N87-24252

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PARTICLE PROPAGATION CHANNELS IN THE SOLAR WIND

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ABSTRACT

The intensities of low energy solar-interplanetary electrons and ions at 1 AU occasionally change in a "square wave" manner. The changes may be increases or decreases and they typically have durations of from one hour to a few hours. In some cases these channels are bounded by discontinuities in the interplanetary field and the plasma properties differ from the surrounding solar wind. In one case solar flare particles were confined to a channel of width 3×10^6 km at Earth. At the Sun this dimension extrapolates to about 12000 km, a size comparable to small flares.

1. INTRODUCTION

Bartley et al. in 1966 reported that highly anisotropic fluxes of 1 to 13 MeV protons from solar flares occasionally changed their flow direction suddenly and by as much as several tens of degrees. McCracken and Ness [1966] showed that the change in flow direction was due to changes in the direction of the interplanetary magnetic field (IMF). The time for passage of these bundles of field lines over the spacecraft implied their widths were about 3×10^6 km at 1 AU. Domingo, Page, and Wenzel [1976] described sudden decreases in

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solar particle intensity lasting about one hour and emphasized that such an effect meant that little transport of particles across interplanetary field lines was occurring.

In 1968, Jokipii and Parker used Leighton's hypothesis of random walk of magnetic field lines associated with granules and supergranules [1964] to develop a picture of an interplanetary medium composed of a tangle of field lines frozen into the solar wind, but whose feet were carried about by the random motions at the solar surface. Jokipii and Parker noted that using a correlation length of 15 000 km—about the radius of a supergranule—the magnetic structure would be 3×10^6 km in size at 1 AU. This is close to the size of the filaments as determined by Bartley et al. and McCracken and Ness. These workers did not find changes in the solar particle intensity, anisotropy ratio or energy spectrum as the spacecraft entered the "filament". More recently the IMF has come to be regarded as containing many discontinuities, rather than being made up of many filaments [Burlaga, 1969].

In this paper we discuss changes in the intensity of low energy solar-interplanetary electron and ion intensities observed at distance 1 AU from the Sun on the International Sun-Earth Explorer ISEE-3 spacecraft. These changes are characterized by particle increases or decreases, often having a square wave appearance, and lasting from one to a few hours.

Our measurements extend the previous ones by showing that low energy electrons and ions are "channeled" and that the intensity in the narrow channels may be higher than in the surrounding IMF. The particle intensity changes are usually well-defined, occurring over distances $\lesssim$10,000 km. Most importantly, we show that the net particle flow may be quite different in these narrow channels compared to the flow just outside.

Electrons in the energy range 2 to 10 keV were measured by a swept electric field analyzer and ions of energy in the range 45 keV to a few MeV were measured by a pair of solid state detector telescopes, one of which was covered by a thin foil in order to achieve separation of electrons and ions.

Although the electrons we measured are of quite low energy (2 to 40 keV), such particles have very high speeds (9% to 35% the speed of light), but small gyroradii. In a 5 nT magnetic field at 60° pitch angle the gyroradii are in the range 15 to 70 km. The proton gyroradii are on the order of several thousand kilometers. The axes of the detectors lie in the ecliptic plane and are swept over it by rotation of the spacecraft. The view angles of the electron detector are 10° in azimuth and ±23° in elevation. Because of the restricted viewing in azimuth, variations in the azimuth of the interplanetary magnetic field can cause apparent changes in the count rates, especially when the particle pitch angle distributions are highly anisotropic. We therefore have eliminated from our analysis events contaminated by large and rapid changes in the elevation angle of the interplanetary magnetic field.

2. OBSERVATIONS

Figure 1 illustrates several features of low energy ion and electron propagation channels. During this 24-hour interval two increases in electron intensity can be seen as well as a less well defined decrease beginning near 2000 UT (Universal Time). The ion intensity decreases in coincidence with the two electron increases but are not quite so sharply defined (the ion behavior is not shown in Figure 1).

The clear correlation with solar wind and interplanetary magnetic field parameters are quite striking in this example. The magnetic field changes at the beginning and end of the two electron intensity increases have been identified as tangential discontinuities [Tsurutani, private communication, 1985]. The magnetohydrodynamic (MHD) theory of such discontinuities requires the pressure on the two sides to be equal. In response the solar wind plasma density increases during the times the IMF has decreased.

We have surveyed 15 months of ISEE-3 data during 1978 and 1979 and find about 80 intensity changes, either increases or decreases, resembling those shown in Figure 1. These features are most frequent and clearest in the 2 to 10 keV electron measurements, although ion intensity changes often accompany the electron intensity changes. Only a few of the examples are so clearly defined as the ones in Figure 1 and fewer still are accompanied by tangential discontinuities. Our basic assumption on the nature of these characteristic particle intensity changes is that the particles are confined to a bundle of

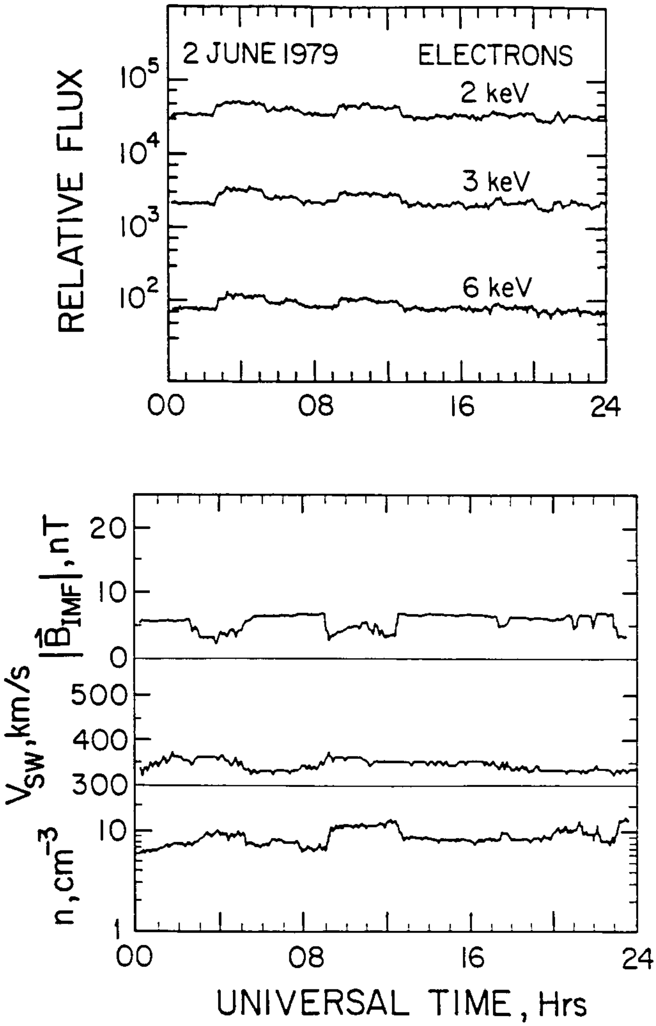

Figure 1. Changes in the intensity of low energy electrons and ions having a "square wave" appearance during long-lived streams of solar particles were a fairly common occurrence over 15 months of observations in 1978 and 1979. In the two-day period shown at least three such events occur. In some cases the intensity changes are associated with solar wind or interplanetary magnetic field changes. For some there is no clear signature.

magnetic field lines and that these field lines are swept past the spacecraft by the solar wind flow. We refer to these features in the IMF as particle propagation channels. Under this assumption we have converted the temporal duration of the propagation channels to a distance D given by

$$D = \sum_{i} V_{sw}^{(i)} \; | \sin \varnothing_i | \; \Delta t$$

where $V_{sw}^{(i)}$ is the solar wind speed averaged over time interval Δt, taken to be 10 seconds, and $\varnothing$ is the angle between the solar wind flow direction and the direction of the IMF during interval i.

We found the widths of the 80 propagation channels measured in this way to range from 1.4 to 5.0×10^6 km with an average value of 3.7×10^6 km.

McDonald and Burlaga [1985] have discussed another form of channeled solar particle propagation. They found regions of compressed interplanetary magnetic field evidently connecting back to the solar corona since solar particles were often found in them. Such channels are much larger in size than those we are discussing here. Their importance lies in the fact that adiabatic energy losses are reduced and thus the particles can reach interstellar space without large energy losses.

We next discuss an example which allows some conclusions about the origin and nature of one particular particle propagation channel. On May 20 and 21, 1979, several small solar flares occurred in McMath plage region 16014, located at about N16 W66. One of the flares in this region accelerated electrons from $\lesssim 2$ keV to above 40 keV and ions $\lesssim 40$ keV to above 270 keV energy (see Figure 2). The electron intensity versus time profile is characteristic of an impulsive injection of particles at the Sun into a medium whose mean free path for pitch angle scattering is on the order of 1 AU. The slow decay phase seen in Figure 2 is consistent with a brief injection phase followed by scattering in the interplanetary medium [Lin, 1974]. This view is supported by the measured pitch angle distributions. Initially, for some tens of minutes, the electrons are highly anisotropic, then become nearly isotropic.

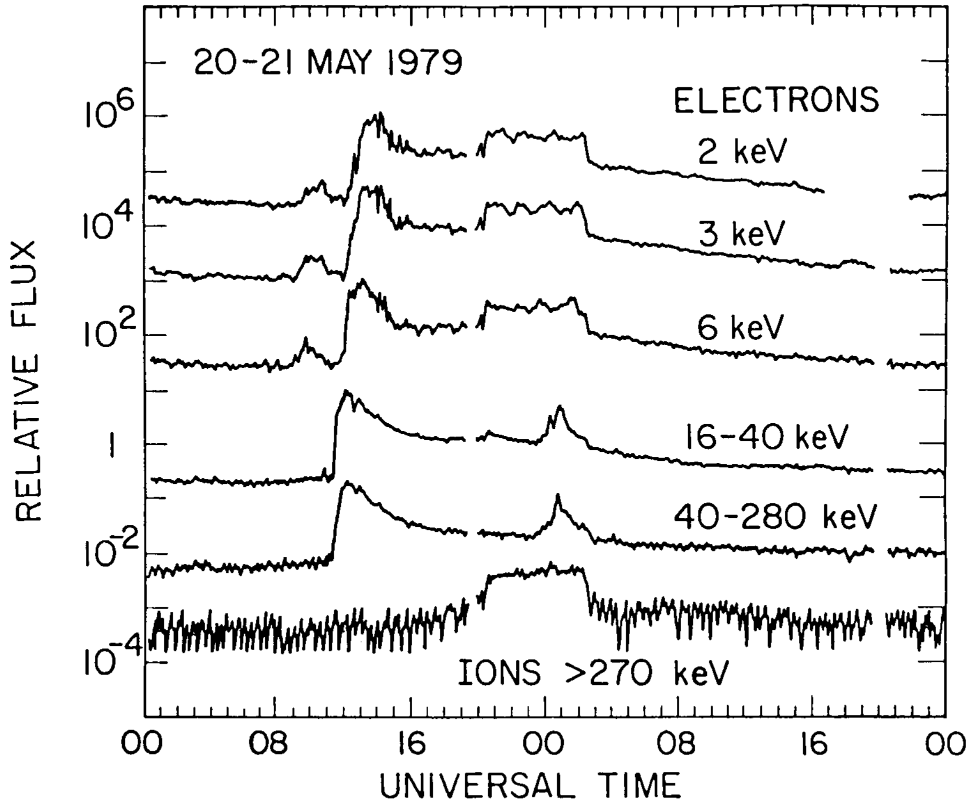

Figure 2. An importance 1N flare began at 1107 UT on May 20, 1979 and injected electrons from 2 to 100 keV and low energy ions into interplanetary space. The spacecraft entered a particle propagation channel at 2030 UT. This channel was 2.5 × 10^6 km in width at 1 AU.

The most remarkable feature during these two days is the sudden increase in the electron and ion intensities at about 2000 UT on May 20, followed about six hours later by a sudden return to the earlier slow decay. The increase is simultaneous at all particle energies. This is also the case for the decrease. During this six-hour period the pitch angle distributions became highly anisotropic showing strong flow of electrons away from the Sun (Figure 3).

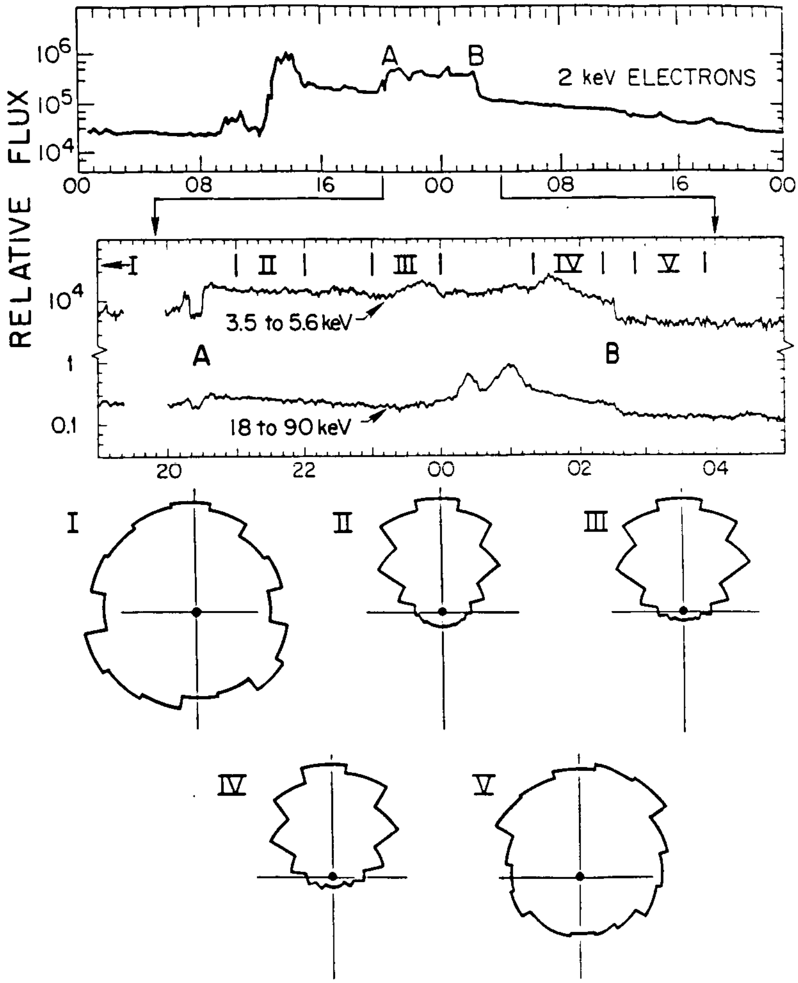

Figure 3. About nine hours after the solar flare that began at 1107 UT, highly anisotropic fluxes of electrons appeared for several hours (A to B). Before and after this time the electron fluxes were nearly isotropic. The vertical lines through the pitch angle distributions at the bottom of the figure lie along the interplanetary magnetic field. The direction of the Sun lies somewhere in the upper half of these diagrams. The pitch angle distributions are indexed to the middle panel by means of Roman numerals.

Evidently the interplanetary field lines have connected to a source region in the solar atmosphere able to continually inject electrons and ions into the interplanetary medium for at least six hours. We suppose that this injection also occurred before and after this six-hour interval. From the observed slow decay of particle intensity during this time, the source could have supplied particles for intervals as long as 20 hours or more.

From the solar wind speed and direction of the interplanetary magnetic field we find the width of the particle propagation channel to be 2.5×10^6 km. Linear extrapolation of this width to the solar surface gives a size of 12 000 km. The magnitude and topology of the magnetic field near the Sun no doubt will affect the actual size, but we appear to be dealing with a dimension which is larger than the size of a small flare but smaller than the plage region. Both at the Sun and in interplanetary space this structure is relatively small. One consequence of this is that if such structures are associated with most active regions they would be a common feature at 1 AU, but would not often be observed because of their small size.

While the spacecraft is located in the particle propagation channel three impulsive, flare-like injections of particles occur (Figure 3). They are identified by their impulsive appearance and their velocity dispersion, consistent with about a 1.3 AU travel distance. One of these electron events can be firmly identified with an optical flare in region 16014. No optical association could be found for the other two particle injections. This is not surprising since we have found from a study of many impulsive low energy electron events that those having very low intensity often have no reported Hα association [Potter, Lin, and Anderson, 1980]. However, it is unusual that three low energy solar electrons events occur in a six-hour interval. This leads us to believe that during the interval the spacecraft is situated on field lines connected to the site of flaring on the Sun. If this is the case the field lines guiding the electrons and ions away from the Sun from 2030 UT on May 20 to 0230 on May 21 have their origin in or near McMath plage region 16014, located at N16 W66 at this time. Since Earth is at a heliographic latitude of 2° S at this time the field lines would have been deflected 18° southward. This result is consistent with the suggestions of Schulz [1973] and by Svalgaard et al. [1975] and Svalgaard and Wilcox [1976], that the current sheet is related to the equator of a solar magnetic dipole. In such a view field lines drawn out by the solar wind near the equator could trace back to latitudes well removed from the equator in the manner shown in Figure 7 of Smith, Tsurutani, and Rosenberg [1978].

The fact that energetic particles stream away from the Sun for periods of time on the order of days has been known for some time. [See, for example, Simnett, 1971 and Anderson, Lin, and Potter, 1982.] There are two general views on the mechanisms behind long-lived emission of solar particles. The first of these is storage of flare accelerated particles in the corona and their subsequent escape. The other hypothesis is continuous acceleration. Present observational evidence is not sufficient to resolve this issue, and there are conceptual difficulties with each hypothesis. Radio wave observations give the best evidence in favor of coronal storage, although the configurations of the magnetic fields have not been made clear in this way. The difficulty with coronal storage is the rapid rate of energy loss of the fast particles to background electrons in the coronal plasma. Only at very high coronal altitudes is the rate of energy loss low enough to permit storage over periods of days [Krimigis and Verzariu, 1971]. The problem with the continuous acceleration hypothesis is that no physical mechanism for it has been identified, and the best understood mechanisms involve shock waves and are therefore impulsive in character. Impulsive acceleration is noisy in the sense of copious X-ray and radio wave emission whereas these emissions are largely absent during periods of long-lived streaming. The present observations provide some additional information on the problem of long-lived emission of solar particles. In the first place only flares of small size are involved here whereas in the past the process has been generally associated with large flares. In the case at hand the largest flare was importance 1N and it accelerated only low intensities of ions in addition to the rather large fluxes of electrons. However, this flare occurred in an active region above which type III bursts frequently appeared, indicating that beams of fast electrons were present in the corona over a period of one or two days.

Secondly, the streaming of solar particles on May 20 to 21, 1979 is restricted to a spatial region whose dimension at the Sun is on the order of 10^4 km. The near perfect confinement of the streaming particles must be associated with discontinuities or major changes in the topology of magnetic fields in the solar atmosphere. However, no magnetic feature could be identified with the particle channel on this occasion. In particular, nothing suggesting a neutral sheet appeared.

The third point we would make using data from the May 20 to 21, 1979 interval concerns the energy spectrum of the electrons. We noted above that the intensity of the 2 to 10 KeV electrons changed very little over a six-hour period. If the small change in intensity is interpreted as due to energy loss of these electrons to background electrons we can set a lower limit to the altitude at which the electrons must reside if indeed they are trapped in magnetic structures. A 10 to 20% energy loss in six hours at the lowest energies requires that the average electron density not exceed 10^5 cm^{-3}. This corresponds to a heliocentric distance of 4 solar radii for the quiet Sun and 19 solar radii if the coronal region is a streamer with enhanced density [Fainberg and Stone, 1971].

We have also compared the energy spectrum of the electrons in the impulsive injection from the 1N flare that began at 1107 UT on May 20 with the spectrum of electrons streaming in the propagation channel. The results are given in Table I. We have fitted the spectral data to a power law for 30 one-hour data samples and obtained the power law exponent for each sample. Ten samples are taken during times preceding entry into the particle channel, 10 samples in the channel, and 10 samples following exit from the channel. The average value for each set of ten samples and the standard deviations are given in Table I. We find that there is no difference in the low energy electron spectra between particles in the propagation channel and those on field lines outside the channel. There can be little doubt that the electrons outside the channel were accelerated by the 1N flare. We take the similarity of the energy spectra to be significant but not conclusive evidence for storage and subsequent escape over a period of many hours of electrons accelerated over a brief period of time by the importance 1N flare which began at 1107 UT on May 20, 1979. We conclude that some of the structure found in the interplanetary magnetic field is established by spatial features on the order of 10^4 km near the solar surface, and that these features persist for at least several days.

Table I.

Time 20-21 May 1979	Number of Intervals	Spectral Index, γ
14:00-19:00	10	3.77 ± 0.08
21:00-02:00	10	3.39 ± 0.29
03:00-08:00	20	3.49 ± 0.07

Comparison of the energy spectra of 2 to 10 keV electrons inside the particle propagation (2100 to 0200 UT) with spectra calculated before and after entry into the channel. The electrons outside the channel are certain to have been accelerated by an importance 1N flare, although at this time they are no longer streaming from the Sun. The close similarity of spectral indices suggests that the particles streaming away from the Sun in the propagation channel were accelerated by the same flare but then were trapped and released over a period of many hours.

ACKNOWLEDGMENTS

This work is the result of research supported by NASA grant NAG5-376.

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