1.Classificação *INPE-COM.9/RRE*	2.Período *September 1975*	4.Critério de Distribuição: interna [ ] externa [X]
3.Palavras Chave (selecionadas pelo autor) *Energetic Storm Particles*		
5.Relatório nº *INPE-732-RRE/025*	6.Data *September 1975*	7.Revisado por - *Luiz Gylvan Meira Jr.*
8.Título e Sub-Título *On the Origin of the Energetic Storm Particles*		9.Autorizado por - *Fernando de Mendonça* *Director*
10.Setor *CEA*	Código *4.01*	11.Nº de cópias - *12*
12.Autoria *René A. Medrano* *Ricardo A.R. Palmeira* *Ivan J. Kantor*		14.Nº de páginas - *21*
13.Assinatura Responsável		15.Preço

16.Sumário/Notas

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17.Observações *Paper presented at the 18th Plenary Meeting of COSPAR, Varna, Bulgaria, 1975.*

ON THE ORIGIN OF THE ENERGETIC STORM PARTICLES

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ABSTRACT

Energetic storm particles are events that are commonly known to occur in association with the passage of interplanetary shock waves. Selected periods of proton data (0.7 - 7.6 MeV) from the cosmic ray experiments on board of Explorer 34 and 41 corresponding to the intervals May 1967 - March 1969 and February - September 1972 have been analyzed. It is found that there exist distinct flux peaks approximately 8 hours behind the shock waves. These peaks show a more clear configuration for events generated by eastern (from the Sun's central meridian) flares. Also they exhibit anisotropies along directions presumably coincident with the interplanetary field lines. A model to explain the possible origin of the ESP events is developed. According to this model the ESP events are particles that propagate directly from the Sun along the tangential discontinuity field lines which is expected to be formed in front of the piston-driven gas. A smoothing-field mechanism is suggested to account for the relative coherency of the particles.

INTRODUCTION

Solar protons of low energies (typically 10 MeV) that come in apparent association with the arrival of interplanetary shock waves are commonly known as Energetic Storm Particles (ESP). The main characteristics of these events can be summarized as follows [1, 2, 3]. i) There exists one-to-one correspondence with the occurrence of Forbush decreases; ii) considerable enhancement in the >10 MeV proton fluxes and, in some cases, may contain relativistic electrons; iii) the proton anisotropy is generally parallel to the actual direction of the interplanetary magnetic field; iv) the energy spectra is softer than the preceding flare effect.

In this paper we report the results of 0.7 to 7.6 MeV protons observed by Explorer 34 (between May 1967 and March 1969) and Explorer 41 (February through September 1972) during active periods associated with storm sudden commencements (SSC). The proton data come from the University of Texas at Dallas cosmic ray experiments on board of both satellites. Description, calibration and performance in space of the detectors are given in [4] and [5]. The amount of data analyzed was restricted only by their availability. The information on solar and geomagnetic activity was taken from several issues of the widely distributed Solar Geophysical Data (World Data Center A).

GENERAL CONSIDERATIONS

Recently Chao and Lepping [6] have made a study relating solar flares, interplanetary shock waves and SSC's. They found that more than 85% of the SSC recorded in the period 1968-1971 were due to interplanetary shock waves. The remaining events were attributed to tangential discontinuities. Although these results are not surprising, the work performed by [6] is of value because of its statistical significance. On this view we have taken all SSC's within the period of proton data availability as being due to the interaction of flare induced interplanetary shock waves with the magnetosphere. We went a little further and took also for this purpose the SSC's that were reported by less than 7 stations (this type of SSC is not underlined in the appropriate section of the Solar Geophysical Data). On the other hand, we selected arbitrary bright flares (seen in the Lyman-α) with importance 1B or more and which were located on the solar disc from E90 through W40 without any restriction in latitude. The remaining 50° (from W40-W90) was considered to be insignificant according to the model of solar square wave propagation proposed by [7] and [8]. Next, we associated every SSC with the most probable flare. This kind of association turned out to be not difficult because of the apparently obvious flare candidates after a reasonable estimate of transit times. Neverthless, there were few occasions where no distinct flare could be associated with reported SSC. Most of these cases were due to flares in the W40 -W90 distance from the central meridian and which were disregarded in this work as mentioned before.

Periods (of the order of 3 months) during which the line

Notice that in general following the flares, the particles arrive at the Earth by considerable perpendicular diffusion (or perhaps a combination of chromospheric diffusion followed by a parallel diffusion) since in all cases, except the May 1972 event, the location of the flare site is on the east of the central meridian. Just about the time of the shock wave arrival (SSC arrows) there is a peak enhancement of the protons in almost all the examples. This peak enhancement has been observed quite often [9, 10]. For several reasons [9] these particles are thought to be the result of an interplanetary acceleration, with the shock front representing the most important ingredient [11]. The origin of these "shock-spikes" must be different from the ESP [9, 10] especially due to the difference in energy and space position between both cases. Conversely, while there are acceptable acceleration models up to the shock-spikes protons [11], it is still difficult to find a convincingly self-consistent model [3] to account for the ESP events. In any case, these spikes are present in the data analized and will not be of interest to us in this paper.

The most important features to be observed in Fig. 1 are the peak enhancements that follow, after some hours, the arrival of the shock waves. In the August 1967 event (upper left diagram in Fig. 1) this peak is located around 2300 UT on the 11th of August. Similar peaks are present in the September and November events (around 1300 and 2100 UT respectively). The peak on September 20 occurred just before a SSC reported by few stations. The lower half diagrams show two events in 1972.

We found that this is a general cheracteristic difference between events associated with eastern and western flares.

In an attempt to make statistical statements about the lag-time of the ESP peaks with respect to the time of arrival of the interplanetary shock waves, we looked for the time of the first significant peak in the flux of 0.7 - 7.6 MeV protons after the time of the recorded SSC (taken here as an indication of the shock arrival). The result of this search is shown in Fig. 2. In this figure we plotted separately the results obtained using first the data of Explorer 34, then Explorer 41, and finally the (additive) combination of both. The upper half diagrams show the frequency of occurrences versus the lag-time (Δt) between the first significant peak of the energetic particle flux and the time of occurrence of the SSC. In this diagram the lag-time plotted has been rounded to the nearest 1/2 hour. The lower half diagrams are the same plots except that these lag-times have been rounded to the nearest hour. In the case of the Explorer 34 there are two general groups. The first one exhibits two peaks at 9 hrs. and 10.5 hrs. respectively in the upper diagram while in the lower (rounded to the hour) those peaks are located at 8 hrs. and 11 hrs. respectively. The mean values ($\langle\Delta t\rangle$) and standard deviation (σ) are indicated on top of both diagrams.

The other group (longer lag-time group) have no particular surface exists. Also a solar wind density peak is expected at this edge [18]. Of course, if the tangential discontinuity field lines are still connected to the flare site, as it is expected, energetic charged particles injected in the interplanetary medium at the flare site will propagate along this field lines if they could survive the perpendicular diffusion and provided the flare continues to be active in terms of cosmic rays. This idea of continuous injection and propagation along the discontinuity was first introduced by [8], and [7] have suggested a possible field line smoothing mechanism such that energetic particles could propagate along the discontinuity with a reduced perpendicular diffusion.

Figure 3 is a polar plot of the anisotropy vectors corresponding to the peaks of the ESP events. Vectors within 15^{o} intervals have been added so that in this manner we could have not only the number of events in a given direction but also the strength of the anisotropy along these directions. As a reference the direction of the Sun is indicated by an arrow. Notice that most of the anisotropy vectors are in the anti-Sun hemisphere. The strengths of the anisotropies are not terribly large but still we can notice a preferential direction away from the Sun and presumably coincidental with the general interplanetary magnetic field direction. If this were true, then the perpendicular directions to these anisotropy vectors would give approximately the projection on the eliptic plane of the general propagation direction of the discontinuity surfaces. Notice that this directions would then resemble the shock orientations given by [6]. With these remarks it

It is clear from Fig. 4 that particles starting from the Sun have to travel a longer distance to reach the eastern side of the driver-gas tangential discontinuity, since these particles should traverse first the western side. In the case of the model offered by [8] the field lines at and behind the discontinuity form a bubble with both ends of the field at the Sun's photosphere. Therefore particles could travel along both eastern and western sides of the discontinuity given a parallel and antiparallel particle anisotropy. This last case might not be so frequent according to [9] whose work was based on type II and type IV radio bursts observations.

We refer again to Fig. 4. What is needed in this model is to find an effective field line-smoothing mechanism to account for the pressumed coherency of the particles on the west side of the discontinuity. One possible candidate is represented by the considerable fluxes of solar cosmic rays injected during flare. If the pressure exerted by the cosmic ray particles becomes greater than the local magnetic field pressure then the field lines will be reordered. The elementary pressure on the field lines exerted by particles of energies between E and E + dE with pitch angle α is found to be given by the following expression:

$$dp \propto (mE)^{1/2} \sin^5\alpha \;\; j(E,\alpha,\Omega)\, dE\, d\Omega$$

where m is the mass of the particles, $d\Omega$ the elementary solid angle, and

2) Most of the anisotropy vectors are presumed to be aligned with the interplanetary magnetic field. The distribution of these vectors, in a polar diagram, resembles the direction of propagation of shock waves found by [6]. The particle anisotropy corresponding to events associated with eastern flares is larger than those generated by western flares. Furthermore, these particles are found to be relatively coherent (in the sense of exhibiting a distinct peak in the particle flux) when the responsible flare is located on the east of the Sun's central meridian.

3) Based on the observations a model of propagation of solar protons along the tangential discontinuity in front of the piston-driven gas is proposed. This model includes a smoothing mechanism of the interplanetary field lines caused by energetic solar particles released at the flare site. It is concluded that this smoothing could be more effective in regions close to the Sun.

The analysis reported indicates that even at these low energies the ESP events are still quite noticeable. However, the August 1972 event (Fig. 1) shows that the peak of activity must be located at somewhat higher energies. Indeed this is true according to experimental observations made by [1] and [2].

As for the model suggested in this paper we recognize that a more complete study is needed. Further studies should be

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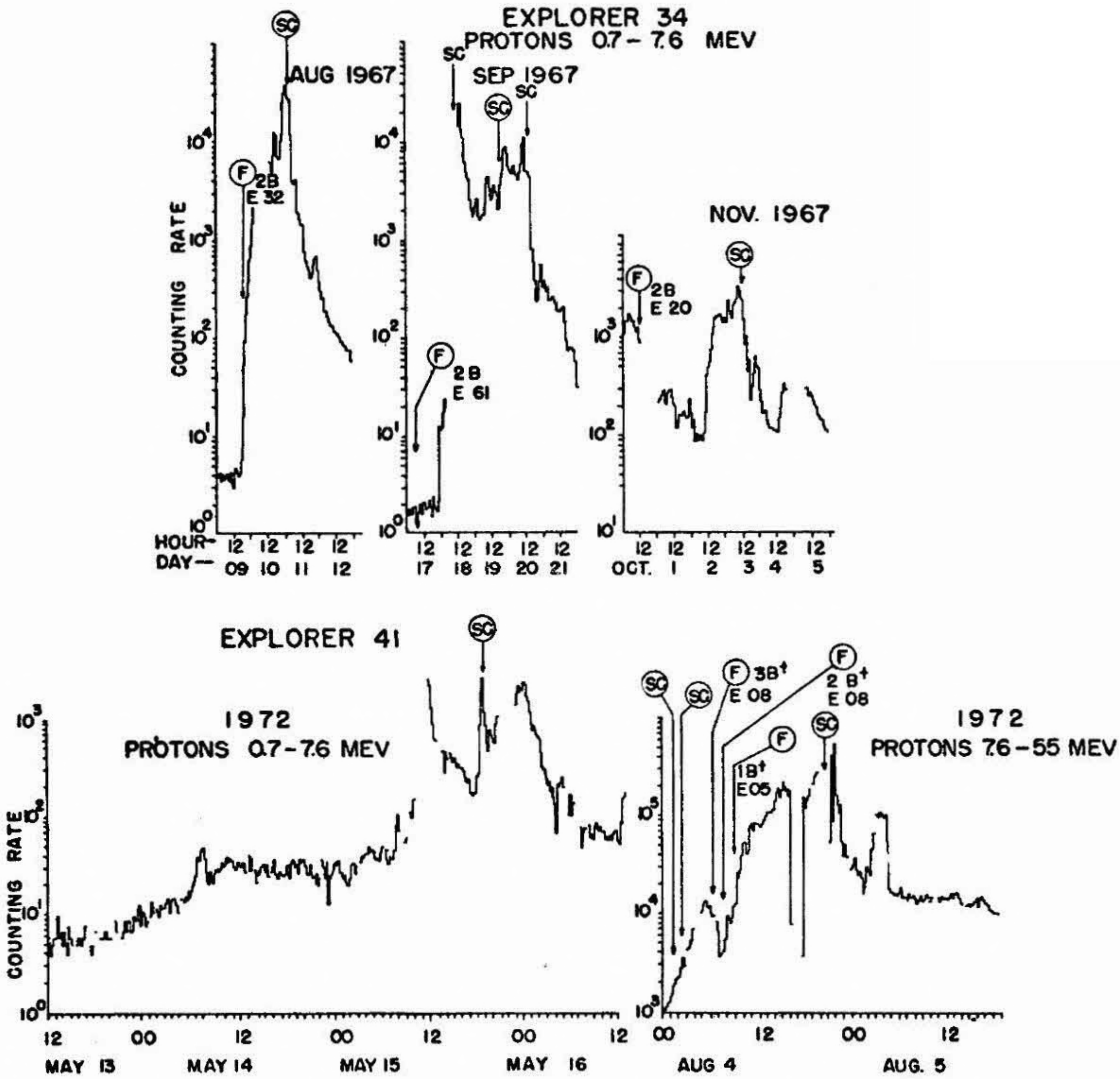
EXPLORER 34
PROTONS 0.7 - 7.6 MEV
AUG 1967
SEP 1967
NOV. 1967
COUNTING RATE
HOUR-
DAY-
EXPLORER 41
1972
PROTONS 0.7-7.6 MEV
1972
PROTONS 7.6-55 MEV
MAY 13
MAY 14
MAY 15
MAY 16
AUG 4
AUG. 5

FIGURE 1

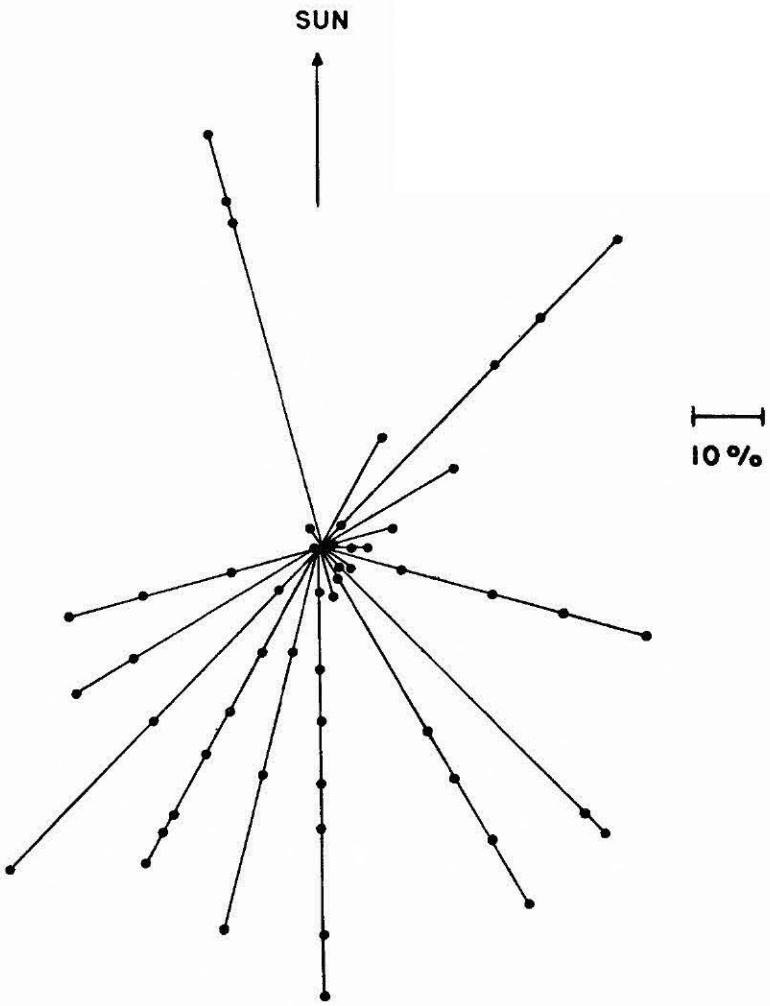

FIGURE 3