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INTERPLANETARY MAGNETIC FIELD LINE MIXING DEDUCED FROM IMPULSIVE SOLAR FLARE PARTICLES

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ABSTRACT

We have studied fine-scale temporal variations in the arrival profiles of ∼20 keV nucleon^{-1} to ∼2 MeV nucleon^{-1} ions from impulsive solar flares using instrumentation on board the *Advanced Composition Explorer* spacecraft at 1 AU between 1997 November and 1999 July. The particle events often had short-timescale (∼3 hr) variations in their intensity that occurred simultaneously across all energies and were generally not in coincidence with any local magnetic field or plasma signature. These features appear to be caused by the convection of magnetic flux tubes past the observer that are alternately filled and devoid of flare ions even though they had a common flare source at the Sun. Thus, we have used the particles to study the mixing of the interplanetary magnetic field that is due to random walk. We deduce an average timescale of 3.2 hr for these features, which corresponds to a length of ∼0.03 AU.

Subject headings: acceleration of particles — interplanetary medium — Sun: flares — Sun: particle emission

1. INTRODUCTION

Interplanetary particle events from impulsive solar flares have several characteristics that distinguish them from the more intense events associated with interplanetary shocks. One key characteristic is the pattern of abundance enhancements in the flare events compared with the solar wind: ^{3}He is ∼10–1000 more abundant, and Ne-Si and Fe are enhanced by factors of ∼3–5 and ∼10, respectively (e.g., Reames 1999 and references therein). An observer at 1 AU detects the electrons and ions from flares that are only at solar longitudes near the intersection of the nominal interplanetary magnetic field line and the solar corona (e.g., Kahler et al. 1987; Cane, McGuire, & von Rosenvinge 1986). The unique abundance signatures that possibly result from wave-particle resonances (e.g., Temerin & Roth 1992; Miller & Viñas 1993), the high-ionization states that imply temperatures above 10 MK (Luhn et al. 1987), and the requirement of a favorable magnetic connection to a flare site all indicate that the energetic particle source is close to the Sun, within a solar radius of the photosphere.

The propagation of flare particles from the flare site to 1 AU yields another characteristic of these events. The acceleration process may take only tens of seconds to fully accelerate ions and electrons (Miller & Viñas 1993). This is much shorter than the timescales associated with the propagation to 1 AU. The distribution of particle speeds therefore produces a measurable velocity dispersion wherein propagation effects dominate. Larson et al. (1997) found that the effect of velocity dispersion revealed details of the propagation of ∼0.14–100 keV electrons from impulsive flares within a magnetic cloud. They interpreted numerous abrupt decreases of the electron fluxes as signatures of the disconnection of one end of the cloud's magnetic field from the solar corona. The electron event profiles in the study of Larson et al. (1997) lasted as long as ∼6 hr.

In this Letter, we present observations of temporal structures in the arrival profiles of ∼20 keV nucleon^{-1} to 5 MeV nucleon^{-1} impulsive solar flare ions made between 1997 November and 1999 July with instrumentation on board the *Advanced Composition Explorer* (*ACE*) spacecraft. At the lowest energies, the ions have minimum times of flight from the flare to 1 AU of ∼24 hr. These low-energy ions propagate to 1 AU faster than the solar wind but slower than the energetic electrons that Larson et al. (1997) discussed. We therefore use these ions as probes of preexisting interplanetary magnetic field structures on the scale of ∼0.03 AU, allowing us to study the magnetic connection to a flare with ions over a much longer timescale than previously possible.

2. OBSERVATIONS

2.1. *Event Profiles: Impulsive versus Shock-associated Energetic Particles*

The ion observations presented here were made with the ultra–low-energy isotope spectrometer (ULEIS) sensor on board the *ACE* spacecraft, which was launched into orbit about the L1 Lagrangian point in late 1997 (Stone et al. 1998). ULEIS is a time-of-flight mass spectrometer that measures the composition and energy spectra of H-Ni in the energy range of ∼0.02–10 MeV nucleon^{-1} (Mason et al. 1998). We have observed numerous interplanetary particle events whose abundances and occasional associations with type III radio bursts and streaming ∼100 keV electrons indicate that the ions were accelerated at an impulsive flare site (e.g., Mason et al. 1986; Reames 1999).

Figures 1*a*–1*d* show examples of impulsive flares observed with *ACE* during 1999 January 9–10. Figure 1*a* shows the energy (in units of MeV nucleon^{-1}) of H-Fe ions versus their

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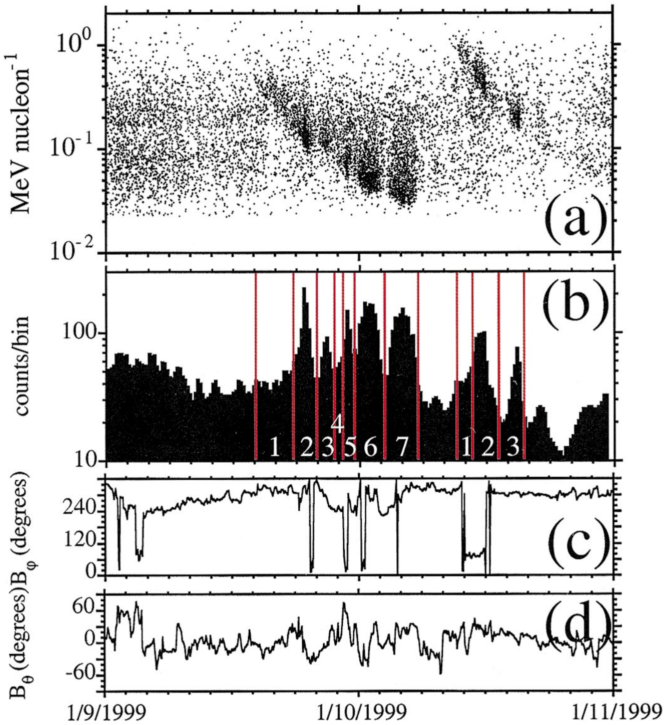

FIG. 1.—(*a*) Energy of H-Fe ions (in units of MeV nucleon^{-1}) vs. arrival time at 1 AU for the impulsive flare events of 1999 January 9. (*b*) H-Fe counts vs. time in smoothed, ∼14 minute bins. The vertical lines show event subintervals as defined in text. (*c*) Interplanetary magnetic field angle in the geocentric solar ecliptic (GSE) *x*-*y* plane. (*d*) Interplanetary magnetic field angle normal to the GSE *x*-*y* plane.

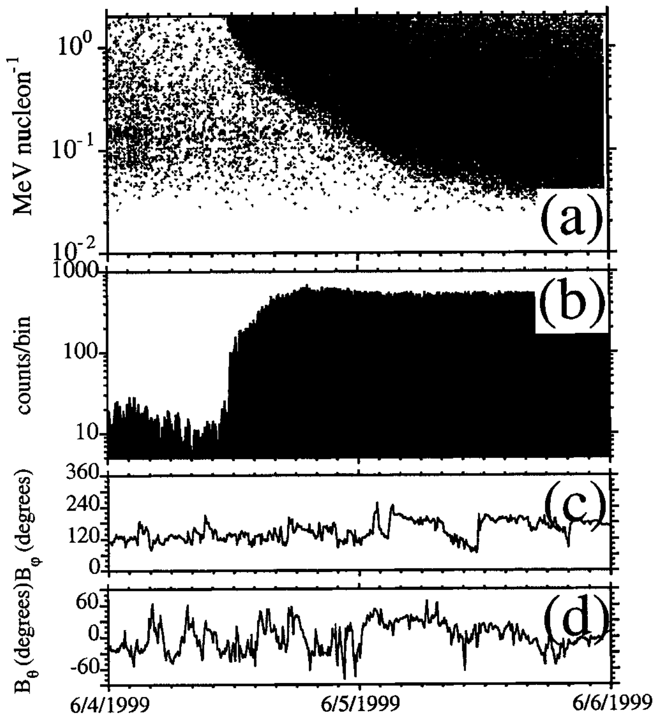

FIG. 2.—(*a*) Energy of oxygen ions (in units of MeV nucleon^{-1}) vs. arrival time at 1 AU for the solar particle event of 1999 June 4. (*b*) Oxygen counts vs. time in 5 minute bins. (*c*) Interplanetary magnetic field angle in the GSE *x*-*y* plane. (*d*) Interplanetary magnetic field angle normal to the GSE *x*-*y* plane.

arrival time. The histogram in Figure 1*b* plots the smoothed ion count rate binned in ∼14 minute intervals in order to better show the intensity variations. At least two particle injections occurred within this 2 day interval: one event began at ∼1400 UT on 1999 January 9, and particles at 1 MeV nucleon^{-1} from another injection arrived at 1 AU on 1999 January 10 at ∼0900 UT. The velocity dispersion tells us that the ions in the first event are from the same source at the Sun; we could not conclude this from the event counting rates alone shown in Figure 1*b*.

We focus on the more intense event that began on 1999 January 9 at 1300 UT: notice the ∼1 hr–long interruptions of the event profile at which the particle counting rate decreased by a factor of 5–10 (e.g., at 1920 UT on 1999 January 9). The modulation of the event profile occurred simultaneously across all energies and did *not* correlate with large changes in the direction of the local interplanetary magnetic field (Figs. 1*c* and 1*d*). The transitions from the relatively high intensity event rates to preexisting particle rates were abrupt, lasting less than 2.5 minutes.

In order to quantify these short-term intensity variations, we analyzed the event histogram of Figure 1*b* in the following way: beginning with the first arrival of ions from the flare at 1407 UT on 1999 January 9, we used the velocity dispersion profile in Figure 1*a* to distinguish the particles of interest from the low fluxes of particles from previous events. From this time, we marked the end of a subinterval (labeled 1 in Fig. 1*b*) and the beginning of another (labeled 2) when the counting rate increased by a factor of ∼1.3. We continued this procedure through the entire event, selecting the start and end times with a peak-to-valley ratio criterion of ∼1.3. This particular threshold was sufficiently low that we could pick out the features clearly seen with the eye in the velocity profiles. The velocity dispersion profile clearly shows when the next event began on 1999 January 10 at 0910 UT, where we measured a new set of intervals using the same technique. We return to the statistics of the subintervals in these and other events in § 2.2.

We next contrast the impulsive time profile of Figure 1 with an event that took place on 1999 June 4 (Figs 2*a*–2*d*) and was associated with a coronal mass ejection and an interplanetary shock. This event also shows a velocity dispersion for ions and electrons with an onset near 0700 UT on 1999 June 4, but we did not observe intensity variations of the kind that were seen in the impulsive flare of 1999 January 9. We also note that the interplanetary magnetic field direction changed by tens of degrees without any significant effect on the event's profile (Figs. 2*c* and 2*d*).

2.2. *Scale Size of the Fine Structure in Impulsive Flare Energetic Particles*

Figure 1 illustrates an example of an impulsive solar flare event that had significant structure in its time-of-arrival profile. In order to characterize these structures more fully and to determine how often they occur, we surveyed the ULEIS observations from 1997 November to 1999 July for events that had the following characteristics: (1) clear velocity dispersion in heavy ions ($Z > 2$), similar to that shown in Figure 1; (2) Fe/O ∼ 1, as is characteristic of particles from impulsive flares; (3) low-intensity events, similar to Figure 1, in order to eliminate the heavy ion–rich onsets commonly seen in shock-associated particle events. We found 25 impulsive flare particle

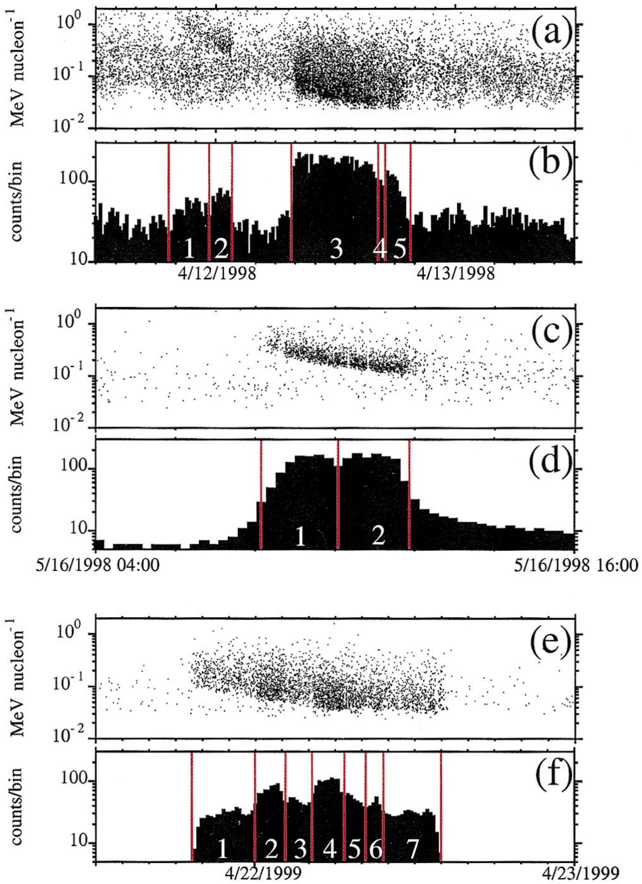

FIG. 3.—(*a*–*f*) Velocity dispersion of heavy ions from three impulsive flares with histograms of corresponding event counting rates.

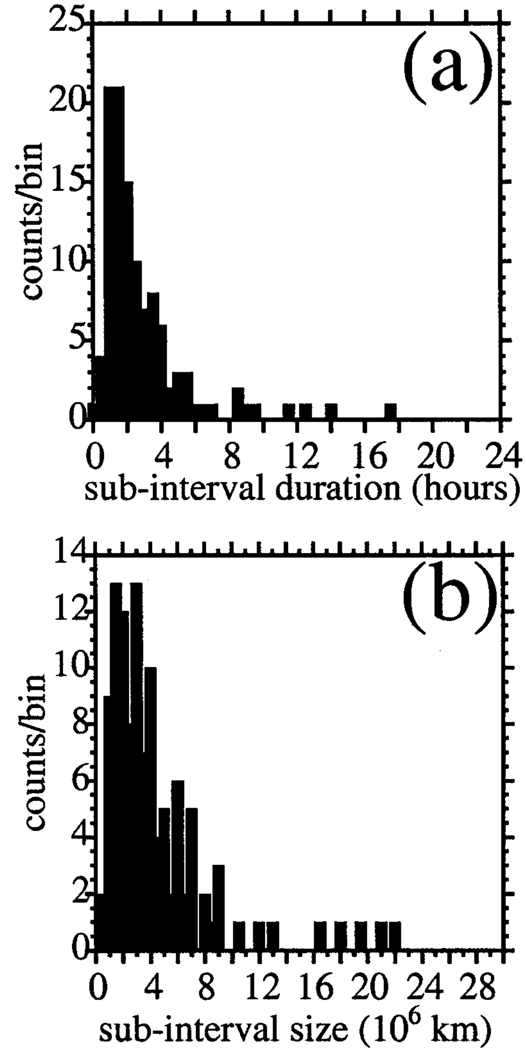

FIG. 4.—(*a*) Distribution of particle event subinterval lengths in a survey of 25 impulsive flares with clear velocity dispersion, *ACE* measurements from 1997 November to 1999 July. (*b*) Distribution of corresponding spatial sizes of flare subintervals.

events from 1997 November to 1999 July that satisfied the survey criteria.

In order to characterize the timescale of the flare particle intensity variations, we applied the same technique as presented in Figure 1 (with a peak-to-valley ratio of ∼1.3) to each event. As an example of the wide variety of profiles observed at 1 AU, Figure 3 shows the velocity dispersion of heavy ions and the intensity histograms of three events along with the derived subintervals. The event of 1998 April 12 (Figs. 3*a* and 3*b*) had an ∼6 hr–long interruption in its profile, in contrast to the many shorter lived intervals observed in the 1999 January 9 events. Note that the velocity dispersion links the two increases in the histogram of Figure 3*b* and that the distinctive pattern in Figure 3*a* makes it clear that the ions are from a single particle injection. Figures 3*c* and 3*d* are examples of an event that we did not observe in its entirety; heavy ions arrived at 1 AU only within a 4 hr–long interval that ended when *ACE* entered the high-speed (∼550 km s^{-1}) solar wind from a solar coronal hole. Particles from the 1999 April 22 event had significant variations superposed on an event profile that lasted ∼19 hr.

Figure 4*a* shows the distribution of the subinterval durations of all 25 events in the survey. The average duration was 3.2 hr, with the bulk of the subintervals shorter than ∼3 hr. We next took the average solar wind speed, also measured on *ACE*, within each subinterval in order to calculate the spatial size of the region filled with energetic particles that convected past the spacecraft. Note that this estimate of the spatial size does not include any possible effects of the flux-tube geometry or its angle with respect to the radial solar wind flow and that, therefore, it is a rough estimate. The histogram in Figure 4*b* shows the distribution of resulting sizes, with an average of 4.7×10^6 km or ∼0.03 AU.

3. DISCUSSION

Using the *ACE*/ULEIS instrument, we have surveyed energetic particles from 25 impulsive solar flares and have found that the low-energy ion intensity profiles exhibited sharp (<2.5 minutes) boundaries and occasional dropouts. The intensity changes occurred simultaneously across all energies and generally were not coincident with signatures of the local interplanetary magnetic field. Since the spacecraft must be magnetically connected to the flare sites in order to see the escaping ions, and since impulsive flare particles originate at compact sites, the observed waxing and waning of the particle intensities is puzzling.

We suggest these effects may be caused by the following. The solar wind continuously convects magnetic flux tubes that are connected to a solar active region to 1 AU and beyond. During the convection to 1 AU, which takes about 3–4 days, the footpoints of these flux tubes become mixed with the footpoints of other flux tubes that are not magnetically connected to the active region. The footpoint motion has the effect that adjacent flux tubes at 1 AU can be significantly separated at the Sun and, conversely, that adjacent flux tubes at the Sun may be separated at 1 AU on scales of ∼0.01 AU. The flare occurs and populates those flux tubes that are connected to the acceleration site with energetic particles; the other unconnected flux tubes remain empty. The particles within each connected flux tube arrive at 1 AU with velocity dispersion. As the mixed flux tubes move past *ACE*, we see either filled flux tubes (and hence the ongoing particle velocity dispersion) or empty flux tubes (and hence the particle dropouts). In this picture, the local interplanetary magnetic field does not necessarily correlate with the dramatic intensity changes we have seen. Variations of the particle acceleration process at the Sun are ruled out as a cause of the intensity changes because the dropouts occur simultaneously at all energies.

The effects of field line mixing are not as obvious in the more intense particle events associated with coronal mass ejections and interplanetary shocks. We can understand this as a result of the relative sizes of the acceleration sites: in shock-related events, the temporal structure observed at 1 AU reflects the ever-changing magnetic connection of an observer to the expanding shock that covers a wide extent in heliolongitude (e.g., Cane, Reames, & von Rosenvinge 1988). Consequently, any flux tube that *ACE* intersects will be populated with energetic ions as the shock propagates outward. This is not the case for impulsive flares because the acceleration site of an impulsive flare is much smaller, and therefore it is more likely that an observer's magnetic connection will wax and wane depending on the detailed magnetic topology near the flare.

These effects have only been glimpsed in prior studies of *impulsive* flare heavy ions (e.g., Reames, Richardson, & Wenzel 1992) mainly because these earlier studies covered energies above ∼1 MeV nucleon^{-1}. At these higher energies, the particle events do not last as long (see Fig. 1*a*), making it less likely to see structure on the timescale of an hour. The falling energy spectra also make the statistical accuracy poorer at the higher energies, putting the detection of such structures reported here outside the capability of prior studies of impulsive flares.

Anderson & Dougherty (1986) observed numerous instances of the modulation of electron and ion intensities during long-lasting solar or interplanetary events. Also, Buttighofer (1998) noted similar abrupt modulations of low-energy electrons observed on *Ulysses* that had no obvious coincident plasma signature. We believe that the particle channels observed by Anderson & Dougherty (1986) and Buttighofer (1998) are the same kind of interplanetary structures that we have examined in this Letter. We also note that the structures discussed here may have led to the electron disconnection events that Larson et al. (1997) observed within a magnetic cloud.

The interplanetary magnetic field structure that we have deduced from these observations should be related to measurements of the solar wind and the interplanetary magnetic field. Matthaeus, Goldstein, & King (1986) studied the characteristic time of correlations between the interplanetary magnetic field and the solar wind speed measured at two different times from a single spacecraft. The average correlation time (3.8 hr) and length (4.9×10^6 km) measured in the solar wind by Matthaeus et al. (1986) are indeed similar to the average flare subinterval duration (3.2 hr) and inferred length (4.7×10^6 km) reported here.

Finally, in an accompanying Letter, Giacalone, Jokipii, & Mazur (2000) discuss a model that relates these observations to a random walk of the magnetic field lines that are line-tied in the supergranulation network of the Sun's photosphere. Particle events on the scale of a supergranule (tens of thousands of kilometers) in the model show structures at 1 AU that are similar to the observations discussed here.

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