of the observed cavities are convecting faster than the solar wind speed [Thomson et al., 1986].

Since the convection speed is always less than or equal to the solar wind speed, the presence of shocks on the earthward edge is a direct indication that the cavities are expanding and that the expansion speed is greater than the fast mode speed relative to the rest frame of the solar wind. Thus the inference that the cavities are expanding because of the large pressure imbalance between the cavity and the solar wind [Thomson et al., 1986] is confirmed by the presence of shocks at the earthward edge.

We suggest that the difference in convection speeds may be an indication of the relative ages of these hot diamagnetic cavity events. In particular, it seems plausible that the structures start expanding while nearly at rest in the spacecraft (or earth's) frame and thus initially form a shock only on the sunward edge. This shock would be relatively strong. As these structures expand, they begin to convect with the solar wind until they are nearly at rest in the solar wind frame. At this time the supersonic expansion of the cavity in the earthward direction allows a weak shock to form there.

In summary, the presence and relative strength of shocks at the edges of some diamagnetic cavity events has potentially important implications regarding the dynamics of these events. These shocks also provide additional information that may help identify the origin of these structures, which at present remains somewhat uncertain.

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