Bidirectional ~1 MeV Ion Flows Observed by IMP 8 Over Two Solar Cycles

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Abstract

The IMP 8 GME experiment has recorded 0.5-4.0 MeV/amu ion anisotropies since launch in October 1973, encompassing more than two 11-year solar cycles. The probability of observing field-aligned, bidirectional ion flows (BIFs) follows solar activity levels, predominantly because of the dependence of interplanetary energetic particle intensities on solar activity, and is increasing in recent data. We illustrate an extended BIF on September 25-26, 1998 inside an ejecta (interplanetary material associated with a coronal mass ejection at the Sun), but note that BIFs can also occur outside ejecta. We also combine anisotropy data from IMP 8 and a spacecraft at L1 (ISEE 3) to identify BIFs associated with convected solar wind structures.

1 Introduction:

Bidirectional ion flows (BIFs) are of particular interest because they are one of the in-situ signatures of ejecta, interplanetary material associated with coronal mass ejections at the Sun (e.g., Gosling, 1990). BIFs may be set up in ejecta by ions circulating around plasmoid-like ejecta field lines, or by particle reflection in the legs of looped magnetic field lines rooted at the Sun. The ions have long mean-free paths because field variances are typically low in ejecta. However, BIFs are not uniquely indicative of ejecta, and can occur elsewhere, if counter-streaming particle flows are set up for some reason (Richardson and Reames, 1993). The present study uses 15-minute resolution 0.5-4 MeV/amu ion data acquired by the IMP 8 GME experiment (McGuire et al., 1986) up to 1998, and extends that of Richardson and Reames (1993) which covered 1973 to 1989.

2 Instrumentation:

The GME LED (geometrical factor: 0.39 cm^2 sr) views ±25° from the ecliptic and accumulates particle counts in 8 azimuthal sectors as the spacecraft spins. Data are accumulated over 15-minute intervals and transformed into the solar wind frame. The zero, first and second-order terms ($A_{0,1,2}$) of a Fourier series fit to the sectored data give respectively, the isotropic, streaming, and bidirectional (two-peaks/rotation) components. To identify BIFs, which are characterized by a relatively large A_2 component, we use the criteria of Richardson and Reames (1993): $A_2/A_1 > 0.8$, $A_2/A_3 > 2.0$, and $A_2 > 0.1$ (to remove nearly isotropic intervals). We also require at least 50 particle counts for the Fourier analysis to be made. Only periods when IMP 8 is in the solar wind (~60% of each ~40 R_e orbit) are considered in this study because interplanetary particle distributions are usually severely distorted inside the bow shock. To distinguish field-aligned flows from "pancake" distributions, peaked perpendicular to the magnetic field, we use the magnetic field direction interpolated from 1-hour averages obtained from the NSSDC OMNI database. The OMNI data are usually based on IMP 8 observations when the spacecraft is in the solar wind.

3 Observations:

Figure 1 summarizes the BIF occurrence rate during the IMP 8 mission. The top two panels show the solar cycle variation in the intensity of ~1 MeV protons, and the percentage of 15-minute intervals in which field-aligned BIFs are observed during successive periods of 82 days (~3 solar rotations). The occurrence rate follows the solar activity cycle and ranges from <1% at solar minimum to ~10% at solar maximum.

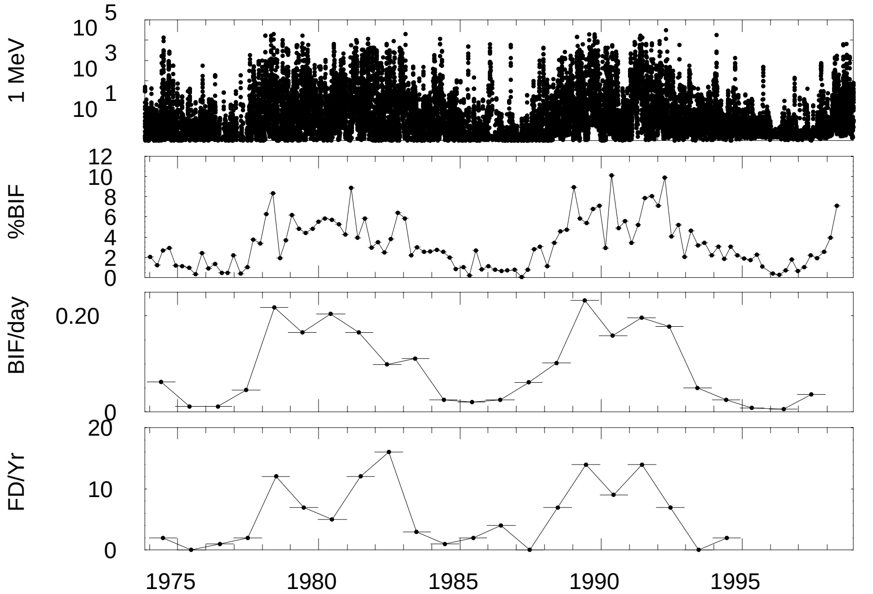

Figure 1: Summary of observations during the IMP 8 mission: ~1 MeV proton intensity; % of 15 min. intervals showing BIFs during 3 solar rotation periods; occurrence rate of extended BIF intervals (see text); and annual number of ≥ 4% cosmic ray decreases (Cane et al., 1996).

However, the BIF occurrence rate is closely correlated with the fraction of intervals in each 82-day period which exceed 50 counts, the best-fit line in Figure 2 corresponding to 7.7% of these intervals having BIFs. This suggests that the BIF solar-cycle variation is predominantly determined by the variation in the energetic ion intensity. Also, ~50% of the individual BIF intervals are isolated (more than 3 hours from another BIF interval) and last only one 15-minute integration period. From examining simultaneous plasma and magnetic field data, we conclude that these BIFs do not indicate small-scale ejecta-like regions. Rather, they may be caused, for example, by statistical fluctuations in the count rate distributions, which occasionally meet the BIF criteria. The IMP 8 particle distributions may also be influenced by proximity to/connection to the bowshock, though we have not considered such effects here.

Previous observations (e.g., Richardson and Reames, 1993) have also shown that only a subset of BIFs are associated with ejecta. Such BIFs typically occur intermittently within an ejecta, and have durations extending up to the ~12-24 hrs characteristic of the passage of ejecta. A reliable method of identifying possible ejecta-related BIFs in anisotropy data (which also considers the complication of data gaps, for example) would be very useful. One technique is to identify extended-duration BIFs. For example, we have grouped together 15-minute BIF intervals separated by < 3 hours, also requiring that BIFs be observed for at least 25% of the duration of grouped interval, and for a minimum of 1.25 hours (6 integration periods). These criteria select the majority of BIFs in 1978 to 1982 which are associated with well-known ejecta that have been previously identified using various ejecta signatures (e.g., Richardson and Cane, 1993). The daily-occurrence rate of these extended BIF events (third panel of Figure 1) again follows solar activity levels, and is increasing as the new solar activity cycle commences. For comparison, the bottom panel shows the yearly number of Forbush decreases ≥ 4% in 1973-1994 (Cane et al., 1996) which indicates the rate at

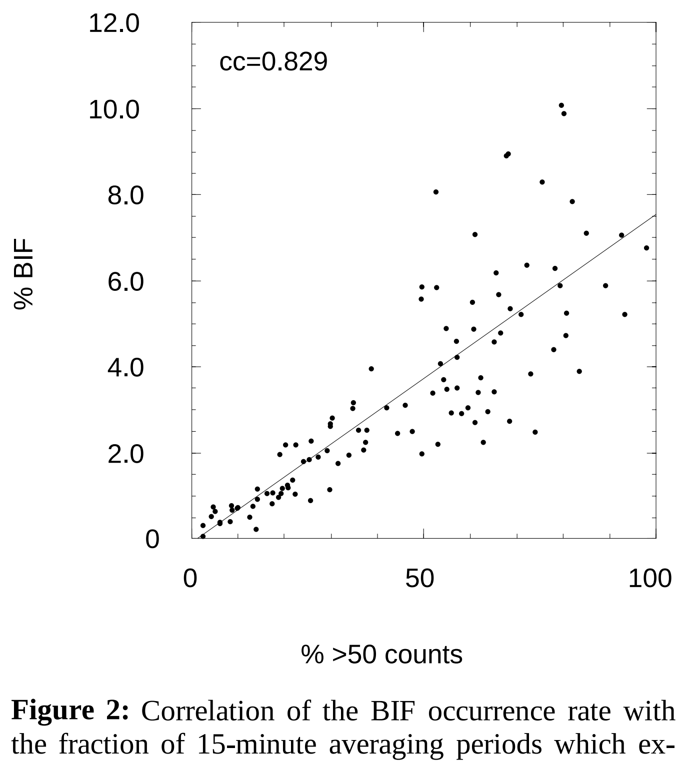

Figure 2: Correlation of the BIF occurrence rate with the fraction of 15-minute averaging periods which exceed the count threshold for anisotropy analysis.

which major ejecta pass Earth. Note that there are some similar details, such as the slight decrease in the rates at solar maximum.

Considering recent observations, 26 extended BIFs have been identified between the launch of the SOHO spacecraft and September 1998 (the current limit of the OMNI magnetic field data). Summarizing, from examining high-time resolution plasma/field data from IMP 8 and WIND, we conclude that BIFs associated with ejecta which are probable magnetic clouds (MCs) were observed on 97/11/03-04; 97/11/07; 98/05/02-03; 98/08/21; 98/09/23; and 98/09/25-26. Other BIFs were associated with ejecta-like regions lacking the magnetic field rotations characteristic of MCs (98/03/25; 98/03/31-04/01; 98/05/27; 98/06/04-06; 98/06/16-17; 98/06/18; 98/08/02; 98/08/08). Four BIFs occurred upstream of transient shocks (97/03/14; 98/01/05; 98/04/06; 98/08/05) and may, for example, have been set up on field lines which intersected the shock at more than one point (Balogh and Erdös, 1983). Another BIF occurred, unusually, in a post-shock region ahead of an MC (98/08/19). Finally, four events (96/12/29; 97/07/28; 98/08/04; 98/09/22) had no associated local solar wind structures, and must have been set up by other processes (Richardson and Reames, 1993). Thus, even these extended BIFs are not uniquely associated with ejecta.

Figure 3 illustrates GME observations on September 23-27, 1998 during a particle enhancement following an M7/3B flare at N18°E09° at 07 UT on September 23. WIND plasma/field data are shown because similar IMP 8 observations are incomplete; solar wind structures pass WIND ~40 minutes earlier than IMP 8. The associated shock, which encountered WIND at 2320 UT, September 24, was followed by passage of the ejecta. The ejecta is indicated, for example, by: (1) the shaded region in the T_p panel where the proton temperature (T_p) is below 50% of the temperature expected for normally expanding solar wind (T_{ex}), also shown in this panel (Richardson and Cane, 1995); (2) an extended BIF (horizontal line in the bottom panel); (3) a magnetic field rotation suggestive of a magnetic cloud and (4) low magnetic field fluctuation levels. Detection of the ejecta at Earth is consistent with the location of the solar event near central meridian. Representative sectored 0.5-4 MeV/amu ion distributions are drawn vs. viewing angle, with the Sun to the top of the page. The unusual flows from the east of the Sun during particle event onset (e.g., September 23 (DOY 266); 1900 UT) are rarely observed outside ejecta (Richardson and Cane, 1996) and suggest that particles may be guided along looped field lines rooted at the Sun. There are indeed signatures suggestive of ejecta material on September 23, such as T_p depressions, rotating and highly inclined magnetic fields, and BIFs. More typical, anti-solar, flows are evident at September 24 (DOY 267); 2015 UT, as the particle intensity ramps up prior to shock arrival. A flow reversal occurs across the shock (September 24-25; 2345-0015 UT,). BIFs extend from September 25; 0715 UT to September 26; 1630 UT during the ejecta. Following exit from the ejecta, particles are again detected flowing sunward from the shock, which was then well beyond 1 AU (e.g., September 27 (DOY 270); 0400 UT).

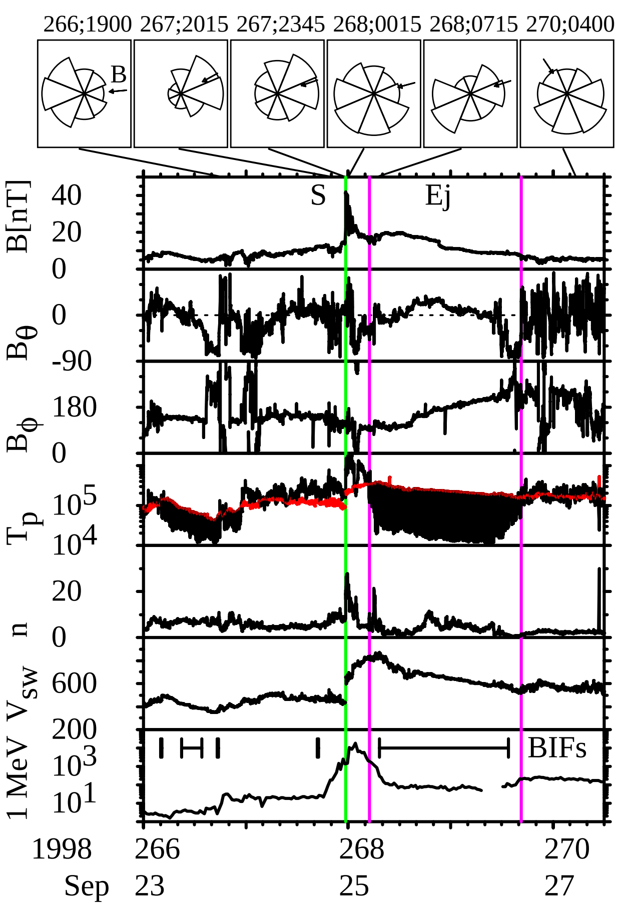

Figure 3: The September 25-26, 1998 ejecta event, with a BIF interval indicated by the horizontal line.

The identification of BIFs can also be improved by considering similar, but independent, anisotropy data sets from the same spacecraft (Richardson and Reames, 1993). An extension of this technique is to combine anisotropy observations from different spacecraft to identify BIFs which propagate from one spacecraft to the other with delays consistent with the solar wind speed. To demonstrate this approach, we have combined IMP 8 data with 15-minute 1-4 MeV ion anisotropy data from the Goddard instrument on ISEE 3 (Richardson and Reames, 1993) obtained in August 1978-October 1982. At this time, ISEE 3 was upstream of the Earth in a halo orbit around L1. Figure 4 shows the probability (%) that, when a BIF is detected at IMP 8, a BIF is detected at ISEE 3 at a time T_d earlier. The maximum at T_d= +0.75 hr corresponds to the typical L1-IMP 8 convection time delay and indicates that at least a fraction of BIFs are associated with convected structures. The ~8 hr width of the peak suggests a maximum scale size of ~0.1 AU for the convected structures in which BIFs occur, which is of the order of the scale size of ejecta. Note that even at large delays, the probability is non-zero because of random variations in the particle distributions. The majority of BIFs observed at ISEE 3 and IMP 8 with appropriate convective delays were associated with other ejecta signatures such as intervals of bidirectional solar wind electron heat fluxes (Gosling et al., 1987).

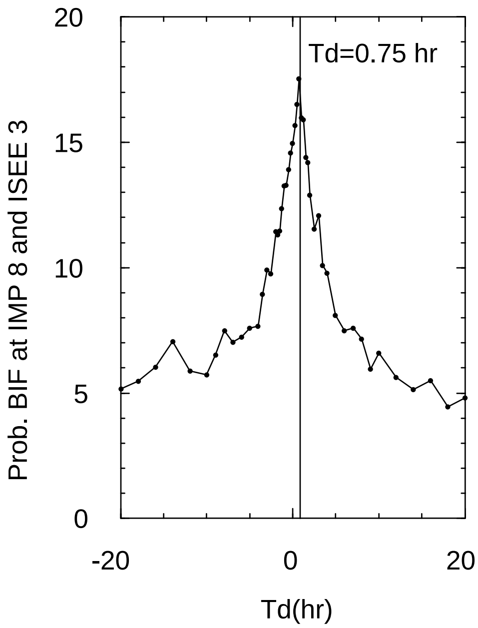

Figure 4: Probability (%) of a BIF at IMP 8 and ISEE 3 vs. ISEE 3-IMP 8 time delay (maximum at +0.75 hour).

4 Summary/Discussion:

The rate at which bidirectional ~1 MeV ion flows are detected in the solar wind varies with solar activity levels, largely because the enhanced particle intensities required for BIFs to be identified occur more frequently around solar maximum. Since energetic solar events and fast CMEs are responsible for the higher particle intensities at solar maximum, the solar-cycle variation in the observation of BIFs is primarily caused by the changing occurrence rate of energetic CMEs. We note that Gosling et al. (1992) suggested that the similar, solar-cycle dependence in the rate of bidirectional solar wind electron (BDE) heat fluxes may directly reflect variations in the CME rate. A similar interpretation in not possible for the BIF rate because some ejecta pass by when elevated particle intensities are not present, whereas BDEs originate in the solar wind heat flux, which is almost always present. In addition, BIFs are not uniquely associated with ejecta, as has been noted in this and earlier studies. The problem of identifying ejecta-associated BIFs may be facilitated by considering multiple anisotropy data sets, either from the same or different spacecraft. The combined Goddard IMP 8/ISEE 3 data show that BIFs are associated with convected structures which have scale sizes $\leq$ 0.1 AU.

Acknowledgements

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