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OBSERVATION OF SOLAR PARTICLE FLUXES OVER EXTENDED SOLAR LONGITUDES

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Abstract. Detailed particle observations from various Pioneer Spacecrafts located at different heliolongitudes during the complex solar flare events of March 30–April 10, 1969 have been utilised to investigate the energy dependence of azimuthal gradients of cosmic ray particles and its effect on the decay of the flare intensity. For an observer located to the east of the centroid of the population, the azimuthal corotation term and the convection term will be additive, resulting in a short decay time constant. An observer located to the west of the centroid of the population will experience a much longer decay time constant, the corotation term partially or completely compensating the loss of particles due to convection. At very low energies, the azimuthal corotation term may even be more than the convection term, thus resulting in a rise in intensity instead of decay during late in the event. Using the relationship showing the dependence of the spectral exponent of the cosmic ray flux late in a flare event on the azimuth from the centroid of the population given by McCracken *et al.*, the energy dependence of the decay time constant and the cross-over energy at which the azimuthal gradient term equals the convection term are investigated. The experimental observations are shown to be generally consistent with the theoretical picture, confirming the importance of convection and the azimuthal gradient in determining the decay profile of flare events.

1. Introduction

In this communication we present simultaneous detailed observations of the comic ray particle fluxes recorded at various heliolongitudes during the time interval March 30–April 10, 1969. This time interval is characterised by the occurrence of a series of complex flare events on the invisible hemisphere of the Sun, the consequent cosmic ray particle enhancements being apparent over a range of solar azimuths extending to almost 360°. In spite of the fact that these cosmic ray events could not be related to any direct optical observations, we have been able to reconstruct a satisfactory model of the complex phenomena due to the availability of simultaneous cosmic ray data from four spacecrafts (Pioneer 6 through 9, see Figure 1) located at different heliolongitudes.

All four spacecrafts are situated in the plane of ecliptic, and are spin stabilised with their spin axes normal to this plane. The cosmic ray detectors on board Pioneers 6 through 9 have been described in detail elsewhere (Bartley *et al.*, 1967, 1968; Bukata *et al.*, 1970). It suffices to say that all four detectors provide a well calibrated measurement of cosmic ray flux in the plane of ecliptic in the energy range 7.5–45 MeV. The

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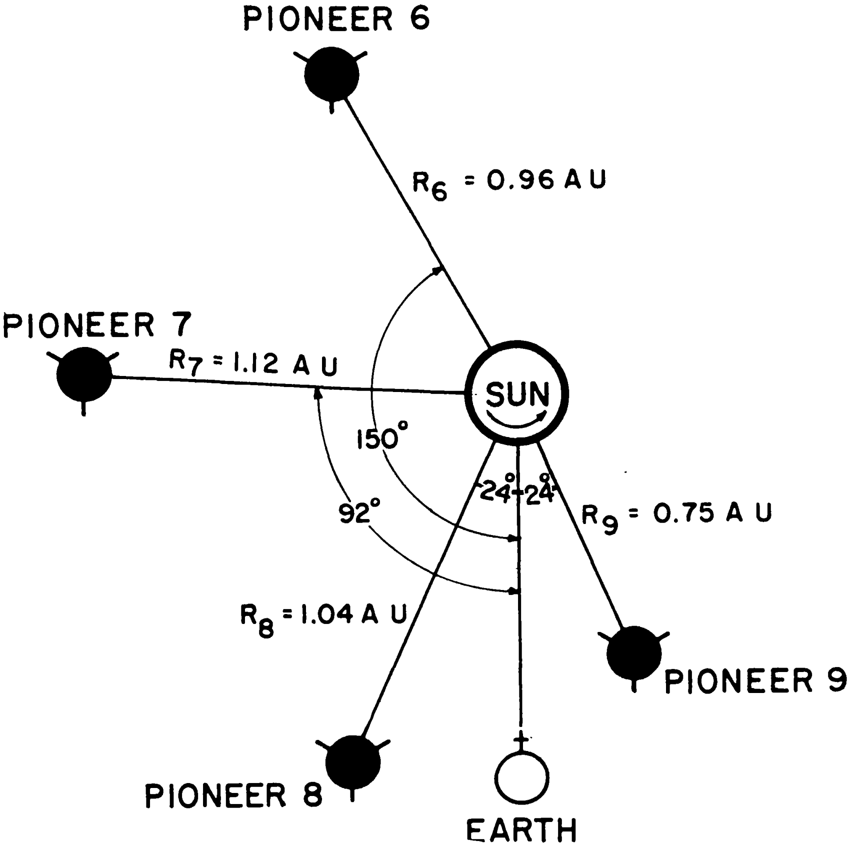

Fig. 1. Showing the location of Pioneers 6 through 9 spacecrafts with respect to the Sun–Earth line.

great advantage of such well calibrated, simultaneous measurements in the interpretation of solar cosmic ray phenomena particularly in distinguishing the time variations from space variations has been clearly demonstrated by McCracken *et al.* (1971). In this communication, we utilize all the available observations to establish the sequence and nature of the events which led to the complex observations of 'back' side solar flare events during March–April, 1969.

2. The Nature of the Observations

Figure 2 illustrates the average hourly omnidirectional particle fluxes obtained from 4 differential energy channels of the Pioneer 8 detector for the time interval March 29–April 10, 1969. The two higher energy curves were obtained from a CsI (Tl) scintillation counter telescope, while the two lower energy curves were obtained from a solid-state detector telescope (Bukata *et al.*, 1970). Figure 3 depicts the temporal profiles recorded by the Pioneer 9 detector for comparable differential energy windows during the same period. At this time, due to the remote location of Pioneers 6 and 7, data acquisition was only possible through the utilisation of the 210 ft paraboloid in California, and consequently was limited to a few hours every few days. Figure 4 illustrates the average hourly fluxes recorded by Pioneers 6 and 7 throughout the period of

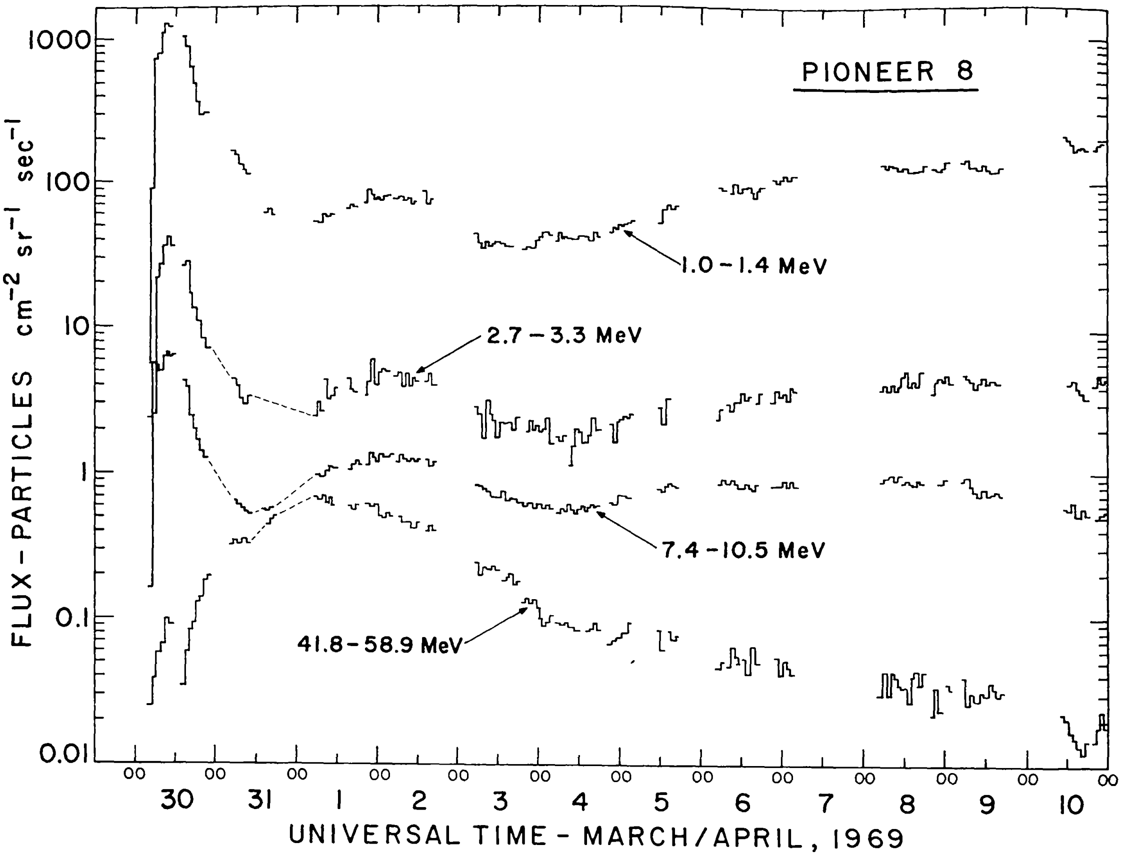

Fig. 2. Showing the particle fluxes in different energy intervals observed on Pioneer 8 during March 30–April 10, 1969.

interest. The data were obtained from a scintillation counter integral energy channel, >7.5 MeV. Also shown in Figure 4 are the fluxes recorded at Pioneers in the nominal differential energy interval 7.5–45 MeV obtained by adding the outputs of 5 contiguous differential energy channels.

A study of Figures 2–4, yields the following observations:

(1) Shortly after 0400 UT, March 30, 1969 Pioneers 8 and 9 observed particle enhancements which had very rapid rise times.

(2) The data available from Pioneers 6 and 7 indicate that enhanced particle fluxes were observed by the middle of March 30 at the location of Pioneer 6 and by early March 31 at the location of Pioneer 7, the times at which Earth communication was re-established at each spacecraft.

(3) Pioneer 8 observed a well-defined rapid-rise (<6 h to reach maximum flux in the lowest energy range) and rapid decay ($T \sim 7$ h) enhancement profile with peak flux occurring at ~0900 UT, March 30. Subsequent to the cessation of this relatively short-lived enhancement, the particle fluxes in each energy channel were noted to increase again. It is apparent from Figure 2 that this short-lived initial enhancement recorded by Pioneer 8 was characterised by a very soft spectrum (differential spectral exponent 4.3 at 0900 UT, March 30) with very rapid hardening occurring at ~1200 UT, March 30. It is clear from Figure 4 that (a) the peak flux recorded at the location of Pioneer 9

on March 30 was over an order of magnitude greater than the peak flux recorded by Pioneer 8, (b) the well-defined short-lived enhancement observed at the location of Pioneer 8 had no obvious counterpart at the location of Pioneer 9, and (c) subsequent to the particle flux decay at Pioneer 8 a second flux enhancement commenced late on March 30, while subsequent to the decay of the short-lived particle flux at Pioneer 9 a second flux enhancement commenced late on April 2, some 3 days later. On the basis of the angular and radial separations of the Pioneers 8 and 9 spacecrafts, it is possible that the delayed enhancement seen on Pioneer 9 is due to the corotation of the particle flux observed earlier.

(4) It is clear from Figures 2–4 that the inner solar system remained densely populated with low energy cosmic radiation from March 30 to April 11, 1969 at which time another solar flare event which has been discussed elsewhere (McCracken *et al.*, 1971) provided yet further particle injection into the interplanetary regime. As evident from the time-intensity profiles depicted in Figure 2 and 3, the particle fluxes between 1 and 3 MeV continued to monotonically increase from April 4 onwards, while the higher energy particle fluxes monotonically decreased. The 7.5–45 MeV time-intensity curves of Figure 4 for Pioneers 8 and 9 show a gradual decrease characterised by an extremely long decay time ($T \sim 6$ days).

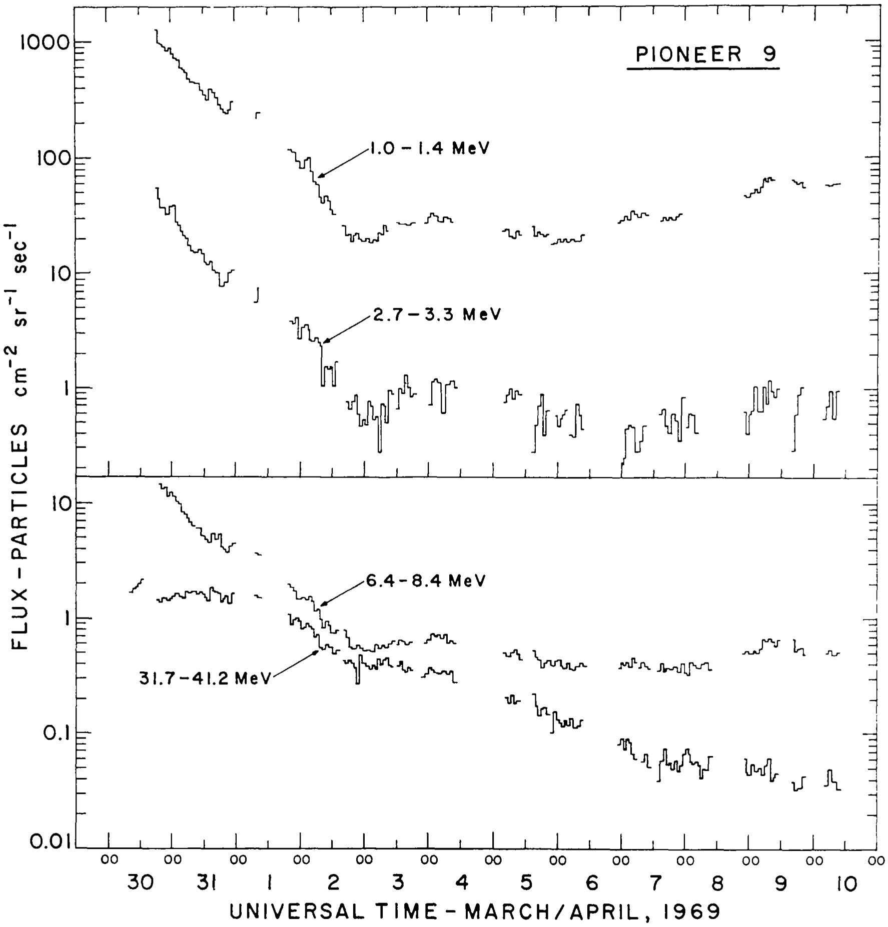

Fig. 3. Showing the particle fluxes in different energy intervals observed on Pioneer 9 during the period March 30–April 10, 1969.

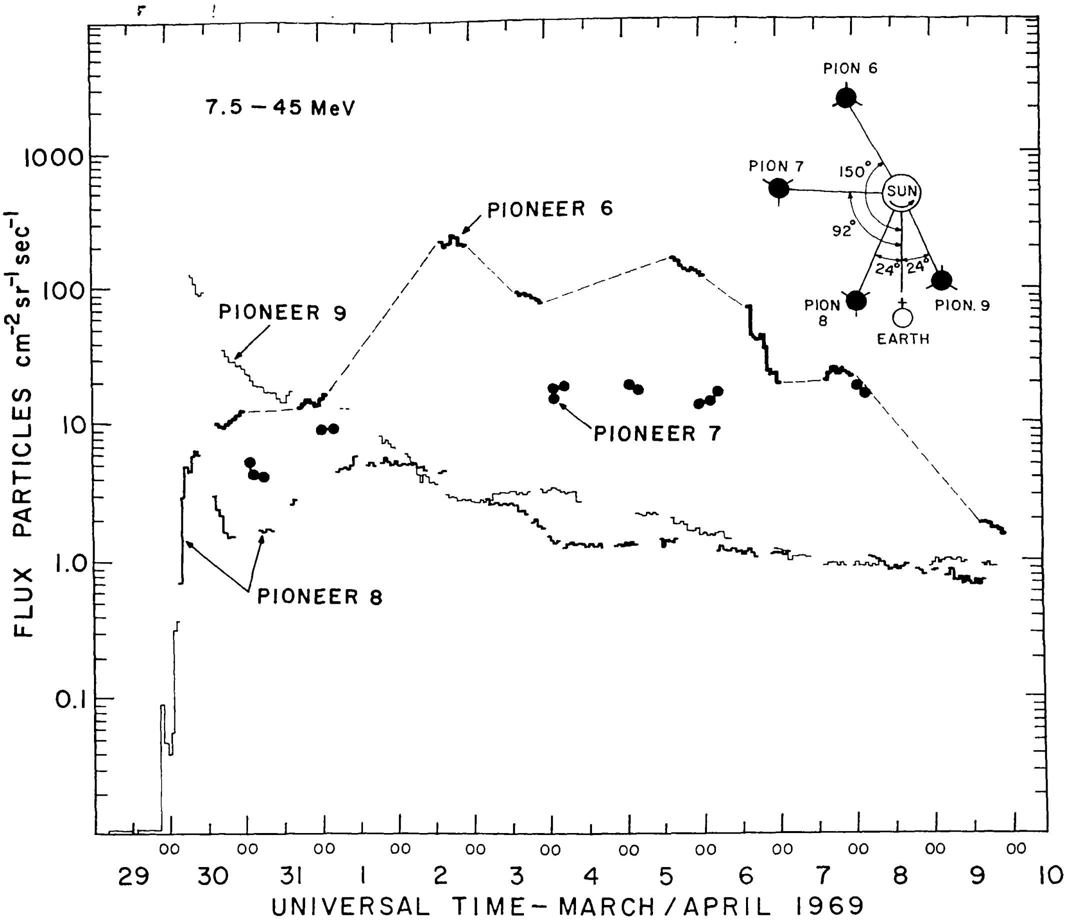

Fig. 4. Average hourly cosmic ray flux of >7.5 MeV observed by Pioneer 6, 7 spacecrafts during the period March 29–April 10, 1969. The data acquisition on Pioneers 6 and 7 was not continuous due to reasons mentioned in the text. The particle flux in the range 7.5–45 MeV observed by Pioneers 8 and 9 during the same period are also shown for comparison.

(5) On the subsequent to April 5, the data are consistent with Pioneers 6 and 7 recording a considerably higher flux than did Pioneers 8 and 9.

The above features apparent from Figure 2–4 together with spectral and anisotropy data are employed in the following to propose a model of the sequence of events which was responsible for the enhanced particle fluxes observed throughout the entire inner solar system between March 29 and April 10, 1969.

3. Sequence of Flare Events

The solar activity commencing on March 30, 1969 could not be definitely related to any specific optical disturbance on the visible solar disk. Smerd (1970) reports observations of a large solar outburst made with an 80 MHz heliograph located in Australia. The event, which contained types II, III, and IV radio bursts, commenced at 0248 UT, on March 30. The burst source, at times, enveloped over half the solar perimeter. Smerd (1970) ascribes the location of the responsible plage region to have been N 19°

W 110°, or some 20° beyond the Western limb as seen from the Earth. The Pioneer data is in agreement with this location for the parent solar flare. Pioneer 9, being in the most favourable position to observe a West-limb solar flare event, recorded a peak flux which was considerably greater than that recorded by Pioneer 8. The large anisotropies recorded at early times on March 30 at the locations of Pioneers 8 and 9 also support such West-limb activity.

We have utilised the Pioneer observations at different heliolongitudes to derive the dependence of cosmic ray density upon solar azimuth, and from this obtain confirmation regarding the location of the parent flare. Figure 5 illustrates the azimuthal gradients measured by the Pioneer network during this interval wherein are plotted the fluxes of 7.5–45 MeV fluxes simultaneously observed by the four Pioneer spacecrafts,

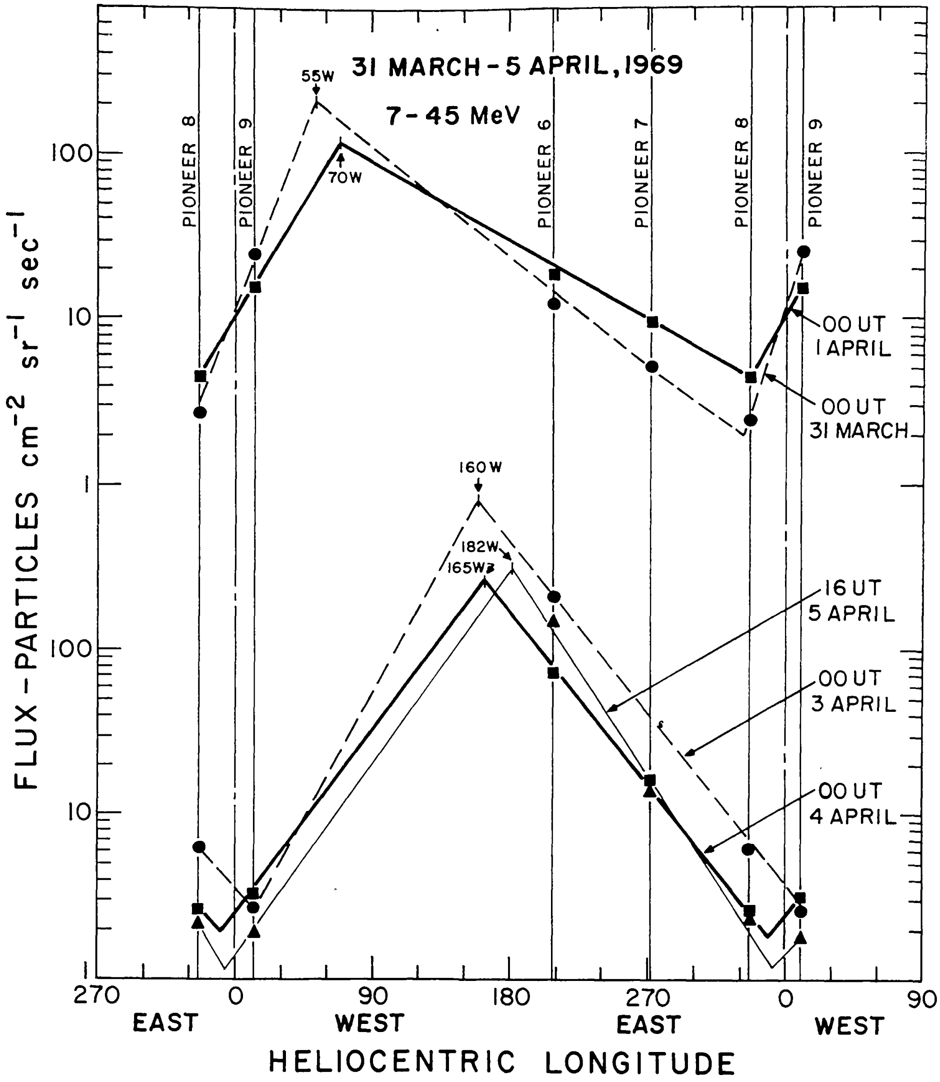

Fig. 5. Showing the azimuthal distribution of particle flux in the range 7.5–45 MeV observed at various Pioneer locations. Simple triangular fits have been employed to derive the azimuthal distribution profile, the peak position of each fit (after correcting for Archimedes spiral field line angle) roughly corresponding to the coordinates of the particle injection at the Sun.

the position of which are plotted in helio-centre longitude. The normal non-flare background is about 10^{-2} particles $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$, which is negligible. The peak in the distribution obtained from a simple triangular fit is seen from Figure 7 to be at 55°W in space on 31 March which implies that the particles must have originated from a point on the Sun near 110±5°W (correcting for the Archimedes spiral field line) which is consistent with the particle injection coordinates inferred from Smerd's observations.

The well-defined short lived rapid rise time enhancement recorded at the location of Pioneer 8 just at the start of the flare activity, is not, however, easily explained. Pioneer 8, situated 135° away from the site of the parent flare recorded the onset of this short-lived low energy event with neither velocity nor time dispersion whereas, Pioneer 9, which was located 55° closer to the site did not observe such a feature. Such minor discrepancies which are often observed may be possibly explained by (Keath *et al.*, 1971) invoking stochastic wandering of the interplanetary field lines, or acceleration by coronal shock waves at far away locations or preferential injection vie coronal magnetic field lines.

Figure 5 also shows the azimuthal distribution of intensity later in the event. Triangular fits are shown to each set of observations to give us an idea of the intensity profile in space. We observe that the peak flux on 3 April was more than a factor of 5 greater than the flux on 1 April, clearly indicates second injection between 0000 UT on 1 April and 0000 UT on 3 April. The triangular fit shows that the centroid of this population was at around 160°W on 3 April. The peak flux (flux at the centroid of the population) was observed to be a factor of about 3 lower on 4 April. At 1600 UT on 5 April, the centroid had corotated to 182°W. However, if the decay time constant observed between 3 and 4 April were to hold good, the peak particle flux would have been about 80 particles $\mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$. The observed peak particle flux of about 300 particles $\mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$ on 5 April suggests another fresh injection between 0000 UT on 4 April and 1600 UT on 5 April, even though the fresh injection took place in the same active region. Making a correction of 55° for the Archimedes field line, the injection point on the Sun would be about 35° beyond the eastern limb ($180° + 55° = 235°$W) of the Sun as viewed from the Earth. This location for the early April flares is consistent with the large fluxes recorded at Pioneers 6 and 7 and accounts for the increased particle fluxes recorded at the location of Pioneers 8 and 9 commencing around April 2. The obvious spectral softening with time illustrated in Figures 2 and 3 (with Pioneer 8 observing this spectral softening more intensely than did Pioneer 9) is consistent with the 'core' or centroid of the flux distribution being to the East of Pioneer 8. Since the spectrum at Pioneer 8 continued to soften for a period of at least 7 days (at which time the solar flare event of April 11, 1969 provided additional particle injections), a conservative estimate of the azimuthal extent of the 'core' of the distribution would exceed 100°.

4. The Azimuthal Gradient of Low Energy Cosmic Ray Fluxes

Following McCracken *et al.* (1971), we can write the time rate of change of the 'corotating' cosmic ray density $U(r, \psi, E, t)$ as:

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{\partial U}{\partial \psi}\frac{\partial \psi}{\partial t} + \frac{\partial U}{\partial t}, \tag{1}$$

where the first term on the left hand side represent the corotating flux of particles, ψ being the heliocentric longitude and $\partial U/\partial t$ represents the flux of particles that are convected out of the solar system. For an observer located to the east of the centroid of the population, the corotation term will add to the convection, resulting in a short decay time constant. On the other hand, for an observer located to the west of the centroid of the population, the corotating flux moving towards the observer will partially or totally compensate the loss of particles due to convection (McCracken and Rao, 1970) resulting in a longer decay time constant. Since the corotation term is really energy dependent, at very low energies it may even exceed the convection term resulting in an increase in the cosmic ray flux with time instead of decaying.

From a number of solar flare particle observation at different helio-longitudes, McCracken *et al.* (1971) showed that the observed spectral exponent at late times in the decay of the flare events is a linear function of the longitude of observation ψ (See Figure 21 of McCracken *et al.* (1971). At the core of the centroid of the population the spectrum is found to be softest and seems to progressively harden in a linear fashion with the increase in longitude from the centroid. This implies that the dependence of the cosmic ray flux upon heliocentric longitude must be more pronounced at lower energies than at high. In other words, the function describing the longitude profile of the cosmic ray flux at different energies can be considered as a separable function of ψ and E or we may write i.e.

$$F = F_0 f(\psi)\, E^{-\gamma} \tag{2}$$

where

$$\gamma = \gamma_0 - k\psi,$$

γ_0 being the spectral exponent at the core. By differentiating Equation (2), we get

$$\frac{1}{F}\frac{\partial F}{\partial \psi} = \frac{1}{\psi_0} = \frac{f'}{f} + k \ln E. \tag{3}$$

From Equation (1), we observe that the time constant T is given by

$$\frac{1}{T} = \frac{1}{\psi_0}\frac{\partial \psi}{\partial t} + \frac{1}{\tau}. \tag{4}$$

When the corotating term is exactly equal to the convection term, the time constant $T = \infty$ or

$$\frac{1}{\psi_0}\frac{\partial \psi}{\partial t} + \frac{1}{\tau} = 0. \tag{5}$$

Substituting the value of ψ_0 derived from Equation (5) and the value of τ the 'convective time constant' (Forman, 1970) obtained from

$$\tau = \frac{3\gamma}{2(2+\alpha\gamma)\,v_c}, \tag{6}$$

where γ is the spectral exponent, v_c is the effective convective velocity and

$$\alpha = \frac{E + 2M_0^{c^2}}{E + M_0^{c^2}} \approx 2\,(E \lesssim 50 \text{ MeV}) \tag{7}$$

(E being the kinetic energy of the individual cosmic rays), Equation (3) reduces to

$$\frac{f'}{f} + k \ln E_\infty + \frac{4(1+\gamma)\,v_c}{3\gamma \dfrac{\partial\psi}{\partial t}} = 0, \tag{8}$$

where $E\infty$ denotes the energy at which the convective term and the corotation term exactly balance each other yielding a time constant $T = \infty$. Substituting

$$\frac{f'}{f} = \frac{1}{\psi_0} - k \ln E_0$$

into Equation (8) yields

$$k \ln\left(\frac{E_\infty}{E_0}\right) + \frac{1}{\psi_0} + \frac{4(1+\gamma)}{3\gamma \dfrac{\partial\psi}{\partial t}}\, v_c = 0. \tag{9}$$

Using observed values of $K = 1.11 \times 10^{-2}$, $\psi_0 = -30°$ at $\psi = 90$ and $E_0 = 10$ MeV ($\nu = 3.25$) and $v_c = 200$ km s^{-1}, E_∞ is found to be ~2 MeV.

Examination of Figure 2 clearly shows that whereas at energies above ~3.3 MeV, the low energy cosmic ray flux shows a slow decay the decay being faster for higher energies, the flux in the energy window 2.7–3.3 MeV shows no sign of decay after 5 April 1969. At still lower energies, the flux shows an increase clearly indicating that the corotation term actually exceeds the convection term.

To illustrate the energy dependence evident during early April 1967, we have plotted in Figures 6 and 7, the energy dependence of the decay time constant as observed by Pioneer 8 and 9 during late in the event. The decay constants have been computed from the omnidirectional flux data taken from five differential energy channels of the solid state detector and six differential energy channels of the scintillation counter telescope. Both sets of observations indicate that the energy dependence of the azimuthal density gradient is significantly greater at low energies than at higher energies and at about ~5 MeV (~10 MeV for Pioneer 8 and ~3.5 MeV for Pioneer 9) the azimuthal gradient balances the normal convective removal, in general agreement with our theoretical interpretation.

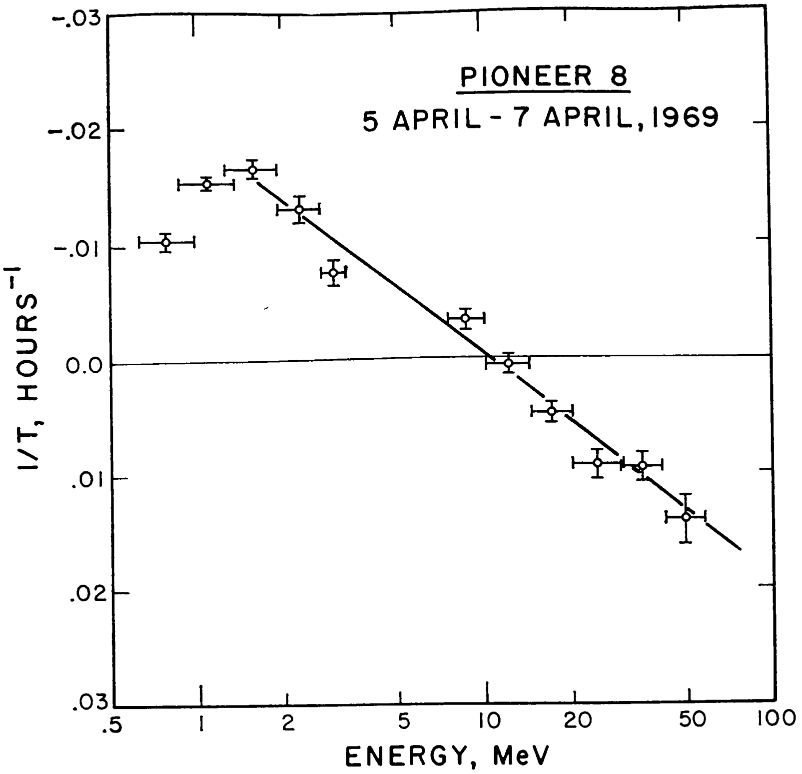

Fig. 6. Showing the inverse of the decay time constant as a function of energy during late times in a flare event as observed on Pioneer 8.

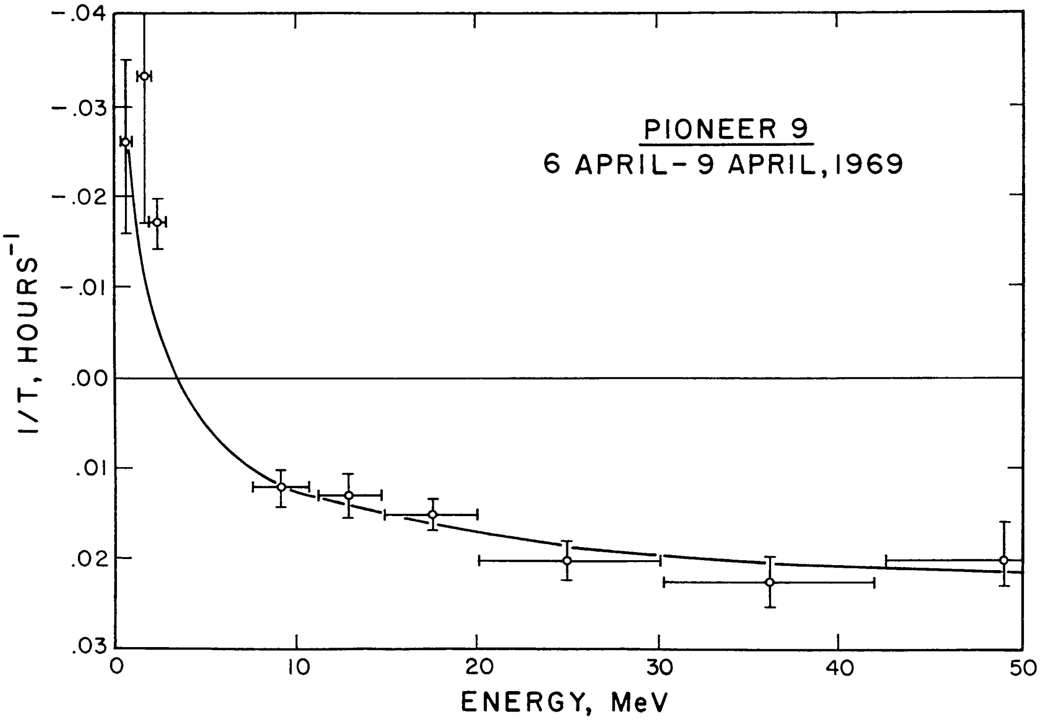

Fig. 7. Plot of the inverse of the decay time constant as a function of energy during 6–9 April, 1969 as observed on Pioneer 9.

5. Conclusions

A study of the complex flare activity which resulted in the observation of solar-induced cosmic radiation over almost 360° of solar azimuth during the time interval March 31–April 10, 1969 has led to the following self consistent conclusions.

(1) Using simultaneous observation, at different helio-longitudes, we can construct a satisfactory model of the flare injection, even when the associated flare has occurred on the back side of the Sun.

(2) From an examination of such data we conclude that particles were initially injected at $\sim$0245 UT March 30 from an active region location $\sim$20° behind the West limb of the Sun as viewed from the Earth. Subsequent to this injection, another injection from 30° behind the East limb of the Sun occurred on April 2 and a second injection from this same Eastern region occurred on April 4. These three 'back' side solar flare effects were thus responsible for the totality of cosmic radiation observed in the inner solar system for the period March 20–April 10, 1969.

(3) Various particle injections mentioned above resulted in cosmic ray populations becoming apparent over a wide range of heliocentric longitudes, these populations displaying corotative behaviour with the Sun.

(4) The energy dependence of the azimuthal gradient is consistent with a corotating density distribution. The spectral nature of the particle fluxes are consistent with the estimated back' side solar injection locations.

(5) The decay effects in a flare event are governed by the azimuthal density gradient and by the convective removal process. The decay constant is larger or smaller depending on wether the observer is to the West or East of the centroid of the flare population. For an observer to the West of the centroid, the convective removal is partially or wholly cancelled by the corotating particle flux. At very low energies, the corotating particle flux will exceed the convective removal process thereby resulting in a low increase of particle flux with time.

(6) From the known dependence of the spectral exponent with the heliocentric longitude at late times, and the observed value of the '*e*' folding angle describing the azimuthal distribution at a given energy, the theoretical calculations shows that the corotating term exceeds the convection term for particles of energies $\sim$2–3 MeV.

The experimental results are shown to confirm the existence of larger azimuthal gradient at lower energies.

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