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ABSTRACT

Prominent intensity spikes in the flux of protons and alphas with less than 0.5 MeV per charge have been observed in the region several hours behind an interplanetary shock front. The small spatial scale of these events and the high anisotropy of the particle flux suggest local acceleration. The spectra of the particles, which are cut off at equal energy per charge, suggest acceleration through an electric field. We examine the possibility that these events have their origin in active magnetic neutral sheets in the shocked solar wind.

It has been known for some years that large increases in the low to medium energy cosmic ray flux accompany interplanetary shock waves. Several authors have suggested that these delayed cosmic ray events are the result of particle acceleration associated with the propagation of the shock wave itself (Axford and Reid, 1962, 1963; Jokipii, 1966; Rao et al., 1967; Lanzerotti and Robbins, 1969; Armstrong et al., 1970; Ogilvie and Arens, 1971; Singer and Montgomery, 1971). Parker (1965) has noted that particle acceleration seems to be a ubiquitous property of the agitation associated with nonequilibrium plasmas as they relax to a more homogeneous state. However, the actual mechanism through which the particle acceleration takes place is not known. Indeed, the panoply of activities of a nonequilibrium plasma is vast and charged particle acceleration is likely to be produced, not by a unique mechanism, but rather by at least several, and perhaps many, mechanisms.

Gloeckler et al. (1974), hereinafter called Paper I) have reported observations of intensity increases of low energy protons and alphas associated with the interplanetary shock wave during 30 October to 1 November 1972. In particular they found a series of prominent but short-lived intensity increases — the so called "post-shock" spikes — several hours behind the shock front. In this letter we present more detailed observations on these post-shock spikes which are evident up to energies of about 0.5 MeV per charge. The peculiar features of these particle spikes, which are discussed in detail in this paper, lead us to suggest that they are evidence of local cosmic ray acceleration in the solar wind and that the particles were observed closely adjacent to the acceleration region. We also explore, in a preliminary way, the possibility that these particles are accelerated through the electric field associated with magnetic field line reconnection in the shocked solar wind.

The observations were made using the University of Maryland experiment on the IMP 7 (Explorer 47) satellite between 1900 and 2100 UT on 31 October 1972 when the spacecraft was in interplanetary space. The instrument uniquely identifies low energy ($\gtrsim$ 100 keV/charge) protons, alphas and heavier particles through a simultaneous measurement of the kinetic energy of an incoming particle and of its deflection in a known electrostatic field (Fan et al., 1971; also see Paper I).

Figure 1 shows the time variations of protons in the energy range 125 to 160 keV and of alpha particles in the range 95 to 135 keV/nucleon. The fluxes of both species exhibit a series of spikes, coincident in time and of several minutes duration. The counting rates between the spikes represent real particles and are not background (Paper I). These spikes, to which we are confining our attention, show the following features in common:

a) The fluxes of protons and alpha particles, with energies greater than about 0.5 MeV per charge show no increase during the spikes (Figure 2, Paper I).

b) The p/α ratio, at equal energy per charge, is constant ($\simeq$20) throughout the time when the spikes occurred, but shows large changes in the spikes when evaluated at either equal velocity or equal rigidity (see Figure 3 in Paper I).

c) The particle anisotropy approaches 95% during the spikes (Ipavich, 1974).

d) The low energy flux of heavier ions ($z > 6$) also exhibits spikes coincident with those in the proton and alpha fluxes; at higher energies the flux of heavy ions shows no increase and its behavior is consistent with the cutoff at about 0.5 MeV per charge displayed by the protons and alphas (D. Hovestadt, private communication, 1974).

e) There is no indication of an increase in the electron flux during these events; from the counting rate of our lowest energy electron channel we estimate that the intensity of electrons between 130 and 180 keV is at most a few percent of the proton flux at that energy.

Magnetic field data obtained with instruments on the same satellite (R. Lepping and N. Ness, private communication, 1974) permit the following further conclusions:

a) These events occurred several hours after the passage of an interplanetary shock wave in the region of high magnetic field; $B \simeq 15\gamma$.

b) At the time that the spikes were observed the magnetic field displayed moderate fluctuations which, very loosely, appear to have a wave-like character.

c) Taking the Compton-Getting effect into account, the particles are found to be streaming generally along the magnetic field from an easterly, antisolar direction.

d) The particle spikes do not appear to be confined to magnetic field lines which intersect the earth's bow shock.

It is interesting to note that the particle fluxes are accompanied by wave-like disturbances in the magnetic field. We suggest that these disturbances may be excited by the particle streams themselves. While a detailed discussion of this question is beyond the scope of the present paper we note briefly that a flux of particles is expected to drive hydromagnetic waves in a plasma when: 1) the streaming speed of the particles exceeds the Alfvén speed; 2) the energy density of the particles is comparable to the energy density of the magnetic field. In the present case 1) the streaming speed of the highly anisotropic beam of particles is of the order of a few times 10^8 cm sec^{-1} which is significantly larger than the Alfvén speed; 2) the flux of particle energy in the beam is of the order of 10^{11} eV cm^{-2} sec^{-1} (see below) so that the energy density due to the particles is of the order of 500 eV cm^{-3}; by comparison the energy density of the 15γ magnetic field is about 600 eV cm^{-3}.

The high particle anisotropy, together with the very well defined, beam-like nature of the observed particle fluxes, suggests that the region of acceleration was nearby to the detector and that the particles were accelerated contemporaneously with their detection. In addition, the particle spectra — protons, helium nuclei and heavy nuclei — in which each species appears to be cut off at the same maximum energy per charge, suggest local acceleration through an electric field. The most promising candidate for the particle acceleration seems to be the electric field associated with the reconnection of magnetic field lines in the presence of resistive plasma instabilities. Although the magnetic field data (R. Lepping and N. Ness, private communication, 1974) show the presence of at least one and perhaps several magnetic neutral sheets associated with the region where the particles are accelerated, we cannot, unfortunately, report having caught one in the act of instability and active particle acceleration. However, in view of the importance of cosmic ray acceleration for astrophysics and in view of the theoretical uncertainties surrounding the question of magnetic field reconnection, it seems worthwhile to pursue the question further and to examine the consequences of assuming that these beams of energetic particles were accelerated in regions of magnetic field reconnection.

Consider the idealized neutral sheet, represented pictorially in Figure 2, having thickness _d_ and lognitudinal and transverse scales _L_. With a density of ions of about 10 cm^{-3}, the observed magnetic field of 1.5×10^{-4} gauss in the shocked solar wind plasma leads to an Alfvén speed, V_A, of about 10^7 cm sec^{-1}. The rate of energy production in phenomena for which magnetic field reconnection is thought to play a central role suggests that the merging velocity, V_m associated with active neutral sheet regions is of the order of 0.1 V_A (see the discussion in Parker, 1973) Then the electric field characteristic of the merging region is

$$E \approx 0.1 \frac{V_A B}{c} . \qquad (1)$$

Using the present values for V_A and B we find that $E \sim 5\times10^{-9}$ st-volt $cm^{-1} \approx 2\times10^{-6}$ volt cm^{-1}. Neutral sheets in the solar wind are thought to have a coherence scale of about 3×10^{11} cm (McCracken and Ness, 1966; Bartley et al., 1966; Michel, 1967; Siscoe et al., 1968; McCracken et al., 1968) and Parker (1972) has already suggested that rapid reconnection of the interplanetary field may occur across such neutral sheets. Associating this scale of 3×10^{11} cm with the longitudinal scale L, we find that the maximum energy (per unit of charge) attained by a particle traversing the neutral sheet region is of the order of 5×10^{5} eV. This energy is very closely the maximum energy at which the spikes are apparent in the present observations. Furthermore the close agreement between the proton to alpha ratio at equal energy per charge, in the spikes, with the proton to alpha ratio in the quiet-time solar wind is in agreement with these ideas of local acceleration through an electric field.

It is instructive to compare the rate at which magnetic field energy enters the dissipation region with the estimated energy appearing in the particle fluxes. The energy density of the 1.5×10^{-4} gauss magnetic field is about 600 eV cm^{-3}. This energy flows into the reconnection region at about 10^6 cm sec^{-1} over an area L^2 on either side of the neutral sheet. Thus, when $L \simeq 3\times10^{11}$ cm, magnetic field energy flows into the reconnection region at a rate of about 10^{32} eV sec^{-1}. In order to estimate the energy in the observed particle beam, it is necessary to know the spectrum at low energies (well below the 125 keV lower limit of our detectors). Now, in the spikes the spectrum varies as $E^{-\gamma}$, where γ is between 2 and 3 in the energy range above 125 keV. If the spectrum were to remain steep — say $\gamma \sim 2$-3 — down to low energies (5 or 10 keV) then we estimate the energy flux in the observed beam to be about 10^{11} eV cm^{-2} sec^{-1}. From the time structure of the particle spikes in Figure 1, together with the velocity of the shocked solar wind ($\sim 7\times10^7$ cm sec^{-1}, H. Rosenbauer and H. Grünwald, 1974, private communication) we estimate that the profile of the particle beams has a small scale (thickness) of about 10^{10} cm and a large scale (width) about equal to L — 3×10^{11} cm. The area of an observed beam is then about 3×10^{21} cm^2 and the particle beam requires about 3×10^{32} eV sec^{-1} for its support. This power is of the order of, but somewhat larger than, the rate at which magnetic field energy is delivered to the reconnection region. Should the spectrum become substantially flatter below the range of our detectors then the estimated power required to sustain the beam of particles falls to between 10^{31} and 10^{32} eV sec^{-1}. The energy balance seems to require that spectrum flattens at low energies. On the other hand, it should be remembered that the simple model we have used here is presented only as a basis for discussion. It is not intended to be a quantitive representation of the acceleration region. The primary conclusion to be drawn from this discussion of the energy balance is: Should our suggestion that these particles are accelerated in interplanetary neutral sheets survive further scrutiny, then particle acceleration through reconnecting magnetic fields in a tenuous medium like the solar wind is an efficient process.

In the absence of collective effects, the electrical conductivity of a plasma is generally too high to permit rapid reconnection of magnetic fields (Parker, 1963). Thus it is thought that reconnection occurs primarily when conditions favor plasma instabilities which interrupt the flow of electrical current and raise the resistivity of the plasma. In the neutral sheet of Figure 2, the electrical current density, $j\,(c\bar{\nabla} \times B = 4\pi j)$, in the neutral layer is $cB(2\pi d)^{-1}$. If the density of electrons in the ambient plasma is ~ 10 cm^{-3}, then the electron-ion relative drift speed is $V_d \sim 10^{14}\ d^{-1}$ cm sec^{-1}. In the solar wind the electron temperature is greater than the proton temperature and, in addition, plasma turbulence tends to preferentially heat the electrons. Under these conditions the plasma is unstable to the growth of ion-sound waves when the electron-ion drift velocity exceeds the ion-sound speed — $\sim 10^6$ cm sec^{-1}. The neutral sheet depicted in Figure 2 is therefore subject to plasma turbulence, driven by ion-sound waves when $d \lesssim 10^8$ cm. (In the initial transient stage, however, it may be necessary for the current layer to be compressed to less than 10^7 cm to get the plasma turbulence going.) 10^8 cm is less than the thickness of the observed layer of energetic particles, as is necessary on the basis of the suggested model.

Altogether the properties of the particle fluxes in the post-shock spikes agree well with the properties that would be expected if these particles were accelerated locally through electric fields associated with the reconnection of magnetic lines of force. In the framework of this model, the short-lived intensity spikes result from the convection, past the spacecraft, of magnetic field lines which connect with the acceleration region. On this basis, the observations suggest that particle acceleration through active magnetic field line merging is a feature of the solar wind magnetic field, at least in the disturbed region behind an interplanetary shock front.

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Figure Captions

Figure 1 Counting rates, integrated over 20 seconds, measured in the 125-160 keV proton channel and 95-136 keV/nucleon alpha particle channel. Particle fluxes (Particles cm^{-2} sec^{-1} Sr^{-1} $(keV/nucl.)^{-1}$) may be obtained by multiplying the counting rates by 1.4 in the case of the protons and 0.8 in the case of the alpha particles.

Figure 2 An idealized representation of a magnetic neutral sheet. a) Crude general aspect of the magnetic field line configuration and length scales. b) Stylized representation of the magnetic and electric fields, B and E respectively, the current j and the merging speed V_m.

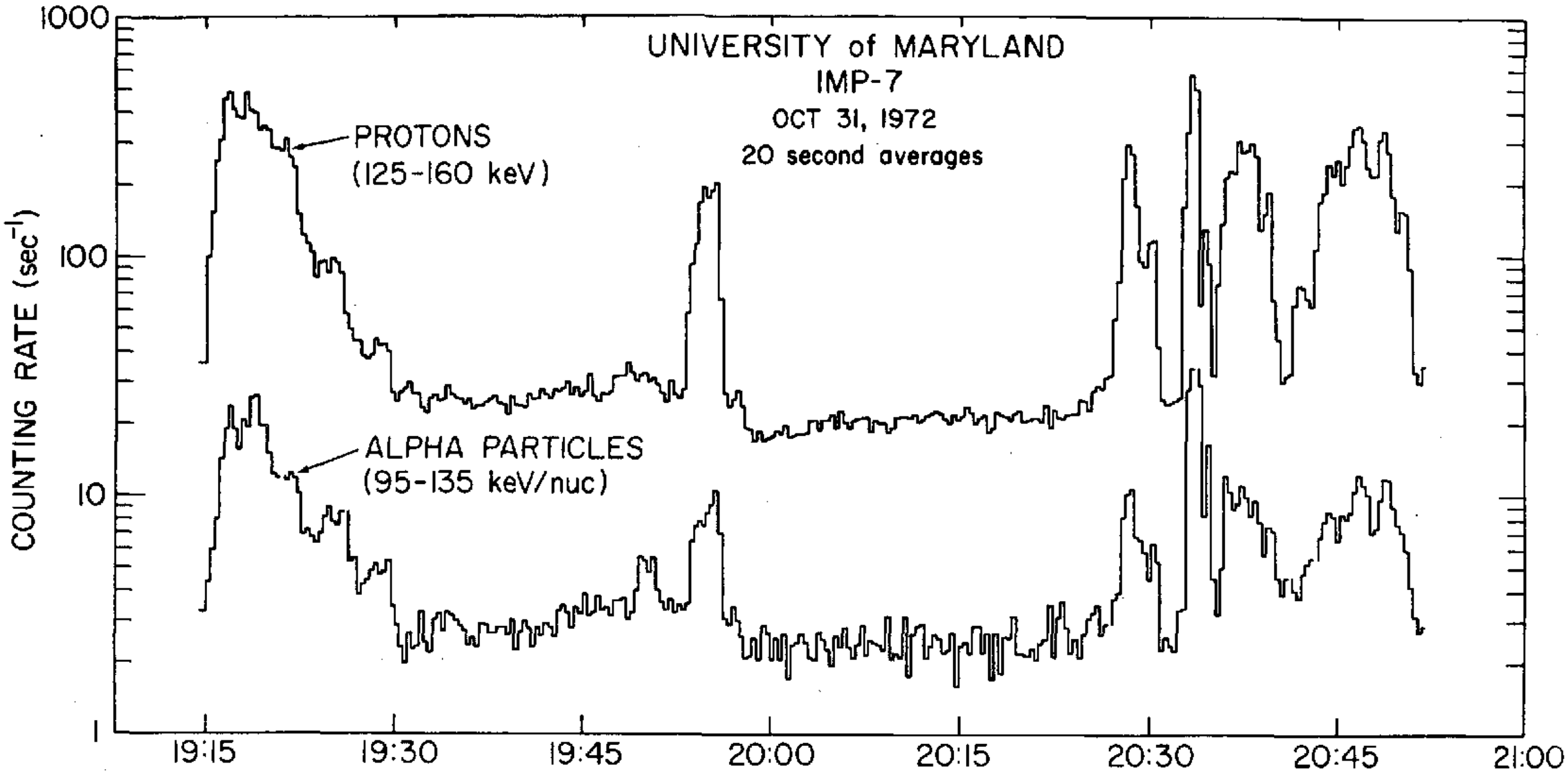
UNIVERSITY of MARYLAND
IMP-7
OCT 31, 1972
20 second averages
PROTONS
(125-160 keV)
ALPHA PARTICLES
(95-135 keV/nuc)
COUNTING RATE (sec⁻¹)
1000
100
10
1
19:15
19:30
19:45
20:00
20:15
20:30
20:45
21:00

Figure 1

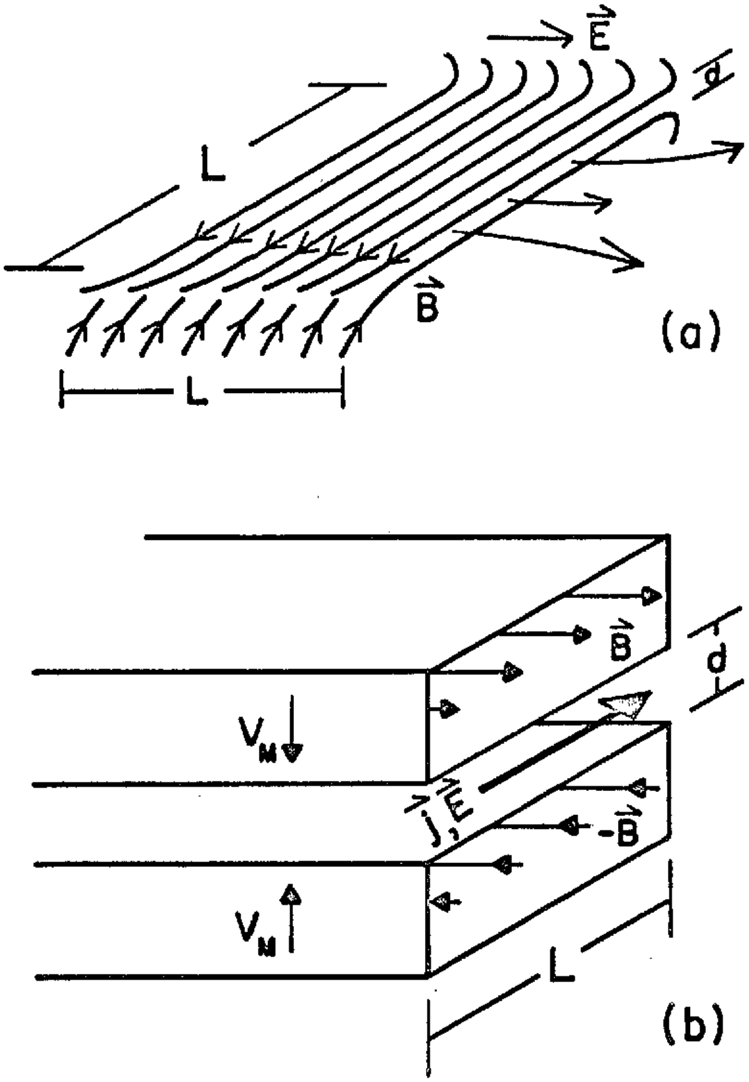

Figure 2