Abstract. A series of energetic storm particle (ESP) events is investigated on the basis of observations of energetic solar protons by IMPs IV and V between 1967 and 1972. The total number and energy of particles associated with 20 ESP events are analyzed in connection with several solar parameters at the shock surface; i.e., magnetic and thermal pressure, magnetic field and plasma mass flux. Correlation is established between the total energy of ESPs in the energy range of 1-80 MeV and the jump in the total pressure. It is pointed out that the amount of shock energy converted to the acceleration of ESP particles is not negligible and could, in principle, contribute to the deceleration of the shock wave.

Introduction

Acceleration of charged particles by shock waves propagating in space plasmas likely plays an important role in the energization of solar particles up to high energies. By observing directly the interaction of cosmic ray particles with interplanetary shock waves one can have a deeper insight into the details of the acceleration process.

The passage of flare-generated interplanetary shock waves is often associated with short events seen in the intensity of low-energy cosmic ray particles. Two distinct classes are generally observed; one of them refers to large increases of short duration (<20 min) appearing in close connection with the shock passage; these are usually called shock spikes. The other group, known as Energetic Storm Particle (ESP) events, has been discussed extensively in the literature [for example, Rao et al., 1967]. General features of ESP events are: their duration is 5-20 hours; they have no unique relation with the time of shock passage; and their energy spectrum (softer than that of the ambient flare particles) extends up to ~30 MeV.

Recently several papers have discussed the connection between ESP events and the kinetic and magnetic properties of the plasma around the shock. Blokh et al. [1975] investigated 10 ESP events on the basis of measurements of cosmic ray protons in the energy range of 1.0 - 4.5 MeV by the satellites Prognoz-1 and -2. The analysis of particle intensities did not show any correlation of the ESP peak intensity with neither the actual values nor with the changes of solar wind plasma parameters at the time of transit of the front. No connection was found between the maximal intensity and the local velocity of the shock wave. On the other hand, Pintér [1975] revealed a definite correlation of the deceleration of flare-generated shocks calculated from correlated radio noise and space probe measurements with the post-shock flux of the plasma as well as with ESP peak intensity.

Our feeling is that although a sole mechanism responsible for the various ESP events does not

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necessarily exist, this phenomenon has several details requiring satisfactory explanation by future models. In this paper we present new experimental correlations between the parameters of the shock wave ambient interplanetary medium and energetic particles in order to elucidate several aspects concerning ESP events.

Data Analysis

In what follows we analyze a series of ESP events on the basis of proton intensity observations by Explorers 34 and 41 during the period of May 1967 - December 1972, published by Van Hollebeke et al. [1974]. This provides a homogeneous data set of hourly intensities in the proton channels of energies 0.9-1.5, 6-19 and 19-80 MeV, respectively. We have used hourly data of plasma measurements as well [Interplanetary Medium Data Book, 1977].

By identifying the time of passage of the interplanetary shock wave with the time of the SSC in the geomagnetic field, this data set enabled us to carry out the analysis of 30 ESP events during the aforementioned period. While the hourly averages may smooth out some minor effects (mainly in the plasma data), our opinion is that this averaging does not affect the physical conclusions seriously. Unfortunately, simultaneous plasma, magnetic field and energetic proton data were available in 13 cases only. In the following we examine the peak intensity, the total number and energy flux of cosmic ray particles appearing in each energy channel in relation to solar wind plasma parameters and their jump at the shock discontinuity. Among the latter parameters are the magnetic field strength, $B$, thermal and magnetic pressure and plasma mass flux.

The comparison of the integrated particle number flux and energy flux densities with the jump of the total pressure, that is, the sum of magnetic and thermal pressure: $P = B^2/8\pi + nk(T_e + T_p)$, $e$ and $p$ indices referring to electrons and protons, respectively, are shown on Figures 1 and 2a. Another correlation of this pressure jump to the peak-background intensity ratio is displayed in Figure 2b for the energy range of 0.9 - 1.5 MeV.

In Figures 3a and 3b time-integrated total energy flux density is correlated with the $S = B_2/B_1$ parameter and the post-shock flux $n_2V_2$ of the plasma.

In the statistical analysis we have taken into account only those events where the ESP was superimposed on a flare particle event; i.e., the flare generating the interplanetary shock observed was clearly identifiable. While the peak proton flux is the parameter generally used for characterizing the size of ESP events, it seems that a better one can be obtained by calculating the total number of

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![Figure 1](image1.png)

**Figure 1.** Dependence of energy flux on the jump of total pressure.

![Figure 2](image2.png)

**Figure 2.** (a) Dependence of the integrated particle flux on the jump of total pressure. (b) Dependence of the peak/background intensity ratio on the jump of total pressure.
Gombosi et al. Connection of Interplanetary Shock Wave

Figure 3. a) Dependence of the total energy flux on $S = B_2/B_1$. b) Dependence of total energy flux on the post-shock plasma flux.

excess particles. Accordingly, we have subtracted the presumed flare decay profile from the observed one and integrated over time from the start until the end of the event. With this procedure we obtained the number of ESP particles cm$^{-2}$ster in 3 energy intervals providing an approximate energy spectrum between 1 and 80 MeV. Thus it was possible to estimate the total time integrated energy flux density (MeV/cm$^2$ster) carried by ESP protons in this energy range. It should be mentioned, however, that assuming a power law dependence ($I = I_0 E^{-\gamma}$) the value of $\gamma$ differential spectral exponent contains a certain statistical error due to the uncertainty of the "background" profile. The $\gamma$ values used in the present analysis were calculated from the counting rate of the two lower energy intervals (above ~20 MeV it turns out to be slightly larger).

Discussion

The details of the acceleration of low-energy charged particles by interplanetary shocks have been studied concerning mainly the spike events. In these calculations the crucial parameter of the acceleration is $S$, i.e., the ratio of magnetic field strengths in both sides of the front. Although certainly there are common features of ESP and spike production mechanisms, the former is a more sophisticated phenomenon. Contrary to the belief that there is little reaction of spikes to the propagation of a generating shock, the relationship found by Pintér [1975] shows that the interaction and energy change of ESP particles and the shock are not negligible. Several estimates of the total energy released by solar flares in the form of an interplanetary shock wave give about $10^{31}$-$5 \times 10^{32}$ ergs [cf. Dryer et al., 1976; Priest, 1976]. According to that the energy flux flowing through a unit cross section and solid angle can be calculated to give a maximum of $10^9$ erg/cm$^2$ster at 1 AU (under the assumption of isotropic expansion; taking into account real cases the anisotropy increases this value by a factor of 2-5). In the largest events the energy flux density of ESP particles can reach about $3 \times 10^7$ erg/cm$^2$ster representing 1-10% of the shock energy.

At the same time, Figures 1 and 2a indicate a correlation between the pressure jump at the shock surface and the number and energy of ESP particles. A detailed inspection shows that an increase of one magnitude in $\Delta P$, in general, corresponds to an ESP event with particle number larger by a factor of 50 to 200 and energy about 100-300. This confirms the fact that, in connection with larger pressure jumps, a larger amount of shock energy is converted into kinetic energy of the ESP particles. A bit looser correlation between $\Delta P$ and the peak to background intensity ratio seen on Figure 2b refers to the less importance of the level of flare produced particle flux. As it is seen from Figure 3a, the ESP energy does not depend clearly on $S$, while the distribution of points on the $kE-S$ plane indicates that at least in several events a process similar to that proposed by Armstrong et al. [1977] may have an important role. There is no definite connection between neither the post-shock plasma flux and ESP magnitude nor between plasma parameters and the $\gamma$ spectral index. We can conclude that the parameter $\Delta P$ likely well characterizes the shock strength and it is significant in the production mechanism of various ESP events.

In order to draw further inference we need a larger set of statistics, and it is also planned to use a more extensive data set with plasma data of better resolution. We also intend to consider details such as the thickness of the front, downstream discontinuities and to take into account more proton energy channels to establish more accurate energy spectra of ESP and flare particles to see their effect on the physical process.
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