LOW-ENERGY PROTON INCREASES ASSOCIATED WITH INTERPLANETARY SHOCK WAVES

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Abstract. Impulsive increases in the low energy proton flux observed by the Explorer 34 satellite, in very close time association with geomagnetic storm sudden commencements are described. It is shown that these events are of short duration (20–30 min) and occur only during the decay phase of a solar cosmic-ray flare event. The differential energy spectrum and the angular distribution of the direction of arrival of the particles are discussed. Two similar increases observed far away from the earth by the Pioneer 7 and 8 deep-space probes are also presented. These impulsive increases are compared with Energetic Storm Particle events and their similarities and differences are discussed. A model is suggested to explain these increases, based on the sweeping and trapping of low energy cosmic rays of solar origin by the advancing shock front responsible for the sudden commencement detected on the Earth.

1. Introduction

Low-energy cosmic-ray particle enhancements (>10 MeV) of interplanetary origin associated with Forbush decreases of high-energy cosmic radiation have been discussed extensively in the literature (Bryant *et al.*, 1962; Rao *et al.*, 1967, 1969). It has been suggested that such enhancements known as 'Energetic Storm Particle Events' (ESP events) are due to low energy solar cosmic ray particles undergoing acceleration in shock fronts. ESP events have a typical time scale of about 6 hours, show a rapid onset and a rapid decay in association with Forbush decreases, and often exhibit pronounced bi-directional anisotropy at the cessation of the ESP event. In recent years, yet another type of enhancement of low-energy cosmic ray particles (~1 MeV) which occurs in close time association (~minutes) with the passage of a shock wave has been reported in the literature (Palmeira *et al.*, 1968, 1969; Singer, 1970; Amstrong *et al.*, 1970; Ogilvie and Arens, 1971). In this paper we discuss the general characteristics of these latter events which are characterized by impulsive spike-like enhancements. Typically, these events have a time scale of about 15–30 min, with an initial slow rise, followed by a very rapid rise to maximum intensity and a rapid decay. We compare these low-energy events with the ESP events and discuss their similarities and differences. Throughout this paper we will call these spikelike increases observed at the time of the passage of the shock front as low-energy ESP events, or LESP for short. From a study of the properties of these events, we suggest

* Part of this work was performed while the author was at the University of Texas at Dallas as a Visiting Professor.

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a model to explain the production of the LESP events in terms of the trapping and sweeping action of the shock front acting on the low-energy particles still present in the interplanetary medium following a solar flare event.

The data utilized herein have been obtained by our instrumentation on the Explorer 34 and 41 satellites. A detailed description of the instrumentation and the methods of data reduction are discussed elsewhere (Rao *et al.*, 1969; Bartley *et al.*, 1971). In brief, we obtain the fluxes of protons (0.7–125 MeV) and electrons (> 70 keV) in 8 directions in the ecliptic plane with respect to the Sun, in a number of contiguous energy channels, thus yielding both anisotropy and detailed spectral information.

2. Time Profile of LESP Events

During the period May 1967–April 1969, we have observed eight LESP events in the Explorer 34 data and three in the first nine months (June 1969–March 1970) of data from the Explorer 41 satellite. In Figures 1 through 4 we show the time profile of the omnidirectional counting rate of 0.7–7.6 MeV protons during four typical LESP events observed on 30 May, 5 June, 29 November, 1967 and 11 January 1968, respectively. The statistical error of each datum point is very small, comparable to the width of the histogram line. The associated geomagnetic storm sudden commencements are also indicated in each of the figures.

In all four cases a significant increase is observed in the low energy proton intensity around the time of the geomagnetic storm sudden commencement. It may also be noted that in all examples cited above, the LESP event occurred during the decay

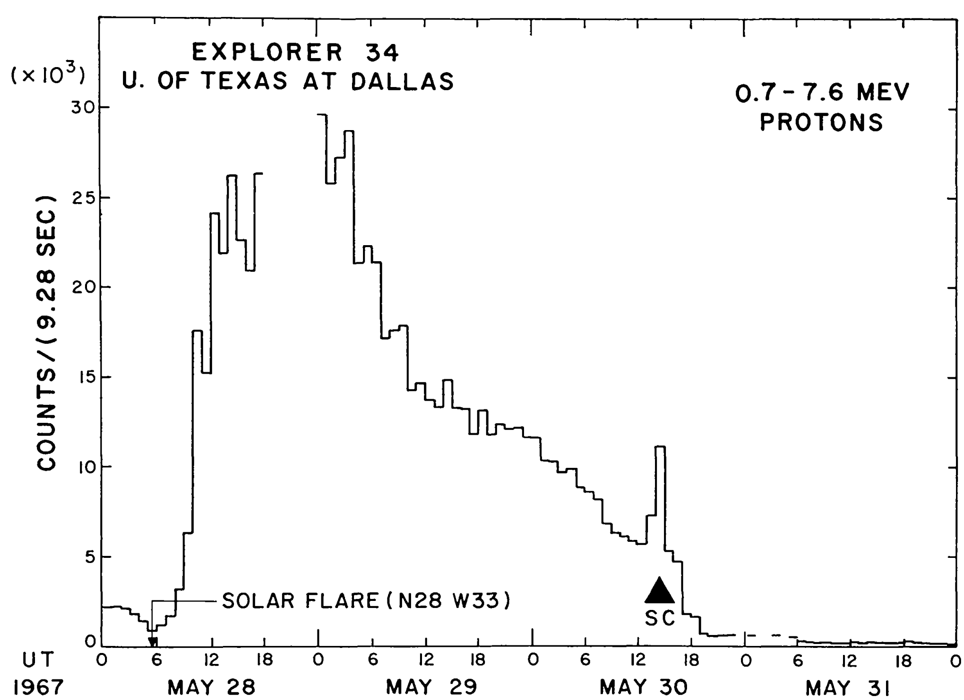

Fig. 1. The hourly averaged counting rate of 0.7–7.6 MeV protons for the period 28–31 May 1967. The short-lived increase is seen to occur at the time of the sudden commencement.

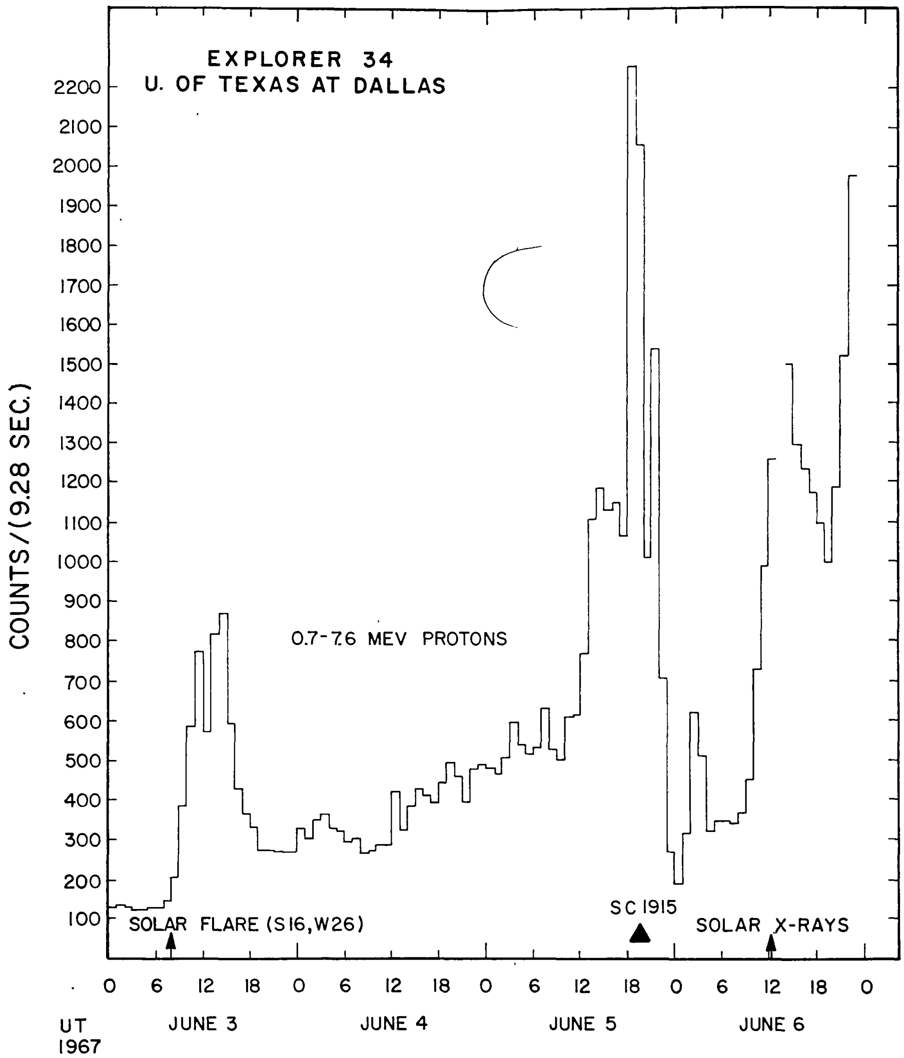

Fig. 2. The hourly averaged counting rate of 0.7–7.6 MeV protons for the period 3–6 June 1967. The sudden commencement on 1915 UT, 5 June is indicated.

phase of a previous flare event and that the cosmic-ray intensity prior to the LESP event was much higher than during quiet periods. In particular, immediately prior to the LESP event of 30 May 1967, which occurred during the decay phase of the flare event of 28 May 1967 (see Figure 1 and also Figure 17 of Rao *et al.* (1971)), the low-energy proton intensity was still three orders of magnitude higher than the quiescent intensity. In contrast to the relatively simple time profiles shown in Figures 1, 3 and 4, Figure 2 shows a complex structure for the time profile of the low energy protons observed during the period 3–6 June, 1967. A large and short-lived increase in the low-energy proton intensity was however detected in time association with the geomagnetic storm sudden commencement which occurred at 1915 UT, on 5 June 1967. The intensity-time profiles around the time of the sudden commencements, for the LESP events shown in Figures 1 through 4, are shown on expanded time scales in Figures 5 through 8 respectively. In these four cases, short-lived (order 15 min) low energy proton increases are observed, with the maximum intensity occurring at the

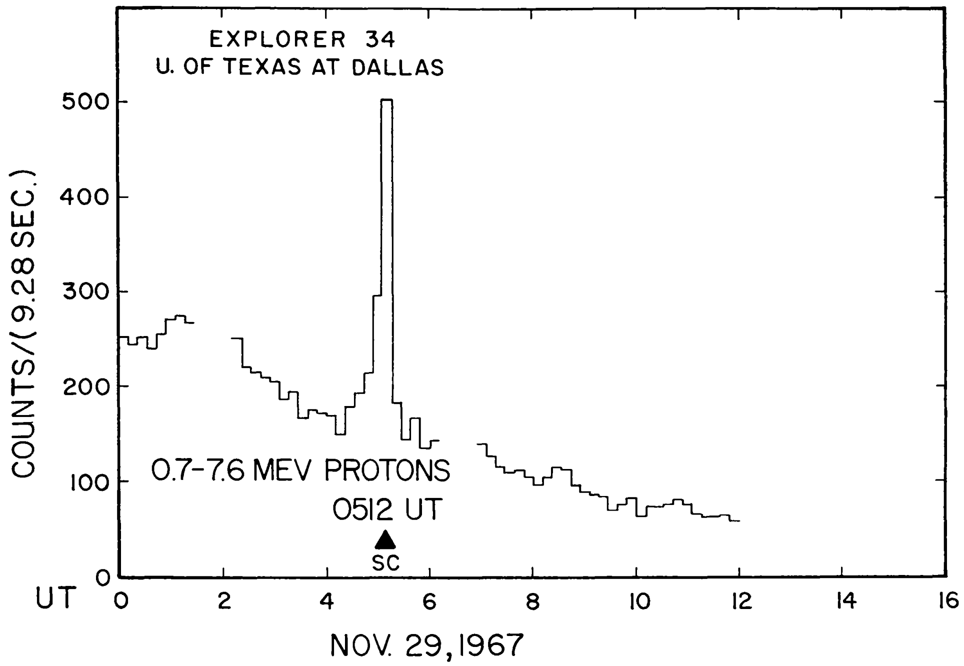

Fig. 3. The 11 minute average counting rate of 0.7–7.6 MeV protons for the interval 0000–1600 UT, 29 November 1967. The time of the sudden commencement at 0512 UT is indicated.

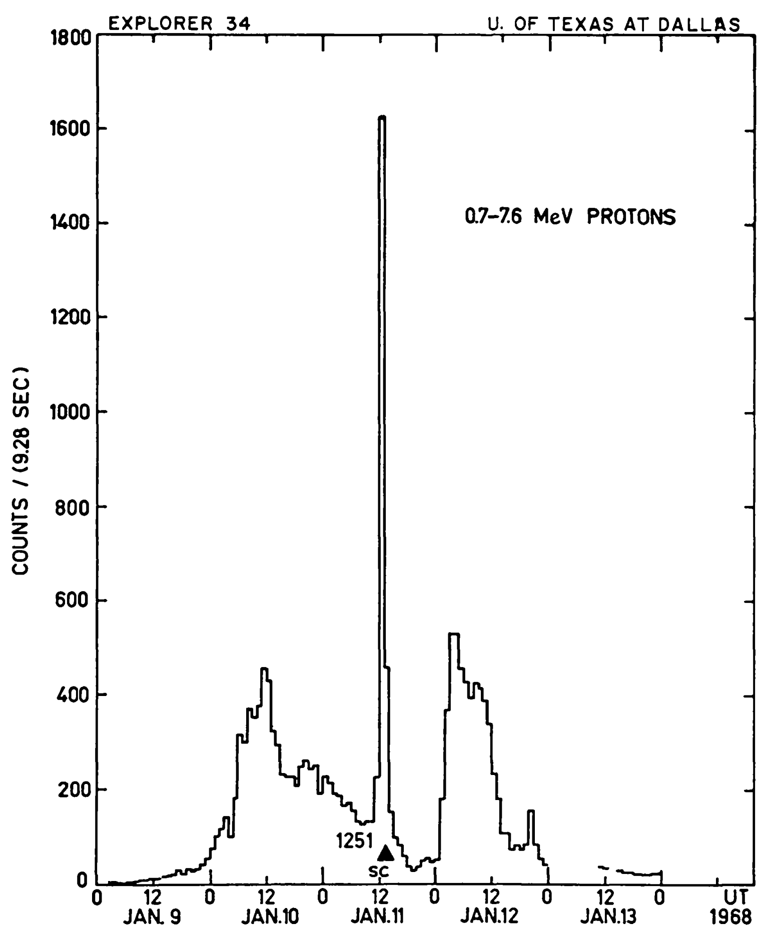

Fig. 4. The hourly averaged counting rate of 0.7–7.6 MeV protons for the period January 9–13, 1968. The sudden commencement at 1251 UT, 11 January is indicated.

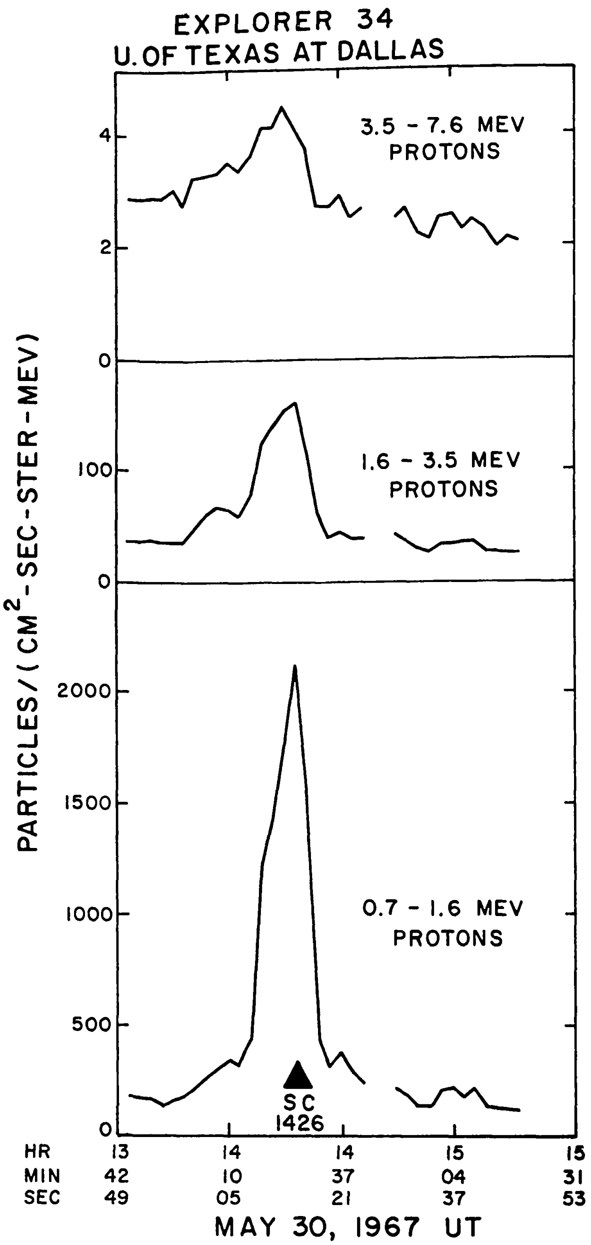

Fig. 5. The proton flux in three energy channels as a function of time for the 30 May 1967 event. Each datum point is a 9.28 s average taken every 164 s.

time of the sudden commencement, within the temporal resolution of the measurements (82 s).

Figure 6 displays also a few other smaller increases within the time interval 1753–2104 UT. These other increases although of short duration are smaller than the main increase at 1914 UT by a factor of 3–4. Ogilvie *et al.* (1968) have reported on the basis of plasma and magnetic field measurements that the Explorer 34 satellite was in the magnetosheath from 1700 to 1915 UT on 5 June. At this time, the shock interacted with the magnetosphere, giving rise to a sudden commencement, pushing the boundary of the sheath toward the Earth and leaving the satellite in the interplanetary medium until 2106 UT. Figure 6 also indicates, by the hatched area, the

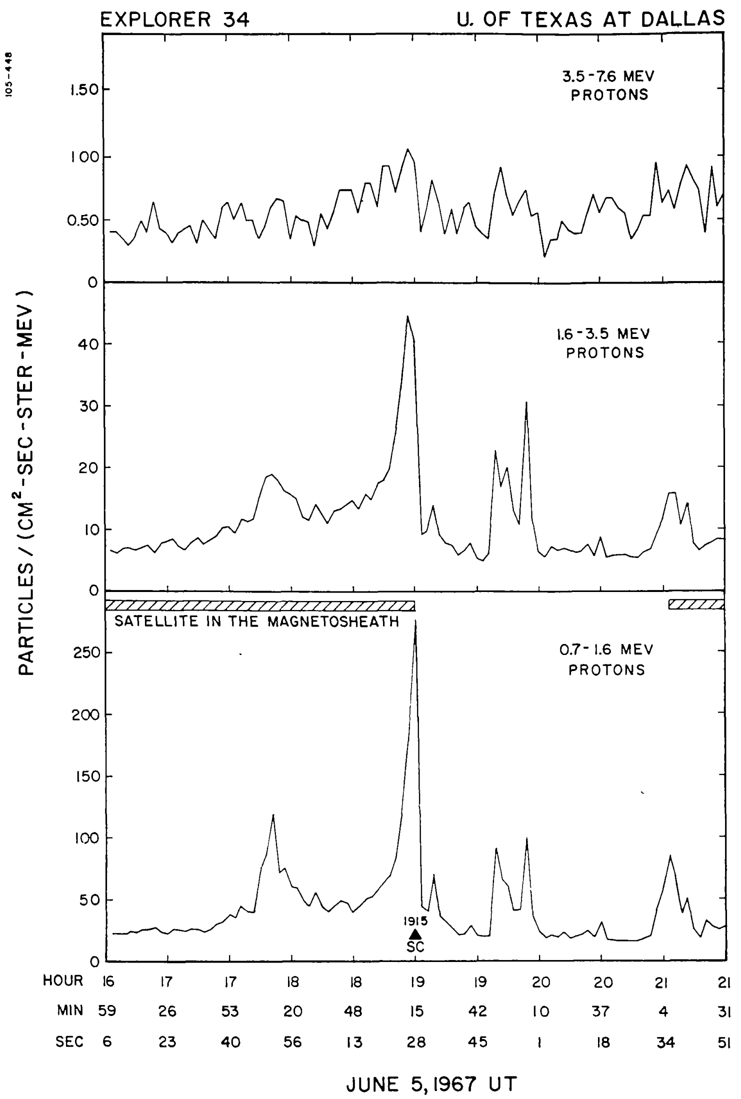

Fig. 6. The proton flux in three energy channels as a function of time for the 5 June 1967 LESP event. The time averages are the same as in Figure 5.

times according to Ogilvie *et al.* (1968) when the satellite was in the magnetosheath. Although the large spike at the time of the sudden commencement and the smaller increase starting at ~2100 UT occurred near the time when the satellite crossed the bow shock, two other smaller increases can be seen in Figure 6 to have occurred when the satellite was in the sheath and in the interplanetary medium, respectively. It is our opinion that the large spike at 1914 UT is connected with the occurrence of the sudden commencement, rather than the crossing of the bow shock and therefore is to be considered as a true LESP event.

Another fundamental characteristic of each of the LESP enhancements shown in Figures 5 through 8 is the initial slow increase followed by a large and very sharp increase, and a rapid decay. Figure 9 shows a sketch of an idealized LESP increase and its time association with a geomagnetic storm sudden commencement. Table I lists all the properties of the 11 LESP events observed by us along with the time of

TABLE I

Characteristics of the eleven LESP events detected by the Explorer 34 and 41 satellites

Event date	SC time (UT)	Time of the maximum of the event (UT)	t_1 (min.)	t_2 (min.)	t_3 (min.)	Maximum flux part./(cm²-sec-ster-MeV) at 1 MeV	Exponent of the energy spectrum	
							Before the event	At the max. of the event
The four events described in detail								
30 May 1967	1426	1427 ± 1	16	11	15	2000	−3.7	−7.0
5 June 1967	1915	1914 ± 1	15	7	13	30	−2.2	−6.5
29 Nov. 1967	0512	0515 ± 1	20	12	23	12	−3.6	−4.2
11 Jan. 1968	1251	1251 ± 1	56–68	3–15	<31	130	−4.5	−5.5
The other seven events								
3 Nov. 1967	0914	0918 ± 1	50	6	16	11	−1.4	−1.6
10 Feb. 1968	1621	1627 ± 1	30	2	16	2	−2.8	−3.9
16 Nov. 1968	0915	0915 ± 1	18	3	8	8	−1.8	−2.3
28 April 1969	0252	<0300	16–30	<5	13–27	1200	−5.6	−6.3
29 Sept. 1969	0452	0456 ± 1	32	16	28	1646 [b]	[c]	[c]
5 March 1970	0804	0834 ± 1	[a]	51	[a]	14	−3.1	−3.6
8 March 1970	1417	1418 ± 2	27–41	5	36	509 [b]	[c]	[c]

[a] Not well defined.
[b] At 3 MeV.
[c] Very high counting rate prevents spectral determination.

the geomagnetic storm sudden commencement. The times t_1, t_2 and t_3 (defined in Figure 9) are the duration of the slow increase, the time between the start of the fast increase, and the occurrence of sudden commencement, and the duration of the main increase, respectively. All the observed spike-like enhancements in our data occurred only in association with geomagnetic storm sudden commencements and during the decay phase of a flare event when the solar system was still populated by a large number of low-energy cosmic ray particles. Table I clearly shows that the initial slow rise in intensity lasts for nearly 30 min which is then followed by a sharp increase and a rapid decay, this phase of the event lasting $\lesssim$20 min.

3. Energy Spectra of LESP Events

Figures 5 through 8 also show that an LESP event is clearly a very low-energy phenomenon, with the intensity increase being observed predominantly below 3.5 MeV. The differential energy spectrum of the particles responsible for the 30 May 1967 LESP event is shown in Figure 10. Also shown for comparison are the spectra of the 28 May flare event, for three periods: near the maximum intensity of the flare event, immediately before, and immediately after the LESP event. Figure 10 clearly shows that the energy spectrum of the cosmic ray population responsible for the LESP event is much steeper compared to the flare particle spectrum observed earlier, either near maximum intensity or just prior to the LESP event. The energy spectrum

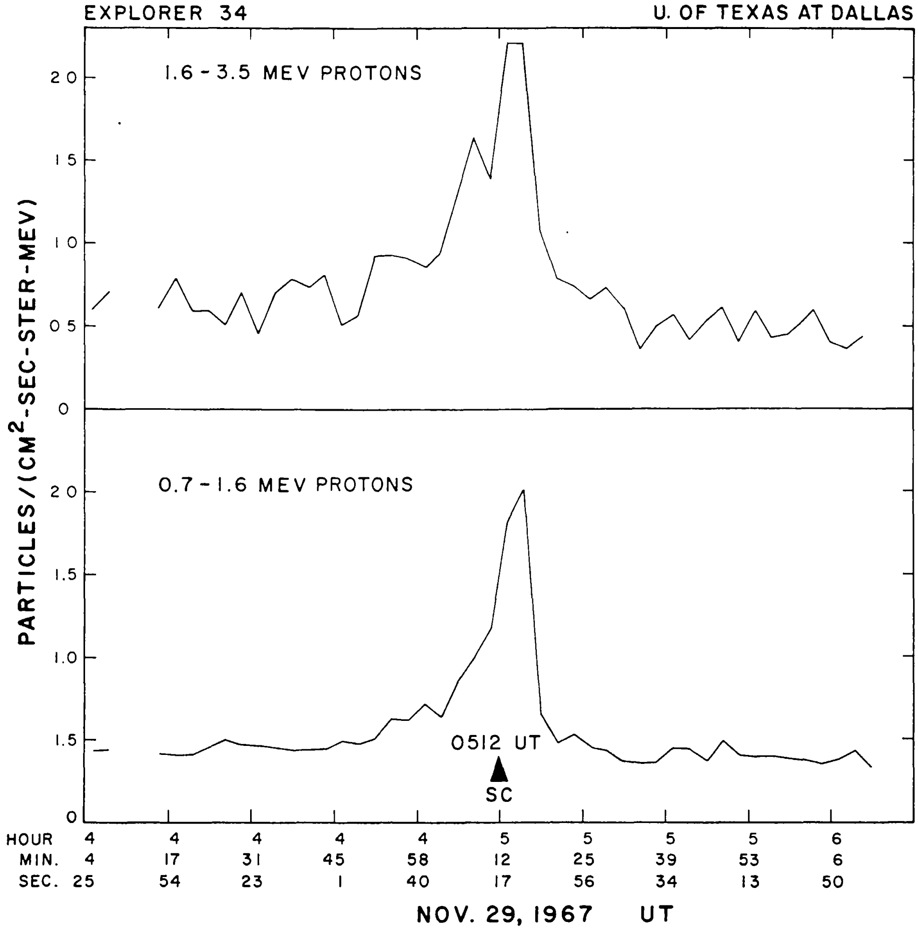

Fig. 7. The proton flux in two energy channels as a function of time for the 29 November 1967 LESP event. The time averages are the same as in Figure 5.

between 1416 and 1427 UT for particles of energy 2–7 MeV can be represented by a power law with an exponent of ~ -7 as against an exponent of ~ -2.5 observed near the maximum of the flare event of 28 May, and ~ -3.7 on 30 May just prior to the LESP event.

The spectrum obtained during the period 1500–1600 UT (shown as a dashed line in Figure 4), i.e., immediately following the low-energy LESP event, displays a very great similarity to the one obtained during the period 1300–1400. The flux is down by a factor of ~ 1.3, but the exponent of the fitted power law spectrum has within the errors of the measurements the same value found for the period 1300–1400 UT.

Table I also lists the spectral exponent of the low-energy cosmic ray enhancement during and prior to all LESP events. It is seen that for all the events, the spectrum of the cosmic ray particles in a LESP event is considerably steeper than the spectrum of the solar-flare produced cosmic rays.

4. Anisotropy Characteristics of LESP Events

Figure 11 shows the 11-minute averaged counting rates from 8 directions in the ecliptic plane for the LESP events discussed above, for protons in the energy range

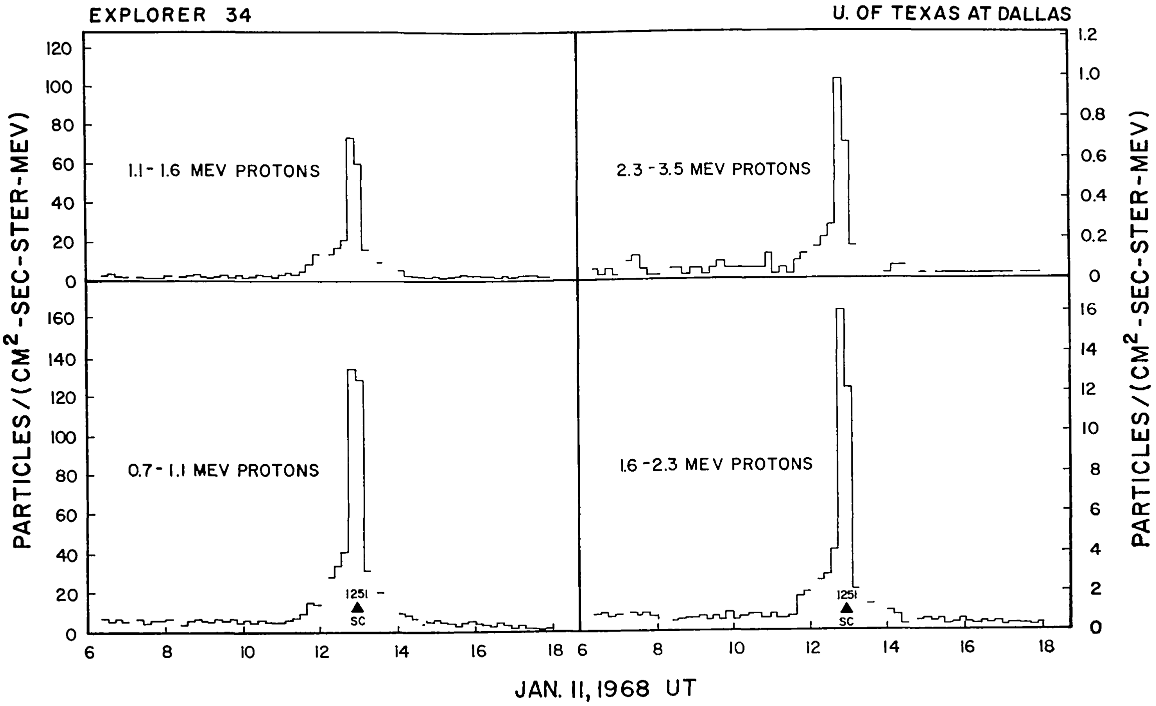

Fig. 8. The 11 min average flux in 4 energy channels as a function of time for the 11 January, 1968 LESP event.

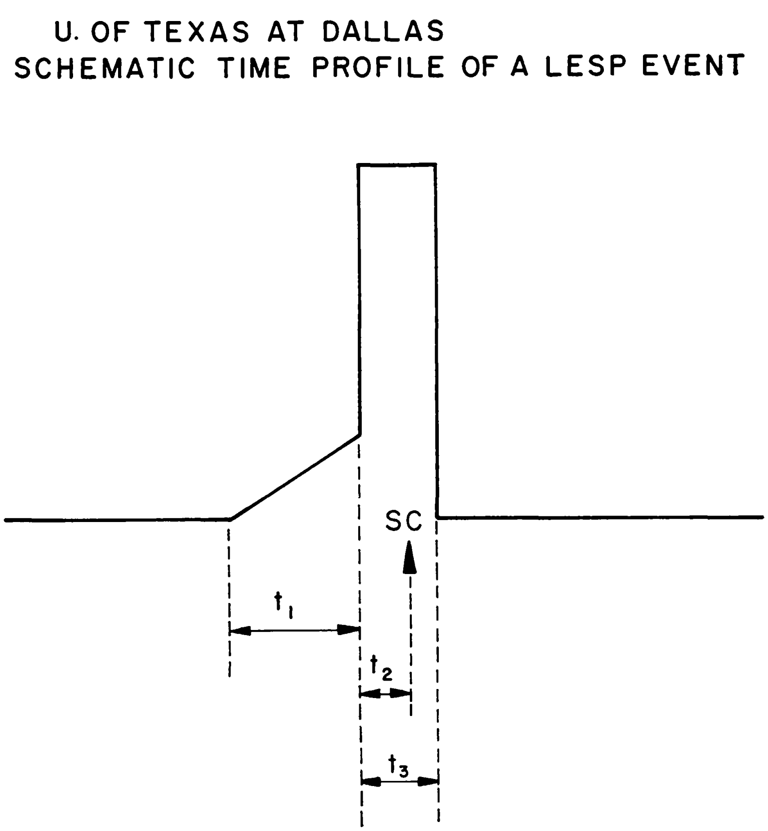

Fig. 9. Schematic representation of the time profile of a typical LESP event, showing the definitions of the times t_1, t_2 and t_3.

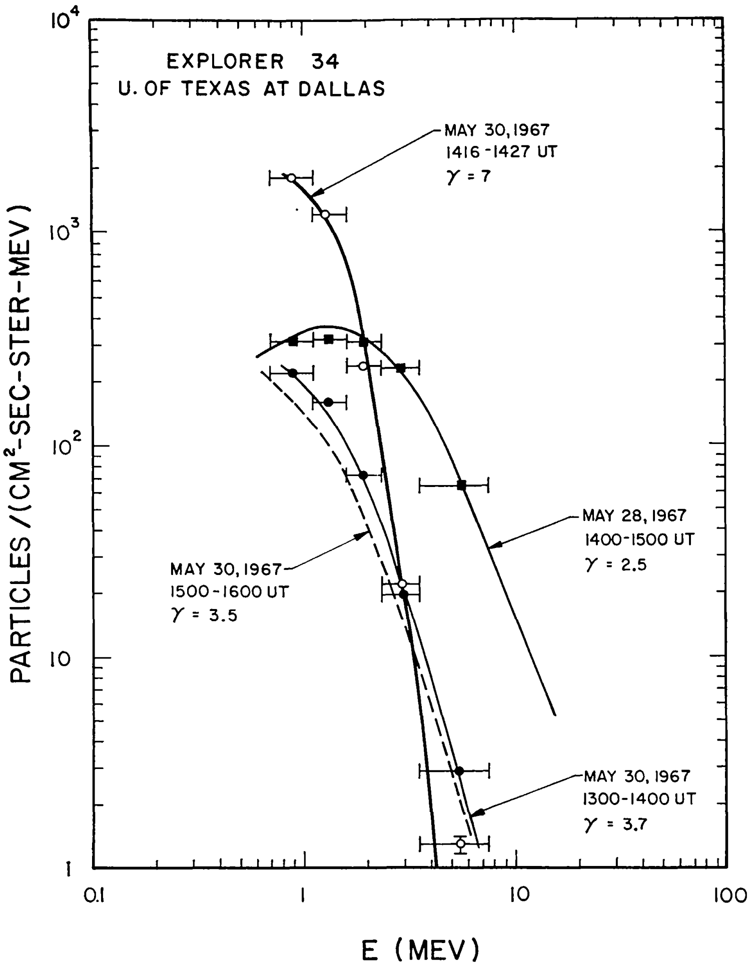

Fig. 10. The differential energy spectrum of the 30 May 1967 LESP event. Also shown for comparison are the spectra of the flare event of 28 May for three periods: near the maximum of the flare event, immediately before, and immediately after the occurrence of the LESP event.

0.7–7.6 MeV. This representation is commonly referred to as a 'snapshot' for a particular time and energy range. As may be seen in this figure, in at least two LESP events (5 June 1967 and 29 November 1967) the angular distribution of the low-energy particles exhibits marked bi-directionality, of amplitudes 18% and 52% respectively, with the direction of maximum flux aligned along the directions 45 °E and 135 °W of the Earth-Sun line. For the LESP event of 11 January 1968, there is a tendency for the distribution to show a bi-directional anisotropy, although not so markedly as in the 5 June or 29 November events.

On Figure 12 we show sample 'snapshots' for data taken over 9.28 s intervals at representative times during the 5 June and 29 November 1967 LESP events. Clearly, both uni-directional and bidirectional distributions are observed during a given LESP event. An examination of all the fine time scale data available indicates that the observed bidirectionality in the angular distribution is restricted to a period of 3–5 min around the time of maximum enhancement, may have an amplitude of up to 55%, and is not present before the onset or after the cessation of the rapid phase of the LESP event. Prior to the development of this bidirectionality, i.e., during the

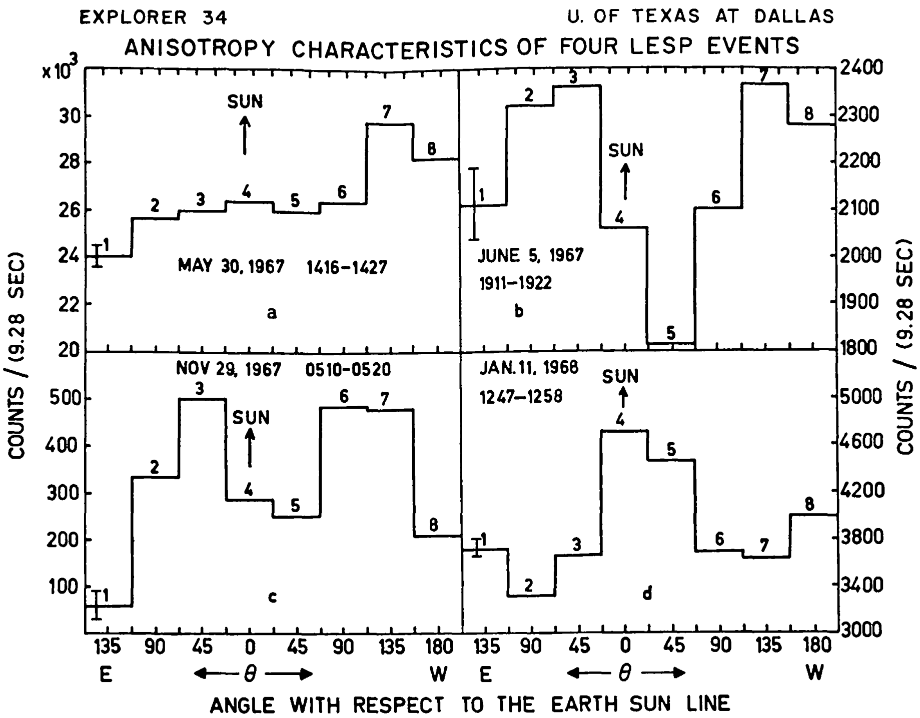

Fig. 11. The angular distribution in the plane of the ecliptic of the counting rate for the four LESP events described in detail in the text. Each 'snapshot' is a 11-min average taken near the time of maximum particle intensity after background subtraction. The average error of the eight directional measurements is shown for the first histogram bar. The octant number corresponding to each directional measurement is also indicated.

slow rise phase of the LESP event, strong unidirectional anisotropies are observed, with amplitudes up to 70%, over periods of the order of 10 minutes. For a given LESP event, the amplitude of the bidirectional anisotropy at the time of maximum intensity is of the same order of magnitude as the amplitude of the unidirectional anisotropy observed during the onset and rise to maximum intensity. The change in angular distribution occurs rapidly (<3 min) and in some cases, this change has occurred within the temporal resolution of the measurement (82 s).

Figure 12 also shows that for the 5 June and 29 November 1967 events, the angular distribution displays again a single maximum immediately after the time of maximum particle enhancement, but before the intensity had dropped to the background level. The direction of maximum flux for this period is approximately 180° away from that pertaining to the angular distribution obtained during the early phase of the event. These two directions of maximum flux also approximately coincide with the two directions of maximum of the bi-directional distribution obtained at the time of maximum particle enhancement.

It should be noted that since the counting rate at the maximum intensity phase of the LESP event is much higher than during the slow increase phase, the 11-min averaged angular distributions shown in Figure 11 reflect primarily the bidirectional distribution pertinent to the time of maximum intensity.

The angular distribution for the 30 May 1967 event, shown in Figure 11a, is

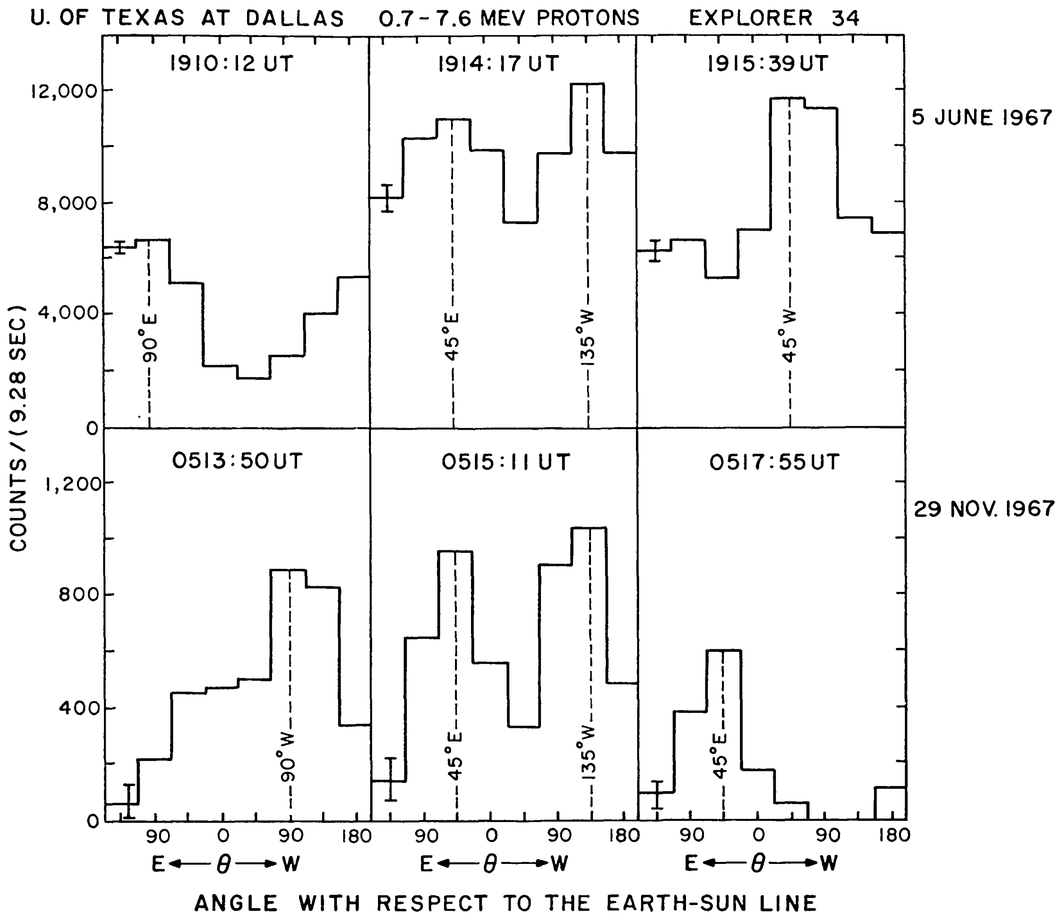

Fig. 12. Representative angular distribution in the ecliptic plane of the particles responsible for the LESP events of 5 June 1967 and 29 November 1967. For each event, three 'snapshots' are shown: before, during and after the maximum particle enhancement. The average error of the eight directional measurements is shown for the first histogram bar. The unidirectional anisotropies are typical of those observed during the slow rise phase of a LESP event. The bidirectional distribution is only observed around the time of maximum particle intensity.

essentially isotropic (~7% anisotropy). However markedly unidirectional anisotropies of rapidly fluctuating phase are observed when the highest temporal resolution data are examined (one measurement every 82 s). Consequently this nearly isotropic distribution is a result of averaging the data over a time interval longer than the characteristic time of the fluctuations. At the time of maximum intensity of the LESP event, no reliable anisotropy measurements could be obtained due to large errors introduced by an S-T type accumulator, when used to measure very high counting rates (Bartley *et al.*, 1971). This is also true for the events of 29 September 1969 and 8 March 1970. For the remaining events listed in Table I, there is a tendency for the angular distribution to exhibit a bidirectional characteristic around the peak intensity of the event.

5. Search for Electron Fluxes in the LESP Events

Our cosmic ray experiment on board the Explorer 34 and 41 satellites, (Bartley *et al.*, 1971) includes a proportional counter sensitive to X-rays with energies >2 keV, electrons with energies >70 keV, and protons with energies >2 MeV. Allum *et al.* (1971) have shown that for pure proton events the regression line defining the relationship between the flux increase observed by the proportional counter and the flux increase above 2 MeV observed by the solid state detector has a slope of almost unity. Thus, a comparison of flux increases in these two counters can be used to infer the presence of electrons during the LESP events. For the LESP events detected when reliable proportional counter data were available, such a comparison indicates that the proportional counter is responding entirely to >2 MeV protons, with the electron flux being negligible. The absence of an electron flux in an LESP event is consistent with the observation that the electron flux before the LESP event was also negligible. No sudden commencement occurred in the decay phase of a solar electron event during the period under consideration, so no information on a possible LESP event following a solar electron event could be obtained.

6. Observation of LESP Events far Away from the Magnetosphere

Cosmic-ray detectors similar to the one herein described were also flown in the deep space probes Pioneers 6, 7, 8 and 9 (Bartley *et al.*, 1967; Bukata *et al.*, 1970). Figure 13 shows the omnidirectional counting rate of >7.5 MeV protons detected by the

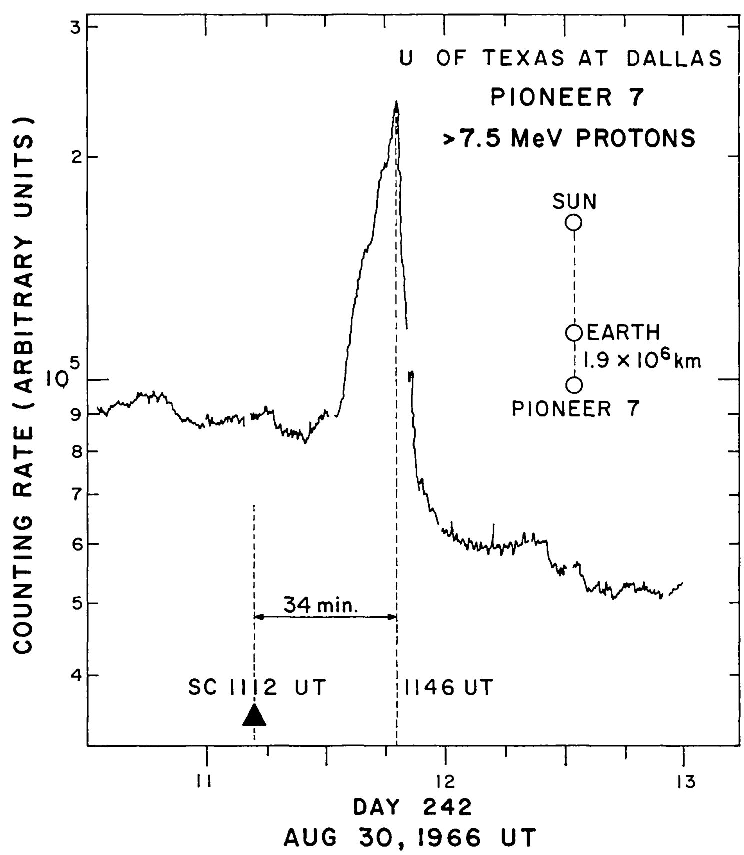

Fig. 13. The intensity-time profile of a LESP event observed at the Pioneer 7 spacecraft on 30 August 1966. Individual data points are taken at 14 s intervals.

Pioneer 7 spacecraft on 30 August 1966. At this time, this spacecraft was located at a distance of 1.9×10^6 km from the Earth, essentially along the Sun–Earth line (see insert in Figure 13). It is clear that an increase very similar to the LESP events reported in this paper was detected, the maximum intensity occurring at ~1146 UT. A sudden commencement was detected on Earth at 1112 UT, ~34 min prior to the maximum of the increase observed by Pioneer 7. This time delay plus the Earth–Pioneer separation implies a maximum value of 935 km/s for the speed of propagation of the shock front from the Earth to the spacecraft, under the assumption that the LESP event was produced by the same shock front that produced the sudden commencement detected on Earth. This calculated speed represents an upper limit, since it was assumed in the calculation that the shock front was propagating along the Sun–Earth line. Similar calculation based on the delay time between the occurrences of the most probable parent flare and the sudden commencement yields an upper limit of 946 km/s for the shock front, in close agreement with the value obtained above. We therefore maintain that the same shock front which produced the sudden commencement on Earth, also produced the LESP event detected by the Pioneer 7 spacecraft some 34 min later, when the shock front passed by the satellite location.

The 5 March 1970 event is the only event reported in this paper for which data from any of the Pioneer 6 to 9 spacecrafts were available at the time of the event. Figure 14 shows the omnidirectional counting rate of 1–1.9 MeV protons recorded by the Pioneer 8 spacecraft on 5 March 1970. Figure 14 shows that a short-lived increase in intensity was detected at 0940 UT, approximately 1 h and 36 min after

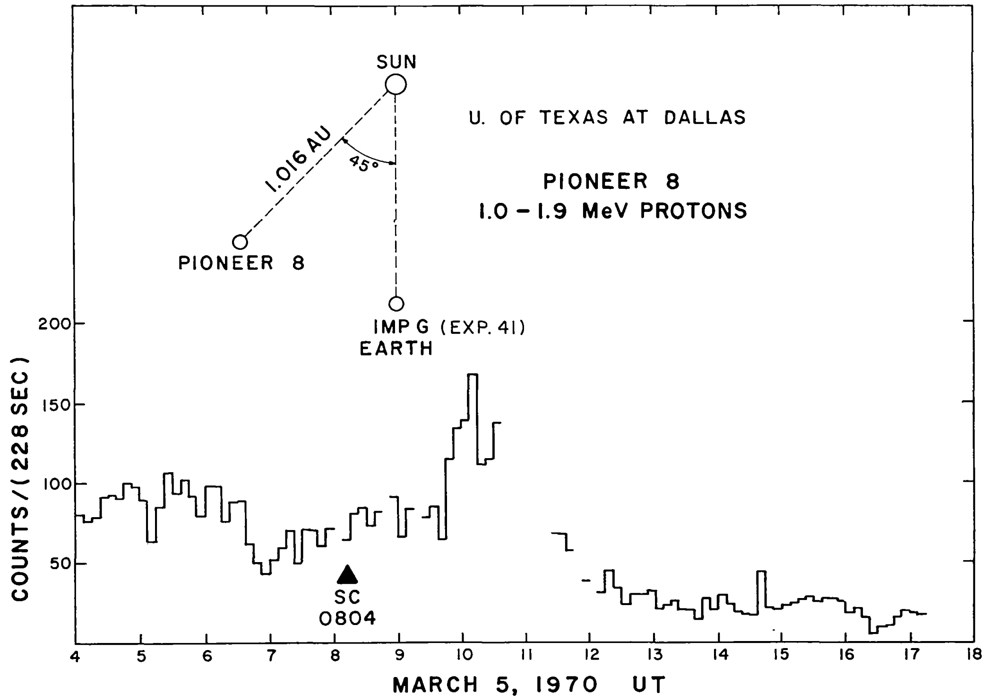

Fig. 14. The 7.5 min averaged counting rate of 1–2 MeV protons for the period 0400–1700 UT, 5 March 1970 recorded by the Pioneer 8 spacecraft. The location of this satellite in the ecliptic plane at the time of these measurements is shown in the insert.

the detection of the sudden commencement on the Earth. This short-lived increase could thus represent another example of a LESP event recorded far away from the magnetosphere. The 1 h and 36 min delay between the sudden commencement and the intensity increase is not inconsistent with the known radial and azimuthal separation of the spacecraft from the Earth, and the western location of the most probable parent flare.

A two-point energy spectrum determination from the Pioneer 8 data yielded a spectrum proportional to $E^{-\gamma}$, with $\gamma = 3.3 \pm 1.5$ between 1 and 1.9 MeV. This is in good agreement with a corresponding value of $\gamma = 3.6 \pm 1.0$ between 1 and 5 MeV calculated from the Explorer 41 data.

7. Discussion

Rao *et al.* (1967) using the data from the Pioneer 6 and 7 deep-space probes discussed the properties and suggested a model for the production of Energetic Storm Particles (ESP) events. The general properties of the 7 ESP events discussed by Rao and collaborators were:

(1) They were seen only in their lowest energy channel (7.5–45 MeV). The energy spectrum was steeper than the one pertaining to the preceding flare effect.

(2) They lasted for a short period, with a typical time scale of 6 h.

(3) They occurred in association with magnetic storms and the Forbush decreases at higher energies.

(4) A bi-directional anisotropy was often observed during the minimum intensity phase of the Forbush decrease, that is, after the cessation of the ESP event, and some 10–20 h after the geomagnetic storm sudden commencement and the onset of the associated Forbush decrease.

Although, there are similarities between these ESP events and the events discussed in this paper, there are also important differences which are summarized below:

(1) In general, the LESP events are restricted to particles of energies less than 7.5 MeV and in some cases to less than 3.5 MeV, as opposed to the 7.5–45 MeV energy range in which the ESP events are detected.

(2) The time scales are different, the typical one for the LESP events being of the order of 20–30 min as compared to 6 h for the ESP events.

(3) The maximum intensity of a LESP event occurs within a few minutes of the time of the sudden commencement. A similar time correlation is not observed for ESP events. In fact, the maximum intensity of the 20 January 1966 ESP event occurred at 0930 UT (Rao *et al.*, 1967), that is, 7.5 h after the detection of the sudden commencement on Earth, and 8.5 h after the passage of the shock front by the Pioneer 6 spacecraft.

(4) The LESP events could occur before the onset of the Forbush decrease detected at higher energies. The 11 January 1968 event, for instance, was recorded 3–5 h prior to the Forbush decrease. The ESP events however occur in approximate time coincidence with the decreasing intensity phase of the Forbush decrease.

(5) Bidirectional anisotropies for the LESP events are observed only *at the time of maximum particle intensity*. However, the bidirectional anisotropies observed by Rao *et al.* (1967) in connection with ESP events occur *after the cessation of the event*.

Rao *et al.* (1967) have suggested that the ESP events were produced by acceleration of existing cosmic rays to somewhat higher energies by an acceleration mechanism within the shock fronts associated with the onset of the Forbush decrease. On the basis of the differences listed above, it is obvious that this suggestion cannot be used to explain the observed properties of the LESP events. Events with properties similar to those LESP events discussed herein have been reported in the literature (Palmeira *et al.*, 1968; Palmeira *et al.*, 1969; Lanzerotti, 1969; Singer, 1970; Armstrong *et al.*, 1970; Ogilvie and Arens, 1971; Palmeira *et al.*, 1971).

Armstrong *et al.* (1970) have described four LESP events using data from the Explorer 33 and 35 satellites during the period July 1967–February 1968. Two of these increases (29 November 1967 and 11 January 1968) were also registered by our detector on Explorer 34 and have been discussed above, while the other two increases (26 January and 20 February 1968) were not detected in our data.

It is worth noting however, that at the time of the sudden commencements on 26 January and 20 February 1968, the intensity of low energy particles recorded by our detector on Explorer 34 had returned to essentially the background level, and therefore, solar particles were no longer present at the satellite position. As discussed later, the presence of solar particles at the time of the sudden commencement is a necessary condition for the observation of a LESP event. In addition, at the time of these two events reported by Armstrong *et al.* (1970), the Explorer 34 satellite was located deep inside the magnetosphere. Among the LESP events detected by the Explorer 34 satellite, the 10 February 1968 was the one corresponding to the deepest satellite penetration into the magnetosphere (see Figure 16). This was also the event with the smallest measured flux. It is thus our contention, that the absence of a LESP event in the Explorer 34 data on 26 January and 20 February 1968 is due to the absence of solar flare particles at our detector threshold level, and/or the location of the satellite deep inside the magnetosphere at those times.

At the time of the 11 January 1968 event, the Explorer 33, 34 and 35 satellites were sufficiently separated from each other, so that a determination of the direction and speed of propagation of the disturbance responsible for the LESP event is possible. The positions of the Explorer 33 and 35 satellites in the ecliptic plane, and the times of maximum enhancement (Armstrong *et al.*, 1970) together with similar quantities from the present experiment are indicated in Figure 15. Neglecting the coordinates out of the ecliptic plane, we find that the velocity component in the ecliptic plane of the disturbance was 544 ± 100 km/s and it was moving in a direction such that its intersection with the ecliptic plane made an angle of $\sim 55°$ (towards the East) with the Earth–Sun direction (see Figure 15). This is in good agreement with the values $(539+70)$ km/s and $(60 \pm 15)°$ obtained by Ogilvie and Burlaga (1969) for similar quantities pertaining to the shock front responsible for the magnetic disturbances

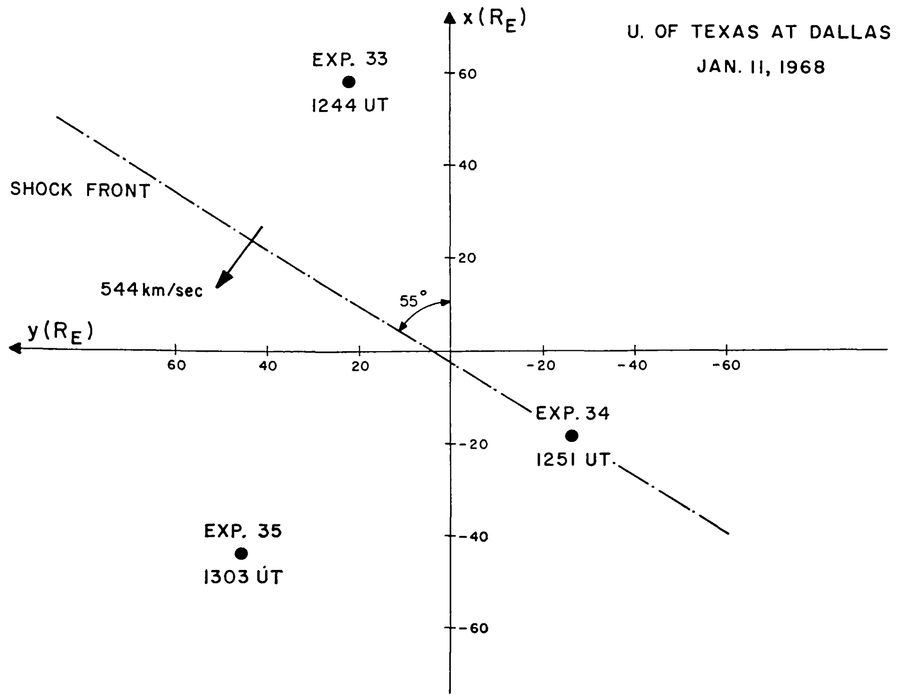

Fig. 15. The projection into the ecliptic plane of the Explorer 33, 34 and 35 satellite positions for the 11 January 1968 LESP event. The times at which the maximum enhancements were observed, are shown. The direction and velocity of the shock front calculated for this event (see text) are also indicated.

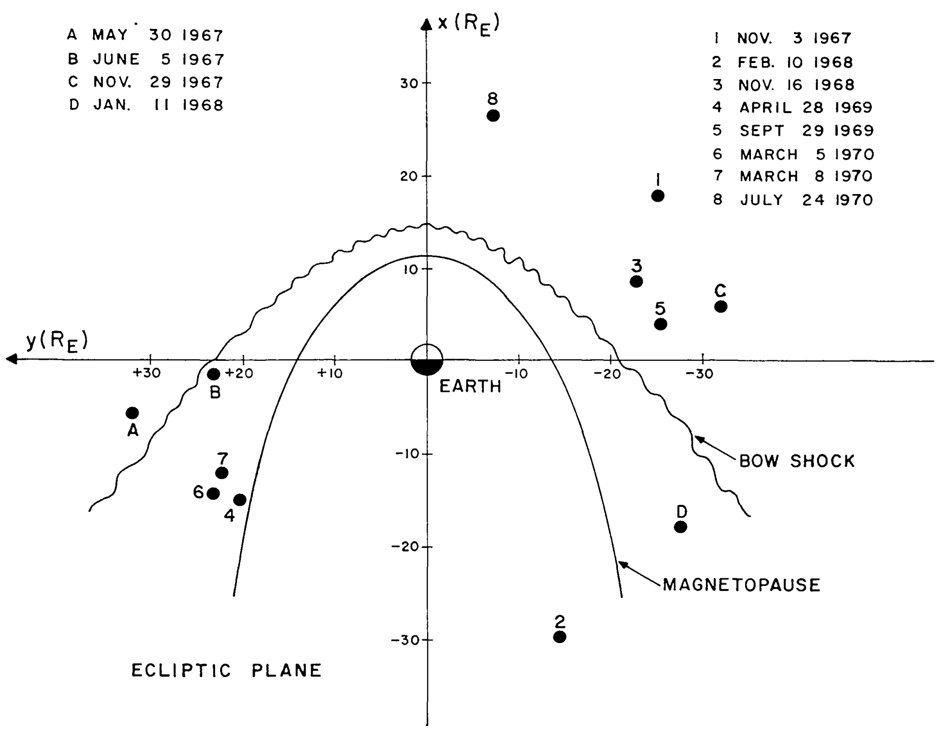

Fig. 16. The projection into the ecliptic plane of the Explorer 34 satellite position at the time of the LESP events listed in Table I. The events labeled A, B, C and D are those shown in detail in Figures 5–8. An additional LESP event which occurred on 24 July 1970 is also included. The nominal position of the magnetopause and the bow shock are shown.

detected at the same three satellites. There is little doubt therefore that the magnetic disturbances observed at the three satellites and the LESP events registered at the same satellites were caused by the same shock front. Similar analysis for the 29 November 1967 event yielded the values of 410–610 km/s and 100°–140° for the velocity and direction of the disturbance respectively, the uncertainty being due to the uncertainty in the time of maximum particle intensity measured by the Explorer 33 satellite. Ogilvie and Burlaga (1966) obtained for the same event the values (360 ± 140) km/s and $(110 \pm 15)°$, respectively.

The angles between the shock front normal and the ecliptic plane were found by Ogilvie and Burlaga (1969) to be 0° and −35° for the events of 11 January 1968 and 29 November 1967 respectively. Since for the 11 January 1968 event the shock normal was essentially in the ecliptic plane, our calculated values are expected to be a good approximation to the true values. For the 29 November 1967 event however, the relatively large angle between the shock normal and the ecliptic renders our calculated values less accurate. Despite this, our calculated values agree closely with those deduced by Ogilvie and Burlaga (1969) using a 3-dimensional model, for both the 11 January 1968 and the 29 November 1967 events.

Figure 16 shows the satellite position in the ecliptic plane at the time of all LESP increases listed in Table I. The nominal positions of the magnetopause and the bow shock are also shown. It can be seen that in the 30 May and 5 June events the satellite was close to the bow shock front and, indeed, Ogilvie *et al.* (1968) reported that the spacecraft had crossed the bow shock a few times before and after the occurrence of the LESP events. In the 29 November 1967 and 11 January 1968 events, however, the satellite was in the interplanetary medium and in the magnetosheath, respectively. It seems, therefore, that the likelihood of detecting a LESP event is independent of the position of the satellite with respect to the magnetopause and the bow shock.

Ogilvie and Arens (1971) using low energy particle, plasma and magnetic field data from the Explorer 34 satellite have reported five cases of low energy proton increases (1–10 MeV) in association with the detection of shock fronts, similar to those reported in this paper. They interpret these increases in terms of a model originally developed by Axford and Reid (1963) based on particle acceleration by successive reflections between the incoming shock front and the Earth's bow shock. However, the observations reported herein of at least two such low-energy flux increases (Figures 13 and 14) at the time of the passage of the shock fronts past the Pioneer 7 and 8 spacecrafts, when these spacecrafts were 1.9×10^6 km and 1.5×10^8 km from the Earth respectively, indicate that the Axford and Reid mechanism, involving particle reflections between the shock front and the Earth bow shock is completely untenable, at least for these two events. Such was also the conclusion for the ESP event (Rao *et al.*, 1967). Another model has therefore to be invoked to explain these increases detected far away from the Earth. The absence of bidirectional anisotropies in the early phase of the LESP events is also inconsistent with the predictions of the Axford-Reid model. Any model seeking to explain the formation of these spike-like increases should predict the following principal properties of these events:

(1) The short duration of the event.

(2) The fact that these increases are usually restricted to <7 MeV particles.

(3) The fact that these increases are detected only when solar flare protons of energies ~ 1 MeV are still present at the detector location.

(4) The slow increase, followed by a rapid increase at the time the shock front passes by the detector, followed by a rapid decay usually below the background level prevalent before the event.

(5) The unidirectional anisotropy during the slow rise of the event, followed by a bidirectional anisotropy around the time of the maximum enhancement.

(6) Their detection far away from the influence of the Earth magnetosphere and bow shock.

We propose here a mechanism that we believe can explain all the important features described above. A similar mechanism has been proposed independently by Fisk (1971). This mechanism assumes that low-energy protons produced in solar flares are efficiently reflected by the shock fronts responsible for the sudden commencements observed on Earth. If, in addition, we assume that those low energy particles, could be trapped ahead of the shock front, we arrive essentially at a model where the low-energy solar particles are effectively 'piled-up' ahead of the shock front, and are thus 'swept away' as the front passes by the observer's position. We expect the trapping and sweeping action of the shock front to be more efficient on the lower energy particles and, therefore, we expect the spectrum of the observed increase to be steeper than the solar particle background spectrum. The very close time association between the maximum of the increase and the arrival of the shock front (as indicated by the sudden commencement) can be understood if the trapping and sweeping efficiency is high, so that the low-energy particles will 'pile-up' ahead of the shock front, and the maximum intensity will be detected at the time the shock front passes the position of the detector. Before the main increase, however, when the shock front is still some distance away, the particle intensity should increase slowly due to those particles that are escaping from the trapping region. The general time profiles of all the LESP events recorded show a slow increase lasting for approximately 20 min. At an average speed of 10^3 km/s this implies that the particle intensity starts to increase at a position 1.5×10^6 km ahead of the shock front. If the shock is very efficient in sweeping out the low energy solar particles, and in screening the high energy galactic particles, the cosmic ray intensity behind the shock front should be reduced to essentially the depressed background galactic level.

An analysis of the anisotropy observed during the LESP events, as typified by the three angular distributions shown in Figure 12 for the events of 5 June and 29 November 1967, lead us to subdivide a LESP event into 3 phases.

Phase A. The slow increase phase

During this phase, when the particles being detected are those that are escaping ahead of the shock front, the angular distribution displays one single maximum, presumably along the local direction of the interplanetary magnetic field.

Phase B. The maximum intensity phase

During this phase the satellite is located immediately ahead of, or inside the shock front. The particles that are temporarily trapped in the shock front would produce an angular distribution of essentially a bidirectional nature (for reasons presented earlier by Rao *et al.* (1967)].

Phase C. The decay phase

The shock front has passed by the satellite, and the particle intensity is decaying rapidly to the background level prevailing behind the shock front. The determination of the angular distribution during this phase is not always easy, since the decay to the background level takes place very rapidly. In the two cases where this determination could be made (see Figure 12) the angular distribution was seen to display again one single maximum, from a direction opposite the direction found in Phase A. We are therefore in this phase detecting primarily those particles that penetrate the shock front from downstream without being efficiently reflected by the front (i.e., diffusion driven by a positive cosmic-ray density gradient).

The mechanism described above could in principle produce an energy gain, since it involves reflection by a moving front. This energy gain, however, is not essential to produce the observed spike-like increase in intensity, which could be produced by an efficient trapping and sweeping action of the shock front on low-energy ($\sim$1 MeV) particles of solar origin. Finally, since this mechanism does not require the presence of the Earth's magnetosphere and bow shock, it can produce a short-lived increase far away from the Earth. This mechanism is thus borne out by the observed properties of the LESP events previously discussed.

The model here proposed is very similar to the model independently suggested by Fisk (1971). This author assumed that low-energy particles (0.3–5 MeV) are reflected by the shock, subsequently traveling radially outwards, but because of extensive scattering by magnetic field irregularities they are eventually backscattered and thus remain near the shock front forming the short-lived particle increase. Using a one-dimensional model in which the particles undergo convection and diffusion, and in which they can gain energy by making repeated collisions with the moving shock front or with the magnetic irregularities directly behind the shock, Fisk (1971) calculated in detail the expected time profile and the energy spectrum of these increases. Using reasonable initial conditions, he found good agreement between the calculated and observed time profiles for the 30 May and 29 November 1967 events. Another result of the Fisk's calculation is that for sufficiently low energies, the energy spectrum at the shock front will be harder than the ambient spectrum. For higher energies, where the particle density has not reached a limiting value, the spectrum is expected to be softer. This limiting energy is estimated by Fisk to be in the vicinity of 1 MeV. In all LESP events that we have detected, the energy spectrum was found to be softer than the ambient spectrum, but since our energy threshold is $\sim$1 MeV, we are unable to test this prediction of Fisk's calculation relating to the energy spectrum.

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References

Allum, F. R., Palmeira, R. A. R., Rao, U. R., McCracken, K. G., Harries, J. R., and Palmer, I.: 1971, *Solar Phys.* **17**, 241.

Armstrong, T. P., Krimigis, S. M., and Behannon, K. W.: 1970, *J. Geophys. Res.* **75**, 5980.

Axford, W. I. and Reid, G. C.: 1963, *J. Geophys. Res.* **68**, 1793.

Bartley, W. C., McCracken, K. G., and Rao, U. R.: 1967, *Rev. Sci. Instr.* **38**, 266.

Bartley, W. C., McCracken, K. G., Rao, U. R., Harries, J. R., Palmeira, R. A. R., and Allum, F. R.: 1971, *Solar Phys.* **17**, 218.

Bukata, R. P., Keath, E. P., Younse, J. M., Bartley, W. C., McCracken, K. G., and Rao, U. R.: 1970, *IEEE Trans. Nucl. Sci.* **NS-17**, 18.

Bryant, D. A., Cline, T. L., Desai, U. D., and McDonald, F. B.: 1962, *J. Geophys. Res.* **67**, 4983.

Fisk, L. A.: 1971, *J. Geophys. Res.* **76**, 1662.

Lanzerotti, L. J.: 1969, *J. Geophys. Res.* **74**, 285.

McCracken, K. G., Rao, U. R., and Bukata, R. P.: 1967, *J. Geophys. Res.* **72**, 4293.

McCracken, K. G. and Rao, U. R.: 1970, *Space Sci. Rev.* **11**, 155.

Ogilvie, K. W., Burlaga, L. F., and Wilkerson, T. D.: 1968, *J. Geophys. Res.* **73**, 6809.

Ogilvie, K. W. and Burlaga, L. F.: 1969, *Solar Phys.* **8**, 422. (Erratum, *Solar Phys.* **11**, 180.)

Ogilvie, K. W. and Arens, J. F.: 1971, *J. Geophys. Res.* **76**, 13.

Palmeira, R. A. R., Allum, F. R., McCracken, K. G., and Rao, U. R.: 1968, *Bull. Am. Phys. Soc.* **13**, 1399.

Palmeira, R. A. R., Rao, U. R., and Allum, F. R.: 1969, Presented at Eleventh International Conference on Cosmic Rays, Budapest, Hungary.

Palmeira, R. A. R., Allum, F. R., McCracken, K. G., and Rao, U. R.: 1971, Proc. of the Seminar on the Problem of Cosmic Ray Generation on the Sun, Leningrad, 1970 (to be published).

Rao, U. R., McCracken, K. G., and Bukata, R. P.: 1967, *J. Geophys. Res.* **72**, 4325.

Rao, U. R., Allum, F. R., Bartley, W. C., Palmeira, R. A. R., Harries, J. R., and McCracken, K. G.: 1969, in C. de Jager and Z. Švestka (eds.), 'Solar Flares and Space Research', *COSPAR Symp.*, 267.

Rao, U. R., McCracken, K. G., Allum, F. R., Palmeira, R. A. R., Bartley, W. C., and Palmer, I.: 1971, *Solar Phys.* **19**, 209.

Singer, S.: 1970, *Trans. Amer. Geophys. Union* **51**, 801.