THE ANOMALOUS DISTRIBUTION IN HELIOCENTRIC LONGITUDE OF SOLAR INJECTED COSMIC RADIATION

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Abstract. Concurrent observations of the solar flare of March 12, 1969 by two spacecrafts separated in solar longitude by 38° show that the accessibility at 1 AU to cosmic ray particles is not a simple function of the relative solar longitude. The cosmic ray flux, degree of anisotropy, and rise time all indicate that the favored path for cosmic ray propagation in this event was some 40° to the east of the nominal Archimedes spiral line of force from the flare location. This is interpreted as evidence for either (a) extreme stochastical wandering of the lines of force of the interplanetary magnetic field, or (b) the redistribution of the cosmic rays in coronal magnetic fields prior to escape onto the nominal Archimedes spiral lines of force.

1. Introduction

It has generally been the implicit assumption that the distribution of the energetic protons which are produced in solar flares can be represented by a Gaussian function centered about the field lines which connect to the active region (O'Gallagher, 1970; Axford, 1965; Jokipii and Parker, 1969). In this paper we will describe the solar flare event of March 12–17, 1969 in which the distribution of the particles during the early phase of the event clearly deviated greatly from this approximation. This event is therefore important in that it raises several basic questions concerning the production of particles and the manner in which they propagate near the solar surface. The data presented here were obtained from the cosmic ray detectors aboard the Pioneer 6 through 9 deep-space probes. The instruments and data handling procedures have been described in detail by Bartley *et al.* (1967) and by Bukata *et al.* (1970). The physical features of these detectors are similar, so that the data from all of the instruments are directly comparable.

2. Observations

The energetic ions, observed during the March 12, 1969 flare event, were clearly associated with an importance 2B optical flare which occurred at 1738 UT on March 12, 1969. This flare was located at N12°–W80° in the McMath plage region 9966, which appeared on the east limb of the Sun around March 1 and was active throughout its transit across the solar disk. The plage region consisted of two parts in an East-West orientation which were connected by magnetic filaments. The two regions were separated in solar longitude by about 20°, as illustrated in Figure 1.

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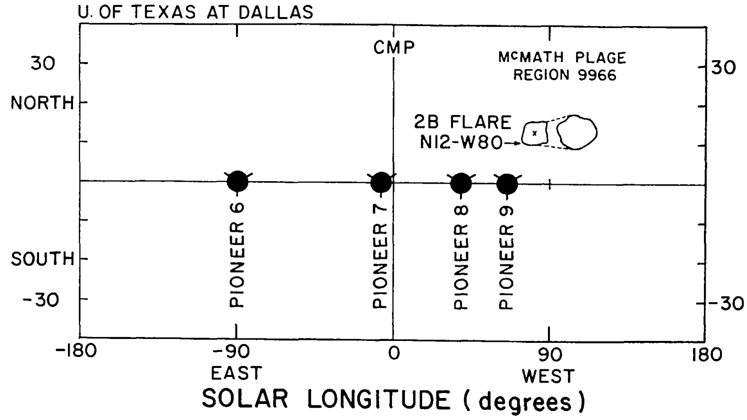

Fig. 1. Showing the projection of the Pioneer spacecraft onto the solar surface via the nominal Archimedes field lines.

TABLE I

Showing the actual location of the Pioneers 6 through 9 spacecrafts on March 12, 1969, along with the onset time and peak fluxes observed by the four spacecraft. θ is the Earth–Sun-Probe angle with positive being to the West. R is the Sun-spacecraft distance.

Spacecraft	Location		Onset time	Peak flux
	θ	R	March 12	7.5–45 MeV particles/(cm^2 sec ster)
Pioneer 6	$-151°$	0.93 AU	~ 2000 UT	2.0
Pioneer 7	$-89°$	1.1 AU	–	0.4
Pioneer 8	$-24°$	1.02 AU	1830 UT	15
Pioneer 9	$+14°$	0.77 AU	~ 1900 UT	2.5

The 1738 UT flare occurred in the trailing region and was accompanied by intense X-ray and radio emission. Both Type II and Type IV radio emissions were observed starting at 1738 UT and ending around 1800 UT. The X-rays were observed at 1738 UT at Earth and produced a severe SID which started at 1973 UT and ended at 1945 UT, with maximum at 1740 UT. Intense solar X-ray fluxes were also reported by Solrad 9 and Explorer 37 at 1740 UT.

The locations of the four Pioneer spacecrafts on March 12 are tabulated in Table I. Using the average solar wind velocity of 390 km/sec observed by the VELA spacecraft at Earth (*ESSA Solar Geophysical Data Bull.*, April 1969), the field lines passing through the Pioneers 6 through 9 can be extrapolated back to the solar surface at respectively, 170°, 87°, 40°, and 15° East of the actual flare location. The positions, after projection, are summarised in Figure 1. From this, it would appear that Pioneer 9 should have been in the most favorable location to observe the solar particles directly from the active region. However, as shown by Figure 2, the particle flux observed by Pioneer 9 was almost an order of magnitude less than that observed by Pioneer 8.

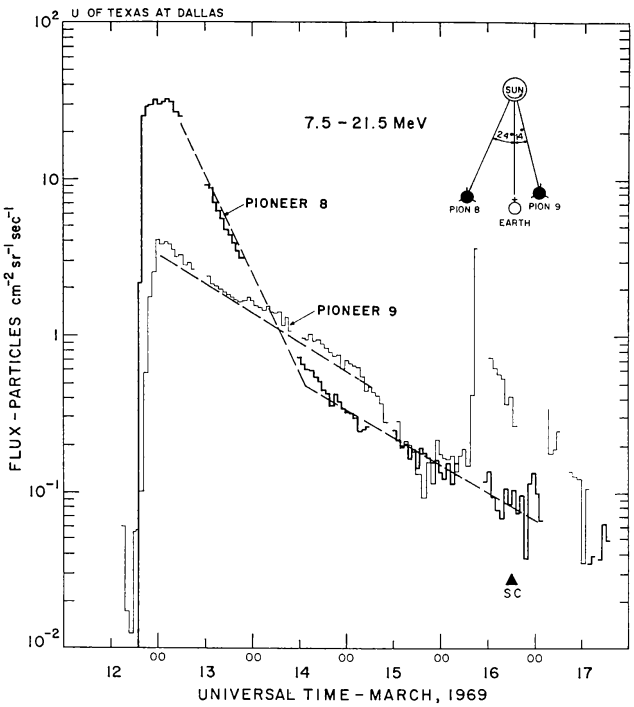

Fig. 2. The temporal variation of the 7.5–21.5 MeV flux observed by the Pioneers 8 and 9 during the March 12–17, 1969 solar flare event.

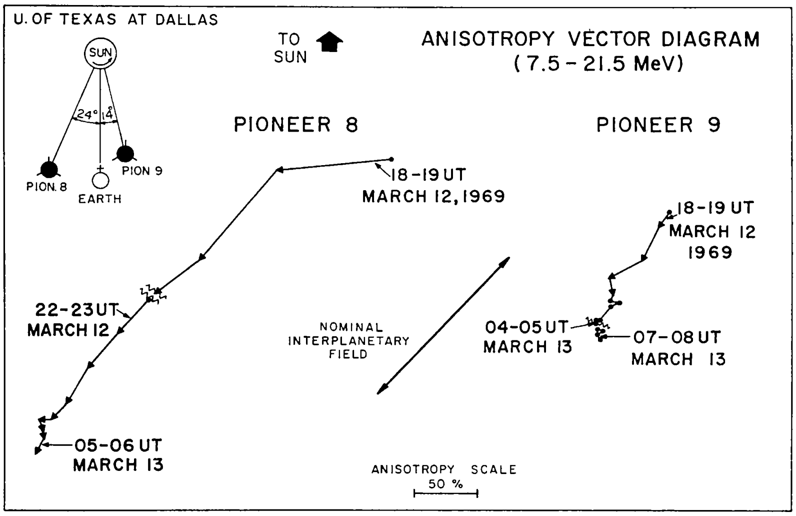

Fig. 3. The cosmic ray anisotropy vector diagram for Pioneers 8 and 9 during the early phase of the March 12 flare event.

The time intensity plots for the Pioneer 8 and 9 spacecrafts are shown in Figure 2. It can be seen that in addition to the considerable difference in the particle fluxes at the two spacecrafts, there were substantial differences in the decay rates. The flux at Pioneer 9 decayed exponentially with a decay time constant of $\sim$34 hr. During the early phase of the event the decay time constant at Pioneer 8 was $\sim$8 hr, however, during the later part of the event (after $\sim$1200 UT, March 14) the decay constant was roughly equal to that observed by Pioneer 9.

There were also considerable differences in the rise time and anisotropy measured at the two spacecrafts. In Figure 3 the vector diagrams of the hourly average anisotropy are plotted for the period from 1800 UT, March 12 until 0800 UT, March 13. During this period the flux at Pioneer 8 was strongly anisotropic (~90% during the first two hours of the event), with the anisotropy aligned with the nominal interplanetary field line. The anisotropy at Pioneer 9, while generally aligned with the nominal interplanetary field, was considerably smaller in amplitude than that observed by Pioneer 8. It can be seen from Figure 4 that the rise time of the flux at Pioneer 8 was much more rapid than that of Pioneer 9. For transit along a nominal Archimedes spiral line of force, the time of flight of the ions that are detected in the lower energy channels of both spacecraft is ≃1 hr. Hence the time interval between the flare occurrence and maximum cosmic ray flux, expressed relative to this minimum time of flight, is 3 for Pioneer 8 and 9 for Pioneer 9. This clearly indicates that the particles which reached Pioneer 9 must have passed through a strong diffusing region before arriving at the spacecraft, while the flux at Pioneer 8 reached the spacecraft with relatively little diffusion. This is consistent with the fact that the observed velocity dispersion of the flux at Pioneer 8 at early times indicates an average path length of 1.3 AU.

In total, the various data clearly indicate that during the early phase of the event, (1) the distribution of particles was not a simple decreasing function of distance from the nominal field line thru the solar flare; (2) that the particles observed at Pioneer 8

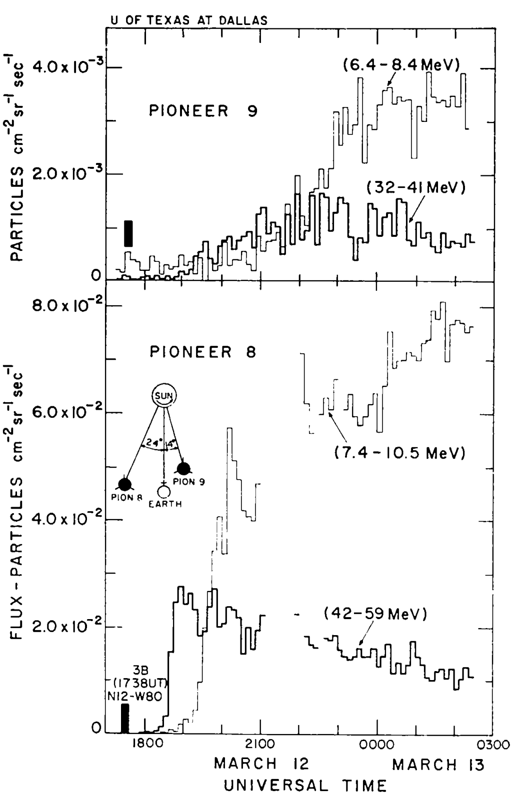

Fig. 4. Illustrating the rise time of the event of March 12 as observed by Pioneers 8 and 9.

propagated directly from their production point to the spacecraft with negligible diffusion, while the particles reaching Pioneer 9 suffered very considerable diffusion and delay, and (3) that the most favorable propagation path through the solar system for particles from the flare was along lines of force some 40° to the east of those to be expected on the basis of the generally accepted models.

In addition to the major discrepancies between Pioneers 8 and 9, Table I shows the Pioneer 6 flux to be greater than that at Pioneer 7, and approximately equal to that observed at Pioneer 9. Since Pioneers 6 and 7 data are acquired only for ~4 hr/every 2–3 days, it is not possible for us to exclude the possibility that the Pioneer 6 enhancement was due to another unrelated flare, possibly associated with the plage region 9996 that was responsible for the major cosmic ray flare activity some 16–20 days later. The altenate hypothesis, namely that the enhancement at Pioneer 6 was correlated with those at Pioneer 8 and 9, merely indicates even greater deviation from the simple Archimedes spiral model and strengthens comment (1) above.

We would stress here that none of the facts enumerated above are evident from the data from either Pioneer 8 or Pioneer 9 alone. Taken in isolation, either set of data could be fitted by an appropriate ad hoc model. Thus if only Pioneer 9 data were at hand, it would be said that the average diffusion coefficient from Sun to Earth along the nominal Archinedes spiral field lines was small at the time. If only Pioneer 8 data were available, the conclusion would be that the cosmic rays had been spread widely in longitude at the Sun, and had then propagated thru a nominal field with a relatively large value of the diffusion coefficient. It is only through the availability of both sets of data that the inapplicability of a model invoking symmetry about the line of force thru the parent flare becomes apparent: we suspect that this might be a common occurrence.

3. Discussion

It is clear that a simple diffusive model based on a nominal Archimedes spiral magnetic field (Reid, 1964; Axford, 1965) is not consistent with the evidence presented herein. It is possible that stochastic wandering of the interplanetary lines of force such as proposed by Michell (1966), or Jokipii and Parker (1969) could explain the observation. However, the deviations from the nominal field seem extreme, since Jokipii and Parker (1969) estimate that the fields may exhibit an rms deviation (i.e. standard deviation) of 15° from the nominal field line; Michel's estimate is less. The evidence herein would require a deviation of ≃40° from the nominal field line, i.e. some 2.7 standard deviations departure from the theoretical mean. This would have a probability of ~2% for chance occurrence.

Two other possibilities exist to explain the observations. Considerable evidence for coronal shock waves (Athay and Moreton, 1961), and the fact that they can accelerate electrons to relativistic energies at points far away from the parent flare (Wild *et al.*, 1968), suggests that the ion acceleration might be occurring at a point far removed from the parent flare. Dodson Prince (private communication) indicates, however, that there was no evidence for a shock wave, nor was there radio evidence for electron acceleration other than in the original parent flare (*ESSA Solar Geophysical Data Bull.*, September 1969; Maxwell, private communication). A shock wave of typical velocity (1000 km sec^{-1}) would travel $\sim 40°$ in solar longitude in 13 min; however, the radio emission shows no evidence of a second enhancement 13 min after the first. We conclude therefore that this model is not consistent with the facts on this occasion.

The remaining possibility is that the cosmic rays, having been accelerated in the vicinity of the parent flare, gained direct access to the interplanetary field only after propagating for a considerable distance in a coronal magnetic field that lead to a point some 40° to the east of the parent flare (Newkirk and Altschuler, 1970). Injection onto other field lines (such as sampled by Pioneer 9) would only be after considerable diffusion. Thus the March 12 event would be explicable in terms of Pioneer 9 being on a nominal Archimedes field line with no 'good connection' to the parent flare, while Pioneer 8 was on a field line that led to a region on the Sun some 40° from the flare, but which had a good magnetic connection to the flare via coronal magnetic fields.

It is not possible at this time to determine which of the two models (a) the stochastic wandering field, or (b) coronal magnetic field transport, plus nominal Archimedes spiral fields, applied at the time of the March 12 event. The event makes it clear, however, that major deviations from the simple theory do occur, and that models must be developed to accommodate them. Thus if the stochastical wandering explanation should prove to be the applicable model, it appears that the degree to which the field lines meander is greater than that estimated on theoretical grounds. Clearly further cosmic ray observations obtained simultaneously by widely separated spacecraft are crucial to such a study, especially if it is a stochastical process that is being observed. Correlated studies with radio receivers exhibiting spatial resolution (e.g. the radioheliograph), and detailed studies of the concurrent coronal magnetic fields will add greatly to the study of this problem.

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