A STUDY OF SOLAR COSMIC RAY FLARE EFFECTS

DISSERTATION

Presented to the Graduate Council of the North Texas State University in Partial Fulfillment of the Requirements For the Degree of

DOCTOR OF PHILOSOPHY

By

Edwin P. Keath, B. S., M. S.

Denton, Texas

May, 1971

The purpose of this study is to determine the characteristics of the solar cosmic ray flux. This report describes the design and construction of a cosmic ray detector system used in this study and describes the analysis of the data obtained from these systems. The cosmic ray detector systems described here were flown aboard the Pioneers 8 and 9 spacecrafts which were launched into heliocentric orbit. The cosmic ray detector systems were designed to provide detailed measurements of a) the temporal variations of the omnidirectional cosmic ray flux, b) the energy spectrum of the cosmic ray particles, and c) the directional properties (i.e., anisotropy) of the cosmic ray flux.

The analysis of the cosmic ray particles indicates that during each event there exists three distinct phases characteristic of the particle flow. At very early time ($t < 1$ day) the cosmic ray anisotropy is large and aligned with the interplanetary magnetic field lines. This indicates that the particles are being driven out of the inner solar system by a negative density gradient along the field lines. During the interval $1 < t < 4$ days the anisotropy is observed to be directed radially with an amplitude of 5 to 15%. This
is interpreted to be the result of the convective removal of particles by the inhomogeneities in the solar wind. At late times (4 days) the anisotropy is observed to be consistently aligned perpendicular to the nominal interplanetary field lines. The fact that the anisotropy at late times is perpendicular to the field lines implies the existence of a positive density gradient along the field lines which drives a diffusive current back towards the sun.

The Pioneer spacecrafts have provided the first direct measurements of the longitudinal gradients in the cosmic ray flux. These measurements indicate the presence of strong gradients in heliocentric longitude even at very late times, which are essentially invariant with respect to time. The presence of these gradients has a major effect on the temporal variations of the cosmic ray flux during the decay phase of the flare effect. The observation of the cosmic ray spectrum indicates that the e-folding angle is smaller at low energies so that the influence of the gradient becomes more pronounced at low energies and may even exceed the convection removal rate.

Since convection is the dominant process at late and very late times in removing the particles from the solar system, the decay rate is determined by the effective convective velocity and is, to first order, independent of the scattering properties of the interplanetary magnetic field.
From the observation of the energy spectrum of the cosmic ray particles it is shown that the spectral exponent is dependent on the location of the observer relative to the centroid of the cosmic ray population. It is shown that the spectral exponent decreases with increasing distance from the population centroid.

Several individual events are presented which demonstrate the effects of the solar and interplanetary magnetic fields on the time-intensity profiles of the events.
A STUDY OF SOLAR COSMIC RAY FLARE EFFECTS

DISSERTATION

Presented to the Graduate Council of the North Texas State University in Partial Fulfillment of the Requirements For the Degree of

DOCTOR OF PHILOSOPHY

By

Edwin P. Keath, B. S., M. S.
Denton, Texas
May, 1971
ACKNOWLEDGEMENTS

This work was carried out at the University of Texas at Dallas and I am grateful for the support extended to me by both the administrative and scientific staff during this work. The success of the Pioneer program was the result of the dedication, hard work, and technical ability of a large number of people.

I am sincerely grateful and indebted to my research advisor, Professor K. G. McCracken, for the privilege of working with him and also to Drs. R. P. Bukata and U. R. Rao. The work presented here is a direct result of the collaboration between Drs. McCracken, Rao, Bukata and myself. They deserve much of the credit for making this study successful. A large portion of the results presented here has been accepted for publication and will appear in forthcoming issues of Solar Physics under joint authorship.

I would also like to thank Drs. R. A. R. Palmeira and F. R. Allum for their interest and advice.

Messrs. Jack Younse, Phil Selva, W. C. Bartley and W. Glasscock are gratefully mentioned for their design and construction of the flight electronics for the experiment.
This study was supported by funds from the National Aeronautics and Space Administration under contracts NSR-44-004-043, NAS2-3332, NAS2-4674, NGR-44-004-108, and NAS2-3945.
TABLE OF CONTENTS

LIST OF TABLES ........................................... v
LIST OF ILLUSTRATIONS ................................. vi

Chapter

I. INTRODUCTION ......................................... 1

General
The Photosphere and Corona
The Interplanetary Field
Characteristics of Solar Cosmic Ray Events
The Statistical Description of Cosmic Ray Propagation

II. THE PIONEER 8 AND 9 COSMIC RAY DETECTOR
SYSTEM .................................................. 20

Introduction
The Detector System (Mechanical)
The Detector System (Electrical)
Instrument Data Format
Physical Properties of the Instrument
In-Flight Performance

III. OBSERVATIONS ....................................... 42

Introduction
The Anisotropy of The Decay Phase
The Dependence of Cosmic Ray Density Upon Heliocentric Longitude at Late Times
The Decay Time Constant
The Decay Time Constant-Experimental Results
The Cosmic Ray Energy Spectrum
The Particle Distribution at Early Times
Anomalous Temporal Variations in The Cosmic Ray Flux
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Detector Logics Utilized in Instrument Measurement Cycle</td>
<td>27</td>
</tr>
<tr>
<td>II. Parent Flares</td>
<td>44</td>
</tr>
<tr>
<td>III. Calculated Decay Time Constants and Their Comparison with The Observed Values</td>
<td>77</td>
</tr>
<tr>
<td>IV. Decay Time Constants during 16 - 20 April 1969</td>
<td>81</td>
</tr>
<tr>
<td>V. Spectral Exponents and Relative Solar Longitude</td>
<td>87</td>
</tr>
<tr>
<td>VI. Location of The Pioneers 6 through 9 Spacecraft on March 12, 1969</td>
<td>95</td>
</tr>
</tbody>
</table>
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Material Structure in The Solar Corona</td>
<td>7</td>
</tr>
<tr>
<td>2.</td>
<td>Magnetic Structure in The Solar Corona</td>
<td>7</td>
</tr>
<tr>
<td>3.</td>
<td>Detailed View of The Scintillation Telescope</td>
<td>22</td>
</tr>
<tr>
<td>4.</td>
<td>The Solid State Detector Tri-Telescope Configuration</td>
<td>24</td>
</tr>
<tr>
<td>5.</td>
<td>The Relative Directional Response of The Solid State Detector Telescope</td>
<td>24</td>
</tr>
<tr>
<td>6.</td>
<td>Pioneer Functional Block Diagram</td>
<td>26</td>
</tr>
<tr>
<td>7.</td>
<td>Octant Configuration within The Ecliptic Plane</td>
<td>29</td>
</tr>
<tr>
<td>8.</td>
<td>Proton Energy Response Curve</td>
<td>31</td>
</tr>
<tr>
<td>9.</td>
<td>Data Collection for The Sun-Synchronous and Telemetry Synchronous Modes</td>
<td>34</td>
</tr>
<tr>
<td>10.</td>
<td>The Assembled Pioneers 8 and 9 Cosmic Ray Detector System</td>
<td>37</td>
</tr>
<tr>
<td>11.</td>
<td>Inflight Calibration Curve</td>
<td>40</td>
</tr>
<tr>
<td>12.</td>
<td>Positions of The Pioneer Spacecrafts</td>
<td>43</td>
</tr>
<tr>
<td>15.</td>
<td>Cosmic Ray Anisotropy Vector Diagrams for Other Flare Events</td>
<td>50</td>
</tr>
<tr>
<td>Page</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>32</td>
<td>Dependence of Spectral Exponent on Relative Population Longitude</td>
<td>86</td>
</tr>
<tr>
<td>33</td>
<td>The Decay at Late Times during the Event of May 30, 1969</td>
<td>90</td>
</tr>
<tr>
<td>34</td>
<td>Projection of the Pioneer Spacecraft onto the Solar Surface</td>
<td>93</td>
</tr>
<tr>
<td>35</td>
<td>Cosmic Ray Flux during the Flare Effect of March 12, 1969</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>Anisotropy Vector Diagram for March 12, 1969 Event</td>
<td>98</td>
</tr>
<tr>
<td>37</td>
<td>Rise Time of the Event of March 12, 1969</td>
<td>99</td>
</tr>
<tr>
<td>38</td>
<td>Cosmic Ray Flux Observed by Pioneer 8 and Explorer 34 for the Period July 12-15, 1968</td>
<td>106</td>
</tr>
<tr>
<td>39</td>
<td>Cosmic Ray Flux during the Time Interval July 6-17, 1968</td>
<td>108</td>
</tr>
<tr>
<td>40</td>
<td>Anisotropy of the Electron Flux on July 12-13, 1969</td>
<td>110</td>
</tr>
<tr>
<td>41</td>
<td>Cosmic Ray Flux during the Flare Effect of September 29, 1968</td>
<td>114</td>
</tr>
<tr>
<td>42</td>
<td>Cosmic Ray Flux during the Flare Effect of October 31, 1968</td>
<td>116</td>
</tr>
<tr>
<td>43</td>
<td>Schematic of the Reid-Axford Model</td>
<td>119</td>
</tr>
<tr>
<td>44</td>
<td>Possible Configuration of Solar Conditions: (A) September Event, (B) November Event</td>
<td>121</td>
</tr>
<tr>
<td>45</td>
<td>$\ln(I' t^{3/2})$ vs. $1/T$ for Solar Event of September 29, 1968</td>
<td>125</td>
</tr>
<tr>
<td>46</td>
<td>Actual and Equivalent Telescope Configurations</td>
<td>137</td>
</tr>
<tr>
<td>47</td>
<td>The Relative Differential Response of the Telescope and Octants</td>
<td>137</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

1.1 General

This study is intended to provide a better understanding of cosmic ray phenomena. It has been recognized for some years that cosmic ray particles provide an effective probe for studying the conditions which exist in the solar system and the galaxy. Traditionally, astrophysical studies have relied on the use of electromagnetic radiation as an information carrier. Since the parameters which affect the production and propagation of the cosmic rays are different from those of the photons, they provide an additional source of information concerning the astrophysical processes. Since cosmic rays are charged particles they are influenced by the presence of solar and galactic magnetic fields. The bulk of cosmic ray research deals with relating the character of the cosmic ray events to the conditions in the regions in which they are produced and also to the conditions in the regions through which they must propagate.
Until the launch of the first scientific satellites in 1958, all of the direct measurements of cosmic rays were obtained from terrestrial instruments. These were either made by balloon and rocket borne instruments or ground based neutron and meson monitors. The common feature of these instruments is that they all respond only to particles with energies greater than $10^8 - 10^9$ eV. At these energies the instruments sample predominantly the galactic flux, i.e., the flux of particles which reach the Earth from outside the solar system. With the advent of in-situ measurements of the low energy ($1 - 100$ MeV) cosmic ray flux, it became immediately apparent that the characters of the radiation in the two energy intervals were dramatically different. In general the character of the low energy cosmic rays is much more complex than that of the higher energy particles, so that the interpretation of the low energy observations is correspondingly more difficult.

The early theories of cosmic ray origin and propagation were based largely on the measurements of the high energy galactic fluxes. These theories were in relatively good agreement with the observations. It is not surprising then that they were inadequate in describing the observations made at the lower energies.
It would be desirable to study the production and propagation of cosmic rays separately. This is impossible since the present measurements are limited to the region near one astronomical unit (1 AU) and thus represent a mixture of the two phenomena. To separate the two would require an exact knowledge of at least one of them. What must be done, of course, is to combine the information on the plasma and magnetic fields derived from other sources with the cosmic ray data to present a unified picture of the combined phenomena.

At the present time the unified picture is not complete for several reasons. Detailed information on the plasma and magnetic fields, while increasing rapidly, is still incomplete. There is also an incomplete theoretical connection between the two sets of data. Finally there is at this time no definitive interpretation of many of the cosmic ray observations. The understanding of cosmic ray events, as represented by the data from cosmic ray detectors, is complicated by the nature of the measurements. They are physically limited to measurements of the conditions at a limited number of points. From these limited samples it is not always easy to infer the conditions at other points in space. Also the measurements are passive in the sense that the experimenter has no
control over the events. The measurements must be made during the periods in which the sun chooses to produce particles and, more important, with the various boundary conditions, i.e., solar and interplanetary conditions, which may exist at these times. Since the boundary conditions vary from event to event, it is necessary to obtain information on a sufficient number of events to determine how each of these boundary conditions influences the character of the cosmic ray events.

1.2 The Photosphere and Corona

The corona represents an extension of the solar photosphere; however, the characteristics of the two regions are very different.

The feature which is most characteristic of the solar corona is its chaotic nature. While the photosphere and chromosphere are in general quite stable, the corona is observed to have a quite complicated structure which sometimes undergoes sudden and dramatic changes. The portion of the solar atmosphere above 1.03 solar radius is usually considered the corona. The corona is an ionized plasma with a composition comparable to the bulk of the sun, i.e., mostly hydrogen, with 10 to 20 percent being helium, and a
small fraction of heavier elements. The corona can be observed by a number of methods. The most direct method is by photographs taken during solar eclipses. The corona is visible largely because of the scattering of sunlight. More quantitative measurements of the densities and temperatures in the plasma have been made by the study of emission lines of the plasma and by radio observations. These observations indicate a temperature throughout the corona of about one million degrees Kelvin. This temperature is much higher than the temperature of the photosphere (6000°K). Apparently the corona is continually heated by hydromagnetic waves which are generated in the interior of the sun. The electron density at the base of the corona is about $10^9$ electrons/cc and is observed to follow a generalized isothermal barometric law $N_e = \text{const} \times \exp\left(\frac{\text{const}}{rT}\right)$ where $N_e =$ electron density, $r =$ heliocentric radius and $T =$ plasma temperature.

Much of the material structure of the corona is associated with sunspot regions in the photosphere. These regions, which may be as large as $10^5$ km in diameter, are cooler by $1000^0$ K to $1500^0$ K than the surrounding photosphere. These spots usually form in broad active regions which often maintain their identity for several solar rotations (27 days per rotation). In many cases the sunspots are interconnected
by complex magnetic field structures. Magnetograms show that the magnetic field strength in the sunspots may reach as high as 3000 gauss. Figure 1 shows an example of the structure within the corona.

The structure of the magnetic fields within the corona has been recently mapped by Newkirk and Altschuler*. An example of their results is shown in Figure 2. Newkirk and Altschuler classify four different field patterns:

1. **Divergent fields** -- These fields spread in all directions from a central region and usually remain close to the solar surface.

2. **Magnetic rays** -- These field lines extend far out from the solar surface with undetermined reconnection points.

3. **Low magnetic arcades** -- These form a series of low magnetic loops. These loops appear to have no preferred orientation.

4. **High magnetic arcades** -- These are similar to the low magnetic arcades except the tops of the loops occur above 1—1.5 solar radius. These loops are sufficiently influenced by the poloidal magnetic fields to show a decided preference of east-west orientation.

The solar flare is probably the most important aspect of visible solar activity as far as interplanetary and
Fig. 1--Showing the solar corona of March 12, 1966. The orientation of the sun is the same as that shown in Fig. 2. (from Newkirk and Altschuler)

Fig. 2--Showing the magnetic field structure of the corona of March 12, 1966. (from Newkirk and Altschuler)
terrestrial effects are concerned. A solar flare is a short-lived burst of light which usually occurs in the vicinity of sunspots and particularly sunspot groups. Associated with the visible burst of light from the flare are also the emission of radio waves, ultraviolet radiation, x rays, and cosmic rays. The solar flares range in size and brightness from the barely visible class 1- flare which may appear every 30 minutes, to the giant class 3+ flare which may be brighter than the surrounding photosphere and cover an area with dimensions of $10^5$ km. The large 3+ flares may occur only a few times per year. The total energy expanded by a solar flare during its 1 to 2 hour lifetime may range from $10^{30}$ to $10^{33}$ ergs. Much of this energy goes into the heating and expulsion of photosphere gases and into the generation of electromagnetic radiation, with only a small fraction going into the acceleration of high energy particles.

At the present time there is no generally accepted model for the production of cosmic ray particles in the solar flares. In fact there is not yet general agreement on the phenomenology of solar cosmic ray production. Most considerations of flare effects have been based on the assumption of a single, impulsive injection of cosmic ray particles at the flare location, however there is evidence for continuous
production of energetic particles\(^2\) and for production at several points on the sun. Wild et al.\(^3\) have reported radio evidence of particle acceleration at points far removed from the flare location. This particle production is evidently triggered by high velocity (1000 km/sec) shock waves generated by the parent flare. A comprehensive study of the acceleration can be found in the IAU-IQSY 'Proton Flare Project, 1966\(^4\).

1.3 The Interplanetary Field

The coronal atmosphere is now known to extend out beyond the orbit of the Earth and it plays a central role in determining the propagation of solar cosmic rays. The existence of a continuous interplanetary plasma was first suggested by Biermann\(^5\) to explain the acceleration of Type 1 comet tails. One can distinguish knots in the tails of comets and their motion can be followed. This motion, particularly the accelerations, can be interpreted in terms of a continual flow of material from the sun, i.e., a "solar corpuscular radiation" or "solar wind". In a series of papers beginning in 1957, Parker\(^5\) developed a model of the expansion of the corona into interplanetary space. Utilizing the available data on coronal temperatures and density, Parker
showed that the plasma should be hydrodynamic in character and have a supersonic velocity. The theory predicted that velocities of $400 - 1000 \text{ km/sec}$ would be observed at the orbit of the Earth. Subsequent studies of the interplanetary medium by artificial satellites and deep space probes have confirmed Parker's solar wind model, with density of $2 - 10 \text{ particles/cm}^3$ and mean velocity of $\sim 500 \text{ km/sec}$ being typical. Parker also predicted the existence of a spiral interplanetary magnetic field structure imbeded in the solar wind. Due to the high conductivity of the plasma, any magnetic fields which are present in the plasma near the sun are effectively "frozen" in and carried outward by the solar wind. If the kinetic energy of the plasma exceeds the energy density of the imbeded fields, then the fields are controlled by the plasma. Near the surface of the sun, the energy density of the magnetic field is usually much greater than the plasma kinetic energy, so that the plasma in the inner corona corotates with the sun. Further out the plasma is dominant and moves radially. At the present time the radial distance to which the plasma corotates has not been accurately determined.

To establish the magnetic field configuration it is necessary only to determine the locus of a stream of plasma continuously emitted from a single region on the sun's
surface. Since the sun is rotating, the plasma will trace out an Archimedean spiral in space as it moves radially outward. The magnetic field will be carried with the plasma and in the Earth's frame of reference, will appear to corotate with the sun. If $X$ is the angle between the tangent to the field line and the radial direction, then, $\tan X = \Omega_s \frac{r}{v_p}$ where $\Omega_s$ is the sun's angular velocity ($2.9 \times 10^{-6} \text{sec}^{-1}$), $r$ is the radial distance and $v_p$ is the plasma velocity. For a plasma velocity of 400 km/sec the field line at 1 AU lies along a direction $\approx 45^\circ$ west of the observer's radial. The spiral nature of the interplanetary field was first demonstrated by McCracken using observations of the arrival directions of high energy cosmic rays from the sun. Direct verification of the spiral nature of the interplanetary field has been made by earth satellite and space probe measurements. These studies also revealed that the interplanetary field is highly variable both in magnitude and direction, with only the large-scale mean field following the theoretical spiral.

The radial distance to which the solar wind continues its supersonic flow is unknown. Parker and Axford have predicted the solar wind to terminate in a quasi-stationary shock wave at the point where the ram pressure of the wind
is equaled by the inward pressure exerted by the interstellar medium. This distance has been reckoned to be \(\sim 100\) AU. Other observations have placed this boundary nearer the sun, with the data from the study of comet tails suggesting it may be as close as 2 AU.

1.4 Characteristics of Solar Cosmic Ray Events

The dominant feature of solar cosmic ray events is the large variations in the particle fluxes. These particles appear shortly after a large solar flare and may reach flux values of as many as 6 orders of magnitude above quiet time levels. The particles are primarily protons, although in some cases the electron flux may be comparable to the proton flux. The alpha particle to proton ratio is of the order of \(10^{-3} - 10^{-1}\), with the ratio decreasing with energy\(^{12}\). In general the events are characterized by the following features:

1. Particles are normally observed after flare activity in a solar active region with the large events usually accompanied, or preceded, by a Type IV solar microwave burst and the production of several kilovolt x rays. In some cases the flare may not be visible from the Earth if it occurs on the invisible solar hemisphere.

2. The energy spectrum can be usually fitted over much
of the energy range by a power law of the form
\[ \frac{dJ}{dE} = E^{-\gamma} \]
with the exponent \( \gamma \) having values of 2 to 6.

3. There is usually a rapid increase in the count rate until a maximum is reached some hours after the flare. If the rise time is very short, the particles show a dispersion in arrival time due to difference in the velocity of particles of different energies. In many cases the rise time is dependent on the heliographical location of the flare, with the slower rise times being associated with flares on the eastern portion of the solar disk. However there are sometimes complex variations which may last for several days. In some events, the low energy particles show no increase until the arrival of disturbances in the solar wind generated by the flare.

4. Following the peak, the flux decreases to the quiet time level exponentially, with the time required to decay by a factor of \( e \) (i.e., e-folding time) being between 12 and 60 hours.

5. During the early phase of most flare events the particles are strongly columniated along the magnetic field lines. The large initial anisotropy decays to an "equilibrium" anisotropy of magnitude 5 - 10 percent, which is directed
along the observer's radial (McCracken et al.\textsuperscript{13}, Rao et al.\textsuperscript{14}).

This behavior can be understood as follows. At early times the net flow of particles at the spacecraft is a result of particles moving outward from the concentration near the sun. Consequently the particles are columniated by the divergence of the interplanetary field. With time, scattering broadens the pitch angle distribution, until the radiation is approximately isotropic in the frame of reference of the solar wind (i.e., in the frame of reference of the scattering medium).

The observer is moving in this frame of reference and will therefore see a radial anisotropy given by Forman\textsuperscript{15} to be

\[ \delta = (2 + \alpha \gamma) \frac{V_p}{V} \]

where the differential energy spectrum is proportional to \( E^{-\gamma} \), \( V_p \) is the solar wind velocity, \( \alpha = \frac{E + 2M_0C^2}{E + M_0C^2} \)

and \( V \) is the velocity of the particles.

1.5 The Statistical Description of Cosmic Ray Propagation

Due to the relatively large fluctuations in the interplanetary magnetic field it is not possible to describe the motions of each individual cosmic ray. For this reason, the general approach to the problem of propagation has been to attempt to describe statistically the bulk motion of the cosmic ray particles. This statistical approach to the
problem was first suggested by Fermi\textsuperscript{15}. Although Fermi was interested only in the acceleration of particles as they were scattered by moving magnetic fields and did not explicitly consider the problem of propagation, his work served to introduce the concept of scattering and the consequent "random walk" of particles. In the early statistical theories the random walk was introduced on an \textit{ad hoc} basis by assuming that the particles were scattered in much the same way as are molecules in the kinetic theory of gases. Due to their \textit{ad hoc} nature, these theories provided no qualitative measure for relating the scattering of the particles to the parameters describing the interplanetary field. To a very good approximation, a cosmic ray particle moving through the solar wind sees the interplanetary magnetic field as being static and time invariant, so that the particle will move along a trajectory which is given by Liouville's equation. Since Liouville's equation is completely deterministic and contains no inference to the statistical concept of random scattering, one is faced with the problem of defining the exact meaning of "scattering". Jokipii\textsuperscript{17} and Roelof\textsuperscript{18} provided an answer to this problem by defining the scattering in terms of the local deviation of the actual particle trajectory from the trajectory of the same particle in a nominal spiral
interplanetary magnetic field. Using this formalism the diffusion tensor describing the scattering can, to sufficient accuracy, be expressed in terms of the power spectrum of the irregularities in the interplanetary field evaluated at the particle's gyrofrequency.

At the present time there is a large number of different models which have been proposed to describe the various features of solar cosmic ray events. Although diffusion plays a central role in determining the propagation of particles in each of these models, they differ widely in the assumptions made on the nature of the diffusion, on the nature of the boundary conditions both near the sun and at large distances, and on the effects of convection and adiabatic deceleration by the solar wind.

Although the diffusion tensor is, in theory, fixed by the power spectrum of the irregularities in the magnetic field, there are observational uncertainties which prevent definitive measurements of the power spectrum. The fluctuations observed by a stationary spacecraft consist of variations convected radially outward by the solar wind, while the particles sample those fluctuations which lie along the magnetic field lines. Recent studies of correlated magnetic field and plasma measurements suggest that a large
number of sharp discontinuities seen in the magnetic data are tangential to the magnetic fields and do not contribute to the scattering of particles. Sari and Ness conclude that half, if not more of the power spectrum may be made up of fluctuations of this nature.

Using the statistical description of cosmic ray propagation, the theoretical problem reduces to solving one of the several forms of the diffusion equation for the phase space density $U(\vec{r}, \vec{v}, t)$, where $\vec{r}$, $\vec{v}$ and $t$ are the position, velocity and time respectively. The anisotropy and omnidirectional intensity follow immediately from $U$. The important point to consider here is that from an observational standpoint one cannot make a definitive comparison of only the omnidirectional flux to the theoretical models; since the models specifically predict both the anisotropy and the omnidirectional flux, both must be used in the comparison. This requires that the detector system be capable of accurately determining both the omnidirectional flux and the anisotropy.
CHAPTER BIBLIOGRAPHY


CHAPTER II

THE PIONEER 8 AND 9 COSMIC RAY DETECTOR SYSTEM

2.1 Introduction

In this chapter is described the cosmic ray detector systems which were flown aboard the Pioneers 8 and 9 deep space probes. Both Pioneer 8 and 9 were launched into heliocentric orbits, with Pioneer 8 being launched into an outbound orbit with predicted aphelion of 1.1 AU and Pioneer 9 being launched into an inbound orbit of predicted perihelion 0.8 AU. A similar instrument was planned for the ill-fated Pioneer 10 mission, which failed to achieve orbit. The predominant feature of these instruments is their ability to provide very accurate measurements of the flux and anisotropy of cosmic rays in the energy range 1 to 100 MeV.

The Pioneer 8 and 9 detector systems consist of a scintillation counter telescope, along with a tri-telescope comprised of three solid state detectors arranged in a fan configuration surrounding a fourth. The physical orientation of the instrument package is such that as the spacecraft rotates about a spin axis perpendicular to the ecliptic plane,
the scintillation counter records the fluxes of cosmic rays whose arrival directions at the spacecraft make small angles with the plane of the ecliptic. In addition, the solid state tri-telescope also possesses the capability of recording the fluxes of cosmic ray particles whose arrival directions at the spacecraft make substantial angles to the plane of the ecliptic.

2.2 The Detector System (Mechanical)

The essential features of the scintillation counter telescope are illustrated in Figure 3. The 12 gm/cm² thick CsI(Tl) crystal scintillator (C) is encased on three sides by a cylindrical veto counter (D) constructed from scintillating polytoluene. Each scintillator is viewed by independent photomultiplier tubes, and logic circuits selects those particles which produce light pulses within the CsI(Tl) crystal unaccompanied by light pulses within the veto counter (i.e., CD logic). Thus, the scintillation telescope is unidirectional, selecting for study only those particles which enter the system through the open end of the veto counter and come to the end of their range in the crystal. Such criteria are satisfied only by particles with range in the CsI(Tl) crystal of less than 12 gm/cm² and whose directions of arrival at
Fig. 3--The essential features of the scintillation counter telescope.
the spacecraft define angles no greater than $\pm 38.2^\circ$ with the plane of the ecliptic. Due to edge effects, the geometric factor of the scintillation telescope is energy dependent and varies from $2.9 \text{ cm}^2\text{sr}$ for high energy particles to $4.8 \text{ cm}^2\text{sr}$ for low energy particles. A detailed description of this effect is described in Appendix I.

The photomultiplier tube associated with the CsI(Tl) crystal is space-coupled to the crystal through a highly reflective light-integrating chamber. Although the space-coupling of the phototube to the crystal results in a reduction of pulse height, such a technique removes any loss in efficiency of the veto counter due to "leakage" of particles to the CsI(Tl) scintillator through the orifice required for direct optical coupling.

The salient features of the solid state detector tri-telescope are illustrated in Figure 4. Detectors A, E, and F are oriented in a fan arrangement around detector B, and when operated in coincidence with detector B define three telescopes AB, EB, and FB. All detectors are silicon surface barrier diodes of 100 mm$^2$ active surface area operated at their total depletion depths of 100 microns.

The physical orientation of the tri-telescope configuration within the instrument package is such that, aboard the
Fig. 4--The solid state detector tri-telescope

Fig. 5--The relative directional response of telescope EB or FB as a function of viewing direction.
Pioneer spacecraft, the mean viewing direction of the AB telescope lies within the plane of the ecliptic, while the mean viewing directions of EB and FB are centered 48° above and below this plane, respectively. Each telescope configuration defines a cone of acceptance of half-angle of 24°. The relative directional sensitivity of either solid-state detector telescope EB or FB is plotted in Figure 5, as a function of the mean viewing direction measured with respect to the plane of the ecliptic.

2.3 The Detector System (Electrical)

The block diagram of the electronics system, shown in Figure 6, can be divided into two major sections. Section (A) shows the functions necessary for converting the analog signals from the detector systems into digital pulse streams, while Section (B) shows the functions necessary for preparing these data for transmission via spacecraft telemetry. Data accumulation is divided into 16 measurements which are recorded cyclically. Table I shows the format of the measurement cycle and gives the detector logics used in each measurement. During each measurement interval, data are accumulated concurrently from two channels. In one of these channels the accumulation of data is synchronous with
Fig. 6--The Pioneer functional block diagram.
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sun Synchronous Channel</th>
<th>Telemetry Synchronous Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Logic</td>
<td>Octants</td>
</tr>
<tr>
<td>0</td>
<td>(AB)₁ᵃ</td>
<td>1, 5</td>
</tr>
<tr>
<td>1</td>
<td>&quot;</td>
<td>2, 6</td>
</tr>
<tr>
<td>2</td>
<td>&quot;</td>
<td>3, 7</td>
</tr>
<tr>
<td>3</td>
<td>&quot;</td>
<td>4, 8</td>
</tr>
<tr>
<td>4</td>
<td>(CD)₁</td>
<td>1, 5</td>
</tr>
<tr>
<td>5</td>
<td>&quot;</td>
<td>2, 6</td>
</tr>
<tr>
<td>6</td>
<td>&quot;</td>
<td>3, 7</td>
</tr>
<tr>
<td>7</td>
<td>&quot;</td>
<td>4, 8</td>
</tr>
<tr>
<td>8</td>
<td>(AB)₂ᵃ</td>
<td>1, 5</td>
</tr>
<tr>
<td>9</td>
<td>&quot;</td>
<td>2, 6</td>
</tr>
<tr>
<td>10</td>
<td>&quot;</td>
<td>3, 7</td>
</tr>
<tr>
<td>11</td>
<td>&quot;</td>
<td>4, 8</td>
</tr>
<tr>
<td>12</td>
<td>(CD)₂</td>
<td>1, 5</td>
</tr>
<tr>
<td>13</td>
<td>&quot;</td>
<td>2, 4</td>
</tr>
<tr>
<td>14</td>
<td>&quot;</td>
<td>3, 5</td>
</tr>
<tr>
<td>15</td>
<td>&quot;</td>
<td>4, 8</td>
</tr>
</tbody>
</table>

ᵃDetectors E and F subcommutated with detector A.
the spin of the spacecraft, while in the other it is synchronous with the spacecraft telemetry.

The Sun-Synchronous Channel

This channel is intended primarily for anisotropy measurements and data are always accumulated over an integral number of spin periods. Measurements of the particle anisotropy (i.e., the direction of preferential particle flow) are achieved by means of "aspect clock" circuitry, similar in nature to that developed for the earlier Pioneer missions\(^1\) which accurately divides each spacecraft spin period into eight identically equal (to within one part in \(10^4\)) time segments. This octant division is shown in Figure 7(A), which illustrates the data accumulation intervals relative to the spacecraft-sun line. During each measurement, data are collected from two of the octants \(180^\circ\) apart (Table I). At the end of each measurement period the accumulated data, along with the number of spacecraft spins over which the data were accumulated are transferred to an output buffer which is read out serially to the spacecraft telemetry. Figure 7(B) illustrates an alternate data collection mode which provides increased directional sensitivity. In this "slipped octant mode", the octants are shifted to the east by \(22.5^\circ\). Data
Fig. 7—Octant configuration within the ecliptic plane in (a) the normal mode and (b) in the slipped octant mode.
are collected alternately from each octant configuration during the flight life-time. Data are collected from two energy ranges for each of the detector logics (AB, EB, FB, and CD) used in the sun-synchronous channel.

The Telemetry Synchronous Channel

The data in this channel are collected from both the crystal and solid state telescopes in six differential energy windows. Data accumulation is synchronous with the spacecraft telemetry, with the data being read out during each telemetry main frame (the spacecraft telemetry operates at five different bit rates varying from 512 bits per second to 8 bits per second, the desired bit rate being initiated by ground command).

Pulses from the various detectors are amplified and fed into linear switches which select those signals necessary to create the logic combinations used in each measurement. The pulses are then fed into one of two pulse height analyzers which determine whether the particle satisfies the energy requirements of the current measurement. The signals necessary for setting the linear switches and for setting the discriminator windows of the two pulse height analyzers are generated by the central control unit. The discriminator
Fig. 8--The proton response curve for the Pioneer solid state telescope.
levels required to obtain the desired energy ranges for the solid-state telescope are obtained from the energy response curves of these detectors. An example of such a proton response curve for a pair of 100 micron detectors operating as a particle telescope is shown in Figure 8. Herein is plotted the energy deposition $\Delta E_2$ in the second detector (detector B for each telescope arrangement) as a function of the energy deposition $\Delta E_1$ in the front detector of the telescope. The corresponding energies of the incident protons are indicated at various positions along the curve. On the basis of such response curves, differential energy windows of 3.3–3.6 MeV for incident protons were selected for anisotropic particle propagation studies.

The functions necessary to prepare the digital data for transmission via spacecraft telemetry are described in detail elsewhere; suffice it to say that the directional data from both the crystal and solid-state detectors are stored in two 9-bit logarithmic accumulators (labeled J and K in Figure 4) while the omnidirectional data are stored in a separate 9-bit logarithmic accumulator (labeled M in Figure 4). A 3-bit binary accumulator (L) acts as a spacecraft spin counter. The 9-bit logarithmic accumulators are so gated as to allow 2752 counts to be accumulated during each measurement. At
a telemetry bit rate of 512 bits per second, these accumulators permit omnidirectional particle fluxes as large as about 400 particles/(cm² sec sr) and directional fluxes as large as $3 \times 10^3$ particles/(cm² sec sr) to be recorded before accumulator overflow occurs.

2.4 Instrument Data Format

The spacecraft telemetry main frame consists of 32 seven bit words (six data bits plus one parity bit) in which the present detector system is allotted five contiguous words for a total of 30 bits (excluding parity). These 30 bits are then used to define the outputs of the 9-bit omnidirectional accumulator M, the two 9-bit directional accumulators J and K and the 3-bit spin counter L.

For the sun-synchronous mode, data accumulation must start and stop with the recording of a pulse from the spacecraft sun sensor. All control signals are synchronous with the telemetry bit stream, and consequently completely asynchronous with the sun pulses. Figure 9 illustrates the manner in which compatibility between these two asynchronous pulse streams is achieved, thereby allowing meaningful directional data to be recorded. The condition depicted therein refers to a bit rate of 512 bits per second, although Figure 9
Fig. 9--Data collection for sun-synchronous and telemetry synchronous modes of operation.
is also representative of the techniques employed for the lower bit rates. Data pertinent to a particular detector logic begin to accumulate coincident with the arrival of a Sun pulse. These data are then accumulated over a time interval which includes the arrival of at least four word-gate pulses. (The selection of four word-gate pulses is somewhat arbitrary, the sole criterion being that this provides a convenient accumulation time at 512 bits per second.) Coincident with the arrival of the first sun pulse subsequent to the fourth word-gate pulse, these directional data are transferred from the accumulators into the output buffer. The accumulators are immediately reset, the detector logic is changed, and a new accumulation is initiated. Upon the arrival of the first word-gate pulse during this new accumulation, the data stored in the output buffer from the former detector logic are read out. Hence, directional data are contained in every fourth (or more, depending upon the relative phases of the word-gate and sun pulse streams) readout, at 512 bits per second. Clearly, the relationship between the frequency of the directional data readout and the word-gate frequency is dependent upon the bit rate and the number of word-gates utilized to define the accumulation time for the
detector logics. Omnidirectional data are read out during each word-gate pulse. Changes in detector logics for both the directional and omnidirectional modes, however, occur simultaneously.

2.5 Physical Properties of the Instrument

The completely assembled Pioneer 8 and 9 cosmic ray detector package contains 421 transistors, 786 diodes, 179 IC's, a high-efficiency power supply, four solid-state detectors, two scintillators, two photomultiplier tubes, and a thermistor network. The assembled detector system weighs 2.56 kg, occupies a volume of 235 cubic inches, and consumes 1.72 watts of electrical power. A front-end view of the completely assembled package is shown in Figure 10. The crystal telescope is located on the lower right portion of the front face, while the solid-state tri-telescope occupies the upper left portion. Aluminized mylar sheets protect the sensitive surface areas of all the detectors.

Since a major aim of the Pioneer program is to provide precise information on the interrelationship of cosmic ray propagation, solar plasma outflow, and interplanetary magnetic field configurations (fluctuations in this latter parameter often being of the order of $10^{-6}$ $\text{Oe}$), extreme care was
Fig. 10--The completely assembled Pioneer 8 and 9 cosmic ray detector package. The scintillation telescope is in the lower right corner of the package and the tri-telescope can be seen in the upper left hand corner.
taken to ensure that the spacecraft and the entire scientific payload conformed to very stringent residual magnetic specifications. The cosmic ray detector package exhibited a magnetic field of less than $2 \times 10^{-5}$ Oe at a distance of 91 cm after an exposure to a magnetic field of 25 Oe. This very low susceptibility to magnetism was achieved through a program of very strict screening of flight-certified parts, and a design directed towards the use of a minimum amount of ferromagnetic material.

2.6 In-Flight Performance

An in-flight calibration sequence of the detector package is initiated periodically by ground command (at least once per day). This calibration sequence monitors the performance of the scintillation telescope, the "aspect clock" circuitry, and the accumulator-buffer system. This sequence is comprised of the following tests, the data being telemetered back to earth, in the normal manner, subsequent to each calibration:

a. A 10 nanocurie Am$^{241}$ source is used to indicate any possible gain shifts in the CsI(Tl) crystal and its ancillary electronic circuitry. During the normal flight mission, the energy thresholds of the CsI(Tl) telescope are set high
enough so as not to record the 5.3 MeV Am$^{241}$ alpha particles. Upon the initiation of a calibration sequence, these thresholds are lowered such that the alpha particle source is detected in the fourth and fifth energy windows in the omnidirectional mode of operation.

b. Pulses are fed into the data conditioning circuitry (beyond the PHA's) at the bit rate frequency. This allows an in-flight comparison of the counting rates from each octant in turn.

A continual check on the performance of the output buffer and one accumulator is executed routinely throughout the normal flight lifetimes of the Pioneer spacecrafts, as one of the omnidirectional measurements monitors the bit rate. This constant monitor of the bit rate also acts as a valuable flag for data handling and processing.

Figure 11 illustrates the spin frequency of the Pioneer 8 spacecraft and the counting rate due to the Am$^{241}$ source as a function of time. During this time there were no observable changes in the behavior of the cosmic ray detector.
Fig. 11—Calibration curve depicting the long-term stability of the Pioneer 8 cosmic ray detector.
CHAPTER BIBLIOGRAPHY


CHAPTER III

OBSERVATIONS

3.1 Introduction

In this chapter several facets of solar cosmic ray events will be discussed. Particular attention will be given to (a) the anisotropic character of the radiation, (b) the distribution of particles in heliocentric longitude, (c) the decay time constants, (d) the energy spectrum, and (e) the influence of the coronal conditions.

The major portion of the data used here was obtained from the Pioneers 8 and 9 detector system. However these data are augmented with similar data from the Pioneers 6 and 7 spacecraft. Much of the analysis is concentrated on data which were obtained during the period from November 1968 through April 1969, since good coverage was obtained for all four spacecrafts. The positions of the spacecrafts during this period are plotted in Figure 12. It can be seen that the spacecrafts sampled the cosmic ray flux simultaneously over a large range of heliocentric longitude.
Fig. 12—The positions of the four Pioneer spacecrafts during the period November 1968 until April 1969.
TABLE II

PARENT FLARES

<table>
<thead>
<tr>
<th>Date</th>
<th>Flare Onset UT</th>
<th>Importance</th>
<th>McMath Flage Region</th>
<th>Flare Co-ordinates</th>
<th>S/C Long PS</th>
<th>P9</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Nov. 68</td>
<td>1017</td>
<td>1B</td>
<td>9750</td>
<td>N21 W87</td>
<td>E22</td>
<td>W1</td>
</tr>
<tr>
<td>2 Dec. 68</td>
<td>2116</td>
<td>3N</td>
<td>9892</td>
<td>N18 E80</td>
<td>E22</td>
<td>W2</td>
</tr>
<tr>
<td>12 Mar. 69</td>
<td>1738</td>
<td>2B</td>
<td>9936</td>
<td>N12 W80</td>
<td>E24</td>
<td>W15</td>
</tr>
<tr>
<td>30 Mar. 69</td>
<td>0248</td>
<td>?</td>
<td>9974</td>
<td>N19 W110</td>
<td>E24</td>
<td>W24</td>
</tr>
<tr>
<td>11 Apr. 69</td>
<td>..</td>
<td>?</td>
<td>..</td>
<td>..</td>
<td>E25</td>
<td>W32</td>
</tr>
</tbody>
</table>

The column "S/C Long" lists the longitudes of the feet of the nominal Archimedes spirals through the spacecraft relative to the parent flare. The identification for the 30 March 1969 flare is based on Smerd9. There was a gap in the flare patrol at the time of the 11 April 1969 event. The "Flare co-ordinate" listed in this case is that of a very active center which was on the solar disc at the time. The cosmic ray data, and in particular the gradient data in Figure 22, are in good accord with this assignment.
3.2 The Anisotropy of the Decay Phase

In a series of papers, McCracken and others\textsuperscript{1,2,3} have shown that the initial anisotropy during solar flare events is large and aligned along the direction of the magnetic field. This large initial anisotropy decays within approximately 12 to 24 hours to an "equilibrium" anisotropy which is aligned with the solar wind velocity and which is independent of the direction of the interplanetary magnetic field. Parker\textsuperscript{4}, McCracken\textsuperscript{2}, and Forman\textsuperscript{5} have shown that this behavior is a result of the distribution of particles becoming isotropic in a reference frame moving with the solar wind. Since the particle flux is isotropic in this frame of reference there will be no net cosmic ray flow, however, a stationary observer will see the particles streaming outward with a net velocity equal to the velocity of the solar wind. This convected current of cosmic rays will produce an anisotropy in the observer's reference frame which is given by

\[ \hat{\delta} = (2 + \alpha \gamma)(V_p/V) \hat{r} \]  

(1)

where $\gamma$ is the exponent of the power law fit to the cosmic ray spectrum $dJ(E) = \text{const. } E^{-\gamma} dE$, $V_p$ is the solar wind velocity, $V$ is the particle velocity, $\hat{r}$ is a unit vector in the outward radial direction and
where $E_c$ and $E_0$ are the kinetic and rest energies of the particles. The anisotropy $\delta_d$ which results from a diffusive flow of cosmic ray particles is given by

$$\delta_d = \frac{3 K \cdot \nabla U}{U}$$

where $K$ is the diffusion coefficient and $\nabla U$ is the gradient in the particle density. Since the diffusion coefficient perpendicular to the field lines is negligibly small compared to that parallel to the field lines, the direction of anisotropy will lie parallel or antiparallel to the magnetic field lines. Thus $\delta_d$ can be written as $\delta_d = \frac{K_\parallel \delta U}{U \delta s} \hat{e}_B$, where $K_\parallel$ is the diffusion coefficient parallel to the magnetic field, $s$ is the distance along the field line and $\hat{e}_B$ is a unit vector in the direction of $\vec{B}$.

The existence of a radial anisotropy at late times in the event implies the dominance of the convective currents over the diffusive current of cosmic rays, i.e., it implies that $(2 + \alpha \gamma) V_p > 3 \frac{K_\parallel \delta U}{U \delta s}$ or that the gradients in $U$ are small.
Fig. 13--The temporal variations of the 7.5-45 Mev cosmic ray fluxes observed by Pioneers 8 and 9 during the solar effect of April 11, 1969. The Pioneer 8 flux should be multiplied by a factor of 1.7. The Vela solar wind velocities have been shifted in time to indicate the solar wind variability at Pioneer 9.
In Figure 13 are displayed the data for a solar flare that occurred on April 11, 1969. It is clear that a quasi-exponential decay was evident over a period of about twelve days. Due to the relatively long lifetime of this event it was studied in some detail in order to provide an insight into the decay phase of solar flare effects.

Figure 14 displays the daily mean anisotropy of the 7.5 to 21.5 MeV protons observed by Pioneers 8 and 9 during the latter part of the decay phase. It is clear that while the anisotropy was initially directed radially away from the sun, its vector direction was from the east of this direction at very late times. It should be noted that the behavior of the anisotropy at both spacecrafts was essentially identical and that the direction of anisotropy remained at approximately 45° east of the sun-spacecraft line for about four days. This would indicate that it is most unlikely that the easterly anisotropy was due to the diffusion of particles along an anomalous configuration of the interplanetary field lines i.e., with the magnetic vector being 45°E of the sun-spacecraft line, as contrasted with the nominal 45°W.

Several other long-lived events have been examined and these, without exception, show easterly anisotropies at late times (t > 4 days). Figure 15 presents anisotropy data for
Fig. 14—The cosmic ray anisotropy vector diagram for Pioneers 8 and 9 for the decay phase of the flare effect of April 11, 1969. The dashed line is drawn 45° to the East of the spacecraft-Sun direction.
Fig. 15--The cosmic ray anisotropy vector diagrams for Pioneers 8 and 9 for the decay phases of three flare effects. The dashed lines are drawn at 45° to the east of the spacecraft-sun direction.
three of these large events, which were observed by both Pioneers 8 and 9. Allum et al.\textsuperscript{6} and Rao et al.\textsuperscript{7} have also reported similar behavior in the anisotropies of the electron component of the cosmic rays.

Figures 16 and 17 summarize the complete evolution of the cosmic ray anisotropy during a solar flare. The anisotropy can be classified into three distinct phases.

**Phase 1.** During this phase the anisotropy is large and directed along the interplanetary magnetic field vector $\mathbf{B}$. This type of anisotropy indicates a dominant diffusive component $K_{\parallel} \frac{\partial U}{\partial s}$.

**Phase 2.** Between one and three days after the start of the event the anisotropy is directed radially ($\pm 20^\circ$) away from the sun, with a magnitude of the order of 5 to 10 percent.

**Phase 3.** At times greater than four days the anisotropy is directed from $45^\circ$ east.

The models of the three phases are shown in Figure 18. During Phase 1 there exists a strong gradient of particles towards the Sun, i.e., $\frac{\partial U}{\partial s} < 0$ which drives a diffusive current $J_d = -K_{\parallel} \frac{\partial U}{\partial s}$ outward along the field lines. As the particle population moves outward the gradient at 1 AU
Fig. 16—Illustrating the evolution of solar cosmic radiation. The parent flare occurred late on March 29, 1969. The vectors are the average anisotropy for each calendar day thereafter.
<table>
<thead>
<tr>
<th>EVENT</th>
<th>DAYS AFTER SOLAR FLARE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Nov. 18, '68</td>
<td></td>
</tr>
<tr>
<td>P8</td>
<td></td>
</tr>
<tr>
<td>P9</td>
<td></td>
</tr>
<tr>
<td>Dec. 3, '68</td>
<td></td>
</tr>
<tr>
<td>P8</td>
<td></td>
</tr>
<tr>
<td>P9</td>
<td></td>
</tr>
<tr>
<td>Mar. 30, '69</td>
<td></td>
</tr>
<tr>
<td>P8</td>
<td></td>
</tr>
<tr>
<td>P9</td>
<td></td>
</tr>
<tr>
<td>Apr. 11, '69</td>
<td></td>
</tr>
<tr>
<td>P8</td>
<td></td>
</tr>
<tr>
<td>P9</td>
<td></td>
</tr>
<tr>
<td>Sept. 27, '66</td>
<td></td>
</tr>
<tr>
<td>P7</td>
<td></td>
</tr>
</tbody>
</table>

**ANISOTROPY VECTOR DIAGRAM**

Fig. 17--Summarizing the vector direction of the cosmic ray anisotropy during five solar flare effects. A dotted arrow to the left indicates an anisotropy which was from the West of the Spacecraft-Sun line. A solid arrow to the right indicates an anisotropy from the East, while an arrow pointing vertically downward indicates a radially directed anisotropy.
Fig. 18—The model for the evolution of the anisotropy of the cosmic ray solar flare effect. (a) Early Times: a convective current, plus a diffusive current driven by a negative cosmic ray density gradient, as shown; (b) Late Times: a convective current alone. There is no diffusive current since the cosmic ray density gradient is zero; (c) Very late Times: a convective current, plus a diffusive current driven by a positive density gradient.
becomes small \((vU = 0)\) and the convective currents \((\mathbf{J}_c = U \mathbf{\hat{V}}_p)\) dominate the anisotropy. As the convection drives the center of the particle population out beyond 1 AU, a positive gradient is set up at 1 AU. This gradient in turn drives a diffusive current back in toward the sun along the magnetic field lines.

In Figures 14 and 15 the dashed lines are drawn at an angle of 45° to the east of the spacecraft-sun line. It is apparent that in each case the anisotropy at very late times adapts a direction which is remarkably close to 45° east of the sun. Within the accuracy of our data, it seems reasonable to assert that at very late times the net cosmic ray vector is normal to the magnetic field \(\mathbf{B}\) (i.e., 45° E ±10°).

A cosmic ray current normal to \(\mathbf{B}\) requires that there exist no net flux along the field lines. This in turn requires that the component of the convective current parallel to the magnetic field is exactly balanced by the diffusive current. The unit vector normal to \(\mathbf{B}\) and lying in the ecliptic plane can be written \(\mathbf{\hat{e}}_n = (\mathbf{\hat{r}} \times \mathbf{\hat{e}}_B) \times \mathbf{\hat{e}}_B\) so that the anisotropy can be written as

\[
\delta = \delta_c + \delta_d = \delta_c \sin \theta \mathbf{\hat{e}}_n + (\delta_c \cos \theta + \delta_d) \mathbf{\hat{e}}_B
\]

where \(\theta\) is the angle between the magnetic field and the
radial. Since the net flux parallel to $B$ is zero, 
\[ \delta_d = -\delta_c \cos \theta \] and the anisotropy is given by 
\[ \delta = (2 + \alpha \gamma) \frac{V_p \sin \theta \hat{e}_n}{V}. \] (2)

An equivalent description of the anisotropy at very late times is obtained by considering the effects of the electromagnetic field in the plasma. To an observer moving outward with the solar wind, the magnetic field is stationary and the electric field is zero due to the high conductivity of the plasma. A stationary observer will see the magnetic field moving outward with the velocity of the solar wind and as a result will see an induced electric field given by 
\[ \vec{E} = \frac{1}{c} \vec{V}_p \times \vec{B} = \frac{1}{c} V_p B (\hat{r} \times \hat{e}_B). \]

The combined electric and magnetic fields produce a guiding center drift of the particle. The drift velocity $V_d$ is given by 
\[ \vec{V}_d = \frac{c}{B^2} (\vec{E} \times \vec{B}). \] Since \[ \vec{E} = \frac{1}{c} V_p B (\hat{r} \times \hat{e}_B) \] the drift velocity is given by 
\[ \vec{V}_d = \frac{c}{B^2} \frac{V_p B}{c} (\hat{r} \times \hat{e}_B) \times B \hat{e}_B = V_p \sin \theta \hat{e}_n. \]
The anisotropy produced by this drift is

\[ \dot{\delta}_{\text{ExB}} = (2 + \alpha \gamma) v_p \sin \theta \hat{\mathbf{n}} / V. \]

If the particles are in equilibrium along the field lines then \( \dot{\delta}_{\text{ExB}} \) will represent the total anisotropy.

The important consequence of the easterly anisotropy is that the flow of particles along the field lines is effectively "stalled" and the removal of particles from the solar system is entirely a result of the ExB drift, which to a first order is independent of the scattering characteristics of the interplanetary field. This point will be discussed in more detail later.

3.3 The Dependence of the Cosmic Ray Density Upon Heliocentric Longitude at Late Times

The cosmic ray density can be written as \( U(r, \psi, E, t) \).

In this function, \( \psi \) is the heliocentric longitude of the intersection of the nominal Archimedes spiral through the point of observation with the solar surface, \( \psi \) is reckoned westward from a fixed point on the rotating sun, \( r, E, \) and \( t \) are the distance from the sun, the particle kinetic energy, and time respectively. Since the cosmic radiation remains associated with the same magnetic tube of force as it is
Fig. 19--A diagramatic representation of the manner in which the position of an observer relative to the centroid of the cosmic-ray population affects the nature of the decay phase of a flare effect. An observer to the east of the centroid will observe a fast decay due to the spatial and temporal terms having the same sign. An observer to the west of the centroid will observe a slower decay due to the temporal and spatial terms having opposite signs.
convected out of the solar system, a cosmic ray population "co-rotates" with the Sun. That is, the population remains associated with the same values of $\psi$ throughout its lifetime in the solar system.

The rate of change of $U$ with time, as observed by a spacecraft is given by

$$\frac{dU}{dt} = \frac{\partial U}{\partial \psi} \frac{d\psi}{dt} + \frac{\partial U}{\partial r} \frac{dr}{dt} + \frac{\partial U}{\partial t}$$

where the term $\frac{\partial U}{\partial t}$ includes the effect of adiabatic deceleration. The second term is small, since $\frac{dr}{dt}$ for the spacecraft is very small, so

$$\frac{dU}{dt} = \frac{\partial U}{\partial \psi} \frac{d\psi}{dt} + \frac{\partial U}{\partial t}.$$  \hspace{1cm} (3)

At late times $\frac{\partial U}{\partial t} < 0$, however $\frac{\partial U}{\partial \psi}$ may be either positive or negative depending on whether the observer is on the eastern or western side of a cosmic ray population (Figure 19) so that the two terms in (3) will add or partially cancel. Any discussion of the decay phase of a flare event observed from Earth, or a spacecraft, therefore requires knowledge of the dependence of $U$ upon heliocentric longitude.

Figure 20 displays data obtained by three Pioneer spacecrafts during a period which exhibited large cosmic ray fluxes of solar origin. Data were also obtained by Pioneer 8 during this period (see Figures 15 and 28). The totality of these data have been used to produce the graphs of the
Fig. 20—Demonstrating the marked differences in the time variations of the solar cosmic ray flux observed at widely separated points in the solar system.
dependence of the omnidirectional cosmic ray flux upon heliocentric longitude which is presented in Figure 19.

Comparing the two periods in Figure 21, it should be noted that the curves for adjacent days are much closer together for April 6-8 than for April 14-19, 1969. This can be attributed to the fact that the spacecrafts were on the western side of the cosmic ray distribution for April 6-8, and on the eastern side for April 14-19. That is, in the latter case, the \( \frac{\partial U}{\partial t} \) and \( \frac{\partial U}{\partial \psi} \frac{d\psi}{dt} \) terms are both negative, while in the former, the \( \frac{\partial U}{\partial t} \) term is negative, while the \( \frac{\partial U}{\partial \psi} \frac{d\psi}{dt} \) term is positive, thereby partially cancelling the \( \frac{\partial U}{\partial t} \) term. That is, the "co-rotation" of the cosmic ray population partially cancelled the temporal change for April 6-8, resulting in a slow decay phase (also see Figure 27).

Comparing the curves in Figure 21, a similarity will be noted between the absolute values of the gradients of the flux over the ranges 90°E - 24°E for April 6-8, and 150°E - 12°W for April 14-19. Over both ranges, the data can be fitted by an exponential relationship \( \frac{1}{U} \frac{dU}{d\psi} = \frac{1}{\psi_0} \), where \( \psi_0 = -28^\circ \) for April 6-8; and \( \psi_0 = +34^\circ \) for April 14-19.
Fig. 21--The cosmic ray flux as a function of heliocentric longitude at very late times in two flare effects. The data for the period 6-8 April, 1969 illustrates the situation when the observer is on the western side of the population, so that the increase in flux due to the corotation of the cosmic ray population partially cancels the depletion of the population due to convection and diffusion. The period 14-19 April illustrates the opposite situation where the observer is on the eastern side of the population.
The similarity of $|\psi_o|$ suggests that there may be a characteristic $\psi_o$ determined by the details of the process whereby the solar cosmic rays are distributed in longitude. In both the cases illustrated in Figure 21 the parent flare injected cosmic rays at heliocentric longitudes such as to negate the possibility of study of the flux distribution near the center of the cosmic ray population. Clearly the distribution will not be the same exponential as noted above at such points in the cosmic ray population, however, it will be necessary to obtain further observations of the longitudinal gradient to resolve this question.

Further consideration of Figure 21 indicates that the longitudinal gradient does not change radically with time during the decay phase of a particle population. Thus the gradient is essentially invariant for $150^\circ E - 12^\circ W$ for the whole of the period April 14-19, 1970. This indicates that the processes whereby cosmic rays are distributed in longitude at early times in a flare effect are no longer effective at late times ($T \lesssim 2$ days from injection).

Note that at no place in the foregoing discussion has it been assumed that the particle population is due to a single flare. Of the two cases considered, the data for the
period 6–8 April clearly correspond to a particle population injected by more than one flare, while those of 14–19 April correspond to a single injection. In the case of the 6–8 April data, cosmic radiation was initially released by a flare on 30 March 1969 which was 20° behind the western solar limb. The Pioneer 6 data in Figure 9 indicates that there was at least one, and possibly two further injections during the period 2–5 April. Since the latter flares were almost certainly associated with a single active center (McMath plage region 9994), this means that the several populations would be superposed upon one another, the maxima of the distribution being essentially coincident.

Clearly the foregoing conclusions, and the data in Figure 21 are strictly applicable to the events in question, alone. In the absence of other data, however, they provide approximate quantitative values and conclusions that will be applied to the flare effect in general.

3.4 The Decay Time Constant

On the basis of the observations by McCracken and others demonstrating the dominance of convective removal processes over diffusion in the escape of ~10 MeV cosmic rays from the solar system, Forman has shown that the cosmic
ray density will vary with time as

$$U = U_0 \exp \left\{ \frac{2V_c}{r} \left( \frac{2 + \alpha \gamma}{3} \right) \cdot t \right\}$$

where the dependence of $U$ on $\psi$ as defined previously has been ignored and $V_c$ is the effective convective velocity, defined as the radial component of the cosmic ray bulk velocity.

From equations (3) and (4) the observed variations can be written as

$$\frac{dU}{dt} = \frac{3\tau}{2V_c (2 + \alpha \gamma)}$$

is the "convective time constant".

Approximating the total change in $U$ to an exponential in which $\frac{dU}{dt} = -\frac{U}{T}$, where $T$ is the observed time constant,

then

$$\frac{1}{T} = \frac{1}{U} \frac{\partial U}{\partial \psi} \frac{d\psi}{dt} - \frac{1}{\tau}$$

and if over a limited range of $\psi$,

$$\frac{1}{U} \frac{\partial U}{\partial \psi} = \frac{1}{\psi_0}$$

as approximated earlier, then

$$\frac{1}{T} = \frac{1}{\psi_0} \frac{d\psi}{dt} + \frac{1}{\tau}$$

In practice, $20 \leq \tau \leq 40$ hours, $\frac{d\psi}{dt} = +0.54^\circ$ hour$^{-1}$,

$\psi_0 = \pm 30^\circ$. As an example, then for $\tau = 20$ hours, the
observed time constant $T = 14.3$ hours, or $31.2$ hours, depending on whether the corotation effect reinforces, or partially cancels the convective decay term.

The anisotropy directed from the sun, and from directions to the east of the sun indicates convective removal of the cosmic rays from the solar system. Reference to Figure 18 indicates, however, that while the convective removal velocity is the plasma wind velocity, $V_p$, when the anisotropy is directed from the sun, it becomes less than $V_p$ when the anisotropy is from the east. Consequently, the convective decay time constant of the cosmic ray population, $\tau$, will be greater than that computed on the basis of the full plasma wind velocity.

The effective convective velocity, $V_c$, can be derived in one of two ways:

1. **On experimental grounds.** The observed anisotropy of amplitude $\delta$ is due to a bulk motion of the particle population, $V_a$, from a direction making an angle $\phi$ with the satellite-Sun line, (Figure 22), where $\delta$ is related to $V_a$ by equation (2) with $V_p$ replaced by $V_a$. Consequently the effective convective velocity is given by

$$V_c = V_a \cos \phi$$

or

$$V_c = \frac{V \cos \phi}{2 + \alpha \gamma} . \quad (7)$$
**CASE 1**

\[ V_c = V_a \cos \phi \]

\[ V_a = \frac{8v}{2 + a\gamma} \]

**CASE 2**

\[ V_c = V_p \sin^2 \theta \]

\[ V_p \sin \theta \]

\[ V_p \theta \]

\[ V_p \text{dif} \]

**Fig. 22**—Illustrating the derivation of the convection velocity, \( V_c \).
As an example, the Pioneer 9 data in Figure 13 exhibit a 4.3 percent anisotropy averaged over the period 17-20 April, inclusive, from the direction 45°E of the sun. Table V suggests \( \gamma = 3.5 \) for this period, from which the mean energy of the data is 10.7 MeV. Using equation (6), these data indicate an effective convective velocity of 152 km sec\(^{-1}\). This is \( \approx 1/2 \) of the observed solar wind velocities. This suggests a factor of \( \approx 2 \) increase may be expected in the value of the decay time constant, \( \tau \), as a result of the diffusive effects at late times in a flare event.

(2) On theoretical grounds. At late times, it was suggested that the anisotropy is normal to \( B \), hence the effective convective velocity is given by

\[
V_c = V_p \sin^2 \theta .
\]  

(8)

For a typical value of \( \theta = 45^\circ \), \( V_c = 0.5 V_p \).

Further, writing \( \eta = V_p / \Omega_s \), then

\[
V_c = V_p (1 + \eta^2)^{-1}
\]

\[
\frac{dV_c}{dV_p} = \frac{1 - \eta^2}{(1 + \eta^2)^2}
\]

(9)

and we note that \( \frac{dV_c}{dV_p} = 0 \) for \( \theta = 45^\circ \). That is, the convective velocity is largely independent of the actual solar wind velocity for \( V_p \approx 450 \) km sec\(^{-1}\) at orbit of Earth.
(when the anisotropy has become normal to B). This is illustrated in Figure 23, which shows that the convective removal velocity, $V_c$, lies in the range $200 < V_c < 215 \text{ km sec}^{-1}$ for $300 < V_p < 600 \text{ km sec}^{-1}$. Figure 23 also illustrates the dependence of the convective velocity upon $r$. It is to be noted that $V_c$ is asymptotic to the solar wind velocity $V_p$ at large $r$.

Writing the convective decay time constant $\tau$ in terms of the effective convective velocity $V_c$, using equations (5) and (7) gives

$$\tau = \frac{3r}{2V \delta \cos \phi}.$$  

Further, the theoretical values of $V_c$ in Figure 23 have been used to calculate $\tau$, using equation (5), these results also being plotted in Figure 23. From equations (5) and (10), and from Figure 23 the following conclusions can be reached regarding $\tau$, the convective time constant:

1. With the passage of time, the evolution of the anisotropy from an anisotropy directed from the sun, to one directed from the east, is accompanied by an increase in $\tau$ by a factor of $\approx 2$ near orbit of Earth.

2. At very late times ($t \gtrsim 4$ days), when the anisotropy is from the east, the time constant $\tau$ will be insensitive to variations in the solar wind velocity, $V_p$. At somewhat
Fig. 23--The theoretical prediction as to the dependence of convective velocity, and the decay time constant $\tau$, as defined in equation 5, upon solar wind velocity and distance from the sun.
earlier times \( (1 < t < 4 \text{ days}) \), when the anisotropy is directed from the sun, \( \tau \) varies as the reciprocal of the solar wind velocity. These two cases are extremes. For these and intermediate cases, the time constant \( \tau \) is expressible in terms of the parameters of the cosmic ray anisotropy.

(3) The convective time constant varies with radial distance from the sun. At times when the anisotropy is directed from the sun, \( \tau \) varies directly as \( r \). At later times, the dependence upon \( r \) is weaker, \( \tau \) increasing by a factor of two for \( r \) increasing from 1 to 4 AU.

(4) The cosmic ray anisotropy, the e-folding angle of the heliocentric longitude gradient, and the time constant \( T \) of the decay observed by a spacecraft are related by

\[
\frac{1}{T} = \frac{1}{\tau} = \frac{2v \cos \varphi}{3r}
\]  

(11)

3.5 The Decay Time Constant - Experimental Results

Figures 13, 24, 25, 26 and 27 represent the time-intensity profiles of the major events covered in this analysis. The characteristics of the solar flare responsible for each of these events is summarized in Table II. It is apparent that in each of these events
Fig. 24--The temporal variations of the 7.5-45 MeV cosmic ray flux observed by Pioneers 8 and 9 during the flare effect of November 18, 1968. The Pioneer 8 flux should be multiplied by a factor of 1.7.
Fig. 25--The temporal variation of the 7.5-45 MeV cosmic ray fluxes observed by Pioneers 8 and 9 during the flare effect of December 3, 1968. The Pioneer 8 flux should be multiplied by a factor of 1.7.
Fig. 26—The temporal variations of the 7.5–45 MeV cosmic ray fluxes observed by Pioneers 8 and 9 during the flare effect of March 12, 1969. The Pioneer 8 flux should be multiplied by a factor of 1.7.
Fig. 27--The temporal variations of the 7.5-45 MeV cosmic-ray flux observed by Pioneers 8 and 9 during the flare effect of March 30, 1969. The Pioneer 8 flux should be multiplied by a factor of 1.7.
that the decay remained approximately exponential over periods of many days and over two to four orders of magnitude changes in particle flux. There are short term fluctuations in the time constant (e.g. Pioneer 9 data in Figure 13), some of which can correlate with changes in anisotropy amplitude and phase, as will be discussed.

To demonstrate the validity of equation (11), the observed decay constant $T_{obs}$ during each of these events has been compared with the time constant predicted by equation (11) using the observed anisotropy amplitude and phase and the available information on the longitudinal gradients. The data used in this analysis is summarized in Table III.

Figure 28 shows the regression between $1/T_{calc}$ and $1/T_{obs}$. The data in this figure have a correlation coefficient of $0.77 \pm 0.10$ and a mean regression coefficient of 0.9. This high degree of correlation in the data, and the closeness of the mean regression coefficient to unity, indicates that equation (11) accurately describes the relationship between the anisotropy, the longitudinal gradient, and the decay time constant of a flare effect.

With regard to the data in Table III, it must be noted that definitive values of $\psi_o$ are only available for the two April 1969 flare events, consequently estimated values for
TABLE III

THE CALCULATION OF DECAY TIME CONSTANTS AND THEIR COMPARISON WITH THE OBSERVED VALUES

<table>
<thead>
<tr>
<th>Period</th>
<th>Spacecraft</th>
<th>r (AU)</th>
<th>$\delta$ (%)</th>
<th>$\phi$ (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-22 Nov. 68 Pion. 8</td>
<td>1.00</td>
<td>4.3 ± .4</td>
<td>40°E</td>
<td></td>
</tr>
<tr>
<td>22-24 Nov. 68 Pion. 9</td>
<td>1.00</td>
<td>5.5 ± .5</td>
<td>43°E</td>
<td></td>
</tr>
<tr>
<td>8-10 Dec. 68 Pion. 8</td>
<td>1.00</td>
<td>6.3 ± .4</td>
<td>45°E</td>
<td></td>
</tr>
<tr>
<td>9-10 Dec. 68 Pion. 9</td>
<td>.99</td>
<td>3.1 ± .5</td>
<td>25°E</td>
<td></td>
</tr>
<tr>
<td>6-8 Apr. 69 Pion. 8</td>
<td>1.00</td>
<td>7.1 ± .5</td>
<td>45°E</td>
<td></td>
</tr>
<tr>
<td>Pion. 9</td>
<td>.75</td>
<td>2.5 ± .5</td>
<td>45°E</td>
<td></td>
</tr>
<tr>
<td>17-20 Apr. 69 Pion. 8</td>
<td>1.00</td>
<td>3.3 ± .4</td>
<td>40°E</td>
<td></td>
</tr>
<tr>
<td>Pion. 9</td>
<td>.75</td>
<td>4.2 ± .3</td>
<td>42°E</td>
<td></td>
</tr>
</tbody>
</table>

The columns are as follows: $r$ = distance from sun; $\delta$ = anisotropy amplitude; $\phi$ = anisotropy phase; $\psi_o$ = e-folding angle for cosmic ray gradient; $\tau$ = calculated convective time constant; $T_{calc}$ = calculated time constant at spacecraft; $T_{obs}$ = observed time constant at spacecraft. The anisotropy data refer to the energy range 7.5-21.5 MeV, while the observed time constant is calculated from the 7.5-45 MeV counting rate data.
TABLE III — Continued

<table>
<thead>
<tr>
<th>$\psi_0$ (Degrees)</th>
<th>$\tau$ (Hours)</th>
<th>$T_{\text{calc}}$ (Hours)</th>
<th>$T_{\text{obs}}$ (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+60^\circ_b$</td>
<td>$42.5 \pm 5.6$</td>
<td>$30.8 \pm 2.8$</td>
<td>$28 \pm 3$</td>
</tr>
<tr>
<td>$-60^\circ_b$</td>
<td>$34.4 \pm 4.3$</td>
<td>$49.9 \pm 9.4$</td>
<td>$35 \pm 5$</td>
</tr>
<tr>
<td>$+55^\circ_b$</td>
<td>$31.5 \pm 2.8$</td>
<td>$24.1 \pm 1.6$</td>
<td>$27 \pm 4$</td>
</tr>
<tr>
<td>$+55^\circ_b$</td>
<td>$47.9 \pm 10.7$</td>
<td>$32.4 \pm 4.8$</td>
<td>$22 \pm 2$</td>
</tr>
<tr>
<td>$-28^\circ$</td>
<td>$27.8 \pm 2.8$</td>
<td>$60.0 \pm 14.5$</td>
<td>$120$</td>
</tr>
<tr>
<td>$-28^\circ$</td>
<td>$60.6 \pm 16.8$</td>
<td>$-215 \pm 100$</td>
<td>. . .</td>
</tr>
<tr>
<td>$+34^\circ$</td>
<td>$55.3 \pm 9.5$</td>
<td>$29.4 \pm 2.5$</td>
<td>$28 \pm 2$</td>
</tr>
<tr>
<td>$+34^\circ$</td>
<td>$33.8 \pm 3.5$</td>
<td>$22.0 \pm 1.4$</td>
<td>$30 \pm 4$</td>
</tr>
</tbody>
</table>

$^b$These $e$-folding angles were not directly measured. See text.
were derived for the two earlier flare effects using Pioneer 8 and 9 data as follows:

(1) 21-24 November 1968. In this event, the absolute value of the fluxes at the two spacecrafts, Pioneers 8 and 9, were approximately the same at November 21, the fluxes thereafter decreasing more rapidly with time at Pioneer 8 than at Pioneer 9. The cosmic ray density distribution was assumed to have a maximum midway between the two spacecrafts, with \( \psi_0 = 60^\circ \).

(2) 8-10 December 1968. In this case, the Pioneer 9 flux exceeded that at Pioneer 8 by a factor of 1.6. It was therefore assumed that this is due to a gradient of e-folding angle of \( 55^\circ \).

It should be noted, that the good correlation in Figure 28, while insensitive to the assumed values of \( \psi_0 \) for the first two events, is strongly dependent on the values of \( \psi_0 \) for the April 1969 events (for which \( \psi_0 \) are well known). That is, the gradients in the region of space sampled by Pioneers 8 and 9 were much stronger in the latter events. This, in itself, is a crucial factor that has permitted the use of these events to demonstrate the validity of equation (11) over a wide range of \( \psi_0 \). The fact that all the points in Figure 29 lie on or near the line of unity slope is evidence of the validity of the equation.
Fig. 28--Illustrating the agreement between the observed time constant and that calculated from the anisotropy and the cosmic ray distribution in heliocentric longitude.

Fig. 29--Illustrating the validity of equation 11 in the case where $\phi_0$ is invariant. That is, this illustrates the interdependence of the decay time constant and the characteristics of the anisotropy.
The several time decay curves, Figures 13, 24, 25, 26, and 27, make it clear that there are short term fluctuations superposed upon the long term decay of a flare effect. For example, by fitting an exponential to 24 hour segments of the Pioneer 9 data for April 16-20, time constants of $19 < T_{\text{obs}} < 50$ hours are obtained, as is demonstrated in Table IV. Furthermore, Figure 14 shows that fluctuations were also observed in the anisotropy observed by Pioneer 9 during this period. Table IV and Figure 29 examine the correlation between these phenomena. Thus assuming $\psi_0 = 34^\circ$ to be the e-folding angle throughout the interval 16-20 April, the time constant $T_{\text{calc}}$ has been computed from the properties of the anisotropy. It is clear from Figure 29 that the calculated values are in agreement with observations.

From the foregoing, it is evident that the anisotropy, and the density gradients in heliocentric longitude, are the quantities that determine the decay time constant. The fact that the anisotropy does vary with time during the decay phase (e.g., Table IV), temporarily deviating from the 45$^\circ$E direction, is presumably due to the spacecraft sampling cosmic rays in a tube of force in which the radial gradient is
### TABLE IV

DECAY TIME CONSTANTS DURING 16-20 APRIL 1969a

<table>
<thead>
<tr>
<th>Day</th>
<th>δ (‰)</th>
<th>( \varphi ) (Degrees)</th>
<th>( \tau ) (Hours)</th>
<th>( T_{\text{calc}} ) (Hours)</th>
<th>( T_{\text{obs}} ) (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 Apr. 69</td>
<td>1.5 ± .1</td>
<td>69°E</td>
<td>202 ± 19</td>
<td>47.8 ± 1.1</td>
<td>43 ± 3</td>
</tr>
<tr>
<td>17 Apr. 69</td>
<td>4.3 ± .2</td>
<td>67°E</td>
<td>62.1 ± 4.1</td>
<td>31.2 ± 1.2</td>
<td>27 ± 2</td>
</tr>
<tr>
<td>18 Apr. 69</td>
<td>5.5 ± .2</td>
<td>24°E</td>
<td>20.8 ± 1.1</td>
<td>15.7 ± 0.7</td>
<td>19 ± 1</td>
</tr>
<tr>
<td>19 Apr. 69</td>
<td>3.4 ± .5</td>
<td>41°E</td>
<td>40.7 ± 8.4</td>
<td>24.8 ± 3.2</td>
<td>32 ± 2</td>
</tr>
<tr>
<td>20 Apr. 69</td>
<td>4.4 ± .6</td>
<td>43°E</td>
<td>32.4 ± 6.2</td>
<td>21.4 ± 2.5</td>
<td>50 ± 4</td>
</tr>
</tbody>
</table>

*The tabular quantities are defined as in Table III. In calculating \( T_{\text{calc}} \), we have taken \( r = 0.75 \) AU and \( \psi_o = +34° \).
insufficient to balance the convective removal parallel to B. The fact that the deviations of the anisotropy phase angle, and decreased time constant on 13 April 1969 (Figure 13) are associated with an increased solar wind velocity is probably significant in this regard.

3.6 The Cosmic Ray Energy Spectrum

Pioneer 8 and 9 both provide six point spectral information in the energy range 5-50 MeV. For each of the flare effects in Figures 13, 24, 25, and 27 the data have been averaged over complete calendar days, to yield daily average spectra throughout the flare event, for each spacecraft. The observed counting rates and the widths of the spectral windows have been corrected for (a) overlying absorber, and (b) the effects due to the FWHM of the pulse height distribution of the detector being comparable to the lower energy window widths. The absolute energy calibration corresponding to each window has been verified (and corrected in the case of Pioneer 8) using the results from periodic calibrations with the Am$^{241}$ source.

Typical spectra obtained in this manner are displayed in Figure 30 for the decay phase of the flare effect of December 2, 1968. Of note is the absence of any large
Fig. 30--Illustrating the insensitivity of the cosmic ray spectrum to the passage of time at late and very late times in the solar flare effect. The standard errors due to the counting rate statistics are smaller than the graphical symbols.

Fig. 31--Illustrating the dependence of the cosmic ray spectrum upon the population longitude, $\psi$, of the observer.
change in spectral slope over the three days in question. This is observed to be the normal situation at late times (T > 2 days) in the flare effects that have been studied to date. Nevertheless, marked differences in spectral character are noted when the spectra obtained during the decay phases of different flares are compared, as is demonstrated in Figure 31.

To characterize these differences in spectral character, a simple power law $dJ = J_0 E^{-\gamma} dE$ was fitted to each spectrum. The values of $\gamma$ for five flare effects are listed in Table V. For each day for which a spectral exponent is given, the longitude of the spacecraft relative to the centroid of the cosmic ray population was computed. Assuming that the center of cosmic ray population lies along the nominal Archimedes spiral field line that passes through the parent flare, then the longitude $\psi$ is given by

$$\psi = \xi_f - \xi_{sc} + \frac{d\psi}{dt} \cdot t - \Delta\xi_A$$

$$= \xi_f - \xi_{sc} + 14.2^\circ \cdot t - 57^\circ \quad (12)$$

where $\xi$ is the heliocentric longitude relative to the central meridian of the Sun as seen from Earth; $t$ is the time (in days) since the flare; $\Delta\xi_A$ is the longitude difference for the nominal spiral line that makes an angle of $45^\circ$ with
the radius vector at orbit of Earth; \( \frac{d\psi}{dt} \) is the solar rotation rate (14.2 degrees per day) and the subscripts \( f \) and \( sc \) represent "flare" and "spacecraft".

In Figure 32 the spectral exponent is plotted against \( \psi \) for late times in the decay phase of the flare events listed in Table V. The data for the short lived event of March 12, 1969 has been excluded from this graph since the particle distribution was known to be anomalous. (See Section 3.6.) Examination of Figure 32 shows that there is a remarkably well defined relationship between the spectral exponent and the population longitude, \( \psi' \). The graph indicates that the observer who is near the Archimedes spiral through the parent flare observed a steep spectrum, with \( \gamma = -4 \) to \(-5\), while an observer less favorably situated relative to the flare sees a considerably harder spectrum. It must be stressed that the observations refer only to late or very late times in the flare effect (\( t > 2 \) days).

One implication of the dependence of \( \gamma \) on \( \psi' \) is that the dependence of cosmic ray flux upon heliocentric longitude must be more pronounced at lower energies than at higher ones. As a result, while the "co-rotation" term \( \frac{\delta U \cdot d\psi}{\delta \psi dt} \) in equation (3) is normally less than the "convection" term
Fig. 32—The observed dependence of the spectral exponent, $\gamma$, upon the position of the observer relative to the centroid of the cosmic ray population injected by a solar flare.
### TABLE V

**SPECTRAL EXPONENTS AND RELATIVE SOLAR LONGITUDE**

<table>
<thead>
<tr>
<th>Date of Flare</th>
<th>$T$</th>
<th>$\psi_8'$</th>
<th>$\gamma_8$</th>
<th>$\psi_9'$</th>
<th>$\gamma_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Nov. 1968</td>
<td>+ 3</td>
<td>- 76</td>
<td>$3.13 \pm 0.06$</td>
<td>- 53</td>
<td>$3.37 \pm 0.04$</td>
</tr>
<tr>
<td></td>
<td>+ 4</td>
<td>- 90</td>
<td>$2.94 \pm 0.05$</td>
<td>- 67</td>
<td>$3.28 \pm 0.06$</td>
</tr>
<tr>
<td></td>
<td>+ 5</td>
<td></td>
<td>- 81</td>
<td>$2.90 \pm 0.09$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ 6</td>
<td></td>
<td>- 96</td>
<td>$2.76 \pm 0.13$</td>
<td></td>
</tr>
<tr>
<td>2 Dec. 1968</td>
<td>+ 5</td>
<td>50</td>
<td>$3.43 \pm 0.03$</td>
<td>74</td>
<td>$3.19 \pm 0.02$</td>
</tr>
<tr>
<td></td>
<td>+ 6</td>
<td>36</td>
<td>$3.91 \pm 0.11$</td>
<td>60</td>
<td>$3.67 \pm 0.03$</td>
</tr>
<tr>
<td></td>
<td>+ 7</td>
<td>22</td>
<td>$4.07 \pm 0.19$</td>
<td>46</td>
<td>$4.08 \pm 0.06$</td>
</tr>
<tr>
<td></td>
<td>+ 8</td>
<td>8</td>
<td>$3.72 \pm 0.21$</td>
<td>32</td>
<td>$3.86 \pm 0.11$</td>
</tr>
<tr>
<td>12 Mar. 1969</td>
<td>0</td>
<td></td>
<td>$2.14 \pm 0.04$</td>
<td></td>
<td>$1.78 \pm 0.09$</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td>$3.08 \pm 0.05$</td>
<td></td>
<td>$2.59 \pm 0.07$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>?</td>
<td>$3.10 \pm 0.27$</td>
<td>?</td>
<td>$2.47 \pm 0.12$</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>$2.60 \pm 0.30$</td>
<td></td>
<td>$2.62 \pm 0.18$</td>
</tr>
<tr>
<td>30 Mar. 1969</td>
<td>+ 5</td>
<td>166</td>
<td>$2.42 \pm 0.10$</td>
<td>-145</td>
<td>$1.29 \pm 0.05$</td>
</tr>
<tr>
<td></td>
<td>+ 6</td>
<td>152</td>
<td>$2.53 \pm 0.10$</td>
<td>-160</td>
<td>$1.89 \pm 0.07$</td>
</tr>
<tr>
<td></td>
<td>+ 7</td>
<td>138</td>
<td>$2.84 \pm 0.13$</td>
<td>-174</td>
<td>$2.03 \pm 0.08$</td>
</tr>
<tr>
<td></td>
<td>+ 8</td>
<td>124</td>
<td>$2.88 \pm 0.20$</td>
<td>172</td>
<td>$2.48 \pm 0.12$</td>
</tr>
<tr>
<td></td>
<td>+ 9</td>
<td></td>
<td>157</td>
<td>$2.48 \pm 0.12$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+10</td>
<td></td>
<td>143</td>
<td>$2.79 \pm 0.13$</td>
<td></td>
</tr>
</tbody>
</table>
TABLE V--Continued

<table>
<thead>
<tr>
<th>Date of Flare</th>
<th>T</th>
<th>( \psi_8' )</th>
<th>( \gamma_8 )</th>
<th>( \psi_9' )</th>
<th>( \gamma_9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 Apr. 1969</td>
<td>0</td>
<td>35</td>
<td>3.82 ± 0.03</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+1</td>
<td>21</td>
<td>3.81 ± 0.03</td>
<td>78</td>
<td>3.18 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>+2</td>
<td>7</td>
<td>4.34 ± 0.07</td>
<td>64</td>
<td>3.33 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>+3</td>
<td>-8</td>
<td>4.12 ± 0.08</td>
<td>49</td>
<td>3.29 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>+4</td>
<td>-22</td>
<td>4.10 ± 0.11</td>
<td>35</td>
<td>3.59 ± 0.25</td>
</tr>
</tbody>
</table>

The spectral exponents, \( \gamma \), for the energy spectra in the 5-50 MeV energy range, for the five flare events and for both Pioneers 8 and 9 are tabulated. \( \psi_8' \) and \( \psi_9' \) are the longitudes of the feet of the nominal Archimedes spiral through the two spacecrafts reckoned relative to the current position of the region of the sun where the flare occurred. That is, these angles are the longitudes of the spacecrafts relative to the centroid of the cosmic ray populations injected by the parent flare. \( \gamma_8 \) and \( \gamma_9 \) are the spectral exponents for the two spacecrafts.
\[ \frac{\partial U}{\partial t} \text{ at high energies, the roles may be reversed at lower energies. Thus, while the convection time constant as defined by equation (5) is independent of energy, and hence } \frac{\partial U}{\partial t} \text{ is likewise independent, the data in Figure 20 imply that } \frac{\partial U}{\partial \psi} \text{ will increase towards lower energies, and consequently that } \frac{\partial U}{\partial \psi} \frac{d\psi}{dt} \text{ can dominate over } \frac{\partial U}{\partial t} \text{ in equation (3). As a consequence, the observed time constant, } T, \text{ in equation (6) will become negative, indicating that the cosmic ray flux at low energies will increase with time if the observer is on the western side of a cosmic ray population (i.e., } \psi' \text{ positive). Such is in fact observed to be the case for } E > 3 \text{ MeV for the March 30, 1969 event.}

Figure 33 shows that while the higher energy flux (greater than } \approx 10 \text{ MeV) decays continually with time after April 3, the low energy flux shows a gradual rise, indicative of a negative decay time constant } T. \text{ Reference to Table III shows that a negative time constant is also predicted by equation (11). The large error in the predicted value of } T \text{ for this event is a result of the convective time constant being approximately equal to the "corotation" term}
Fig. 33—This figure illustrates the energy dependence of the cosmic ray flux observed by Pioneer 8 during the period March 29 to April 10, 1969. During the period April 4 to April 10 the time decay constant was negative for particles with energies < 6 MeV, while at higher energies the decay time constant was positive.
Reference to equation (6) shows that the convective time constant, $\tau$, is sensitive to the exponent, $\gamma$, of the differential energy spectrum. Figure 32 shows therefore that $\tau$ will depend upon the position of the observer relative to the centroid of the cosmic ray population injected by the flare, that is, it will depend upon $\psi'$. Reference to equation 6 indicates that the manner in which the observed time constant, $T$, depends upon the population longitude, $\psi'$, will be determined by both this dependence of $\tau$ on $\psi'$, and by any dependence of $\psi_0$ (the instantaneous value of the e-folding angle) upon $\psi'$. One would expect $\psi_0$ to increase with $\psi'$, thereby tending to cancel the effect due to the increase in $\tau$.

The fact that the spectral exponent is a function of the angular distance from the parent flare is clearly related to the process whereby the cosmic radiation propagates to field lines far distant from the flare. Thus Figure 32 indicates that the propagation is more effective at higher energies, which is in qualitative agreement with the concept of "near sun" diffusion. Given a more thorough understanding of the functional dependence of cosmic ray density upon $\psi$, the variation of $\gamma$ will permit a quantitative test of specific near sun diffusion models.
3.7 The Particle Distribution at Early Times

It has generally been the implicit assumption that the distribution of energetic particles 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, Axford, Jokipii and Parker). In the previous sections it was shown that at very late times this assumption is generally valid. However at early times there are indications that the distribution might be much more complex. This section 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 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°–W30° 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
Fig. 34--The projection of the Pioneer spacecrafts onto the solar surface via the nominal Archimedes spiral magnetic field lines during the event of March 12, 1969. These projections are based on a solar wind velocity of 450 km/sec.
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 34.

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 sudden ionospheric disturbance (SID) which started at 1739 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 VI. Using the average solar wind velocity of 390 km/sec observed by the VELA spacecraft at Earth, 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 34. From this, it would appear that Pioneer 9 should have been in the most favorable location to
### TABLE VI

LOCATION OF THE PIONEERS 6 THROUGH 9 SPACECRAFTS ON MARCH 12, 1969

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Location Θ</th>
<th>Location R</th>
<th>Onset Time March 12</th>
<th>Peak Flux 7.5-45 MeV (cm²sec. ster)⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pioneer 6</td>
<td>-151°</td>
<td>0.93 AU</td>
<td>2000 UT</td>
<td>2.0</td>
</tr>
<tr>
<td>Pioneer 7</td>
<td>-89°</td>
<td>1.1 AU</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Pioneer 8</td>
<td>-24°</td>
<td>1.02 AU</td>
<td>1830 UT</td>
<td>15.</td>
</tr>
<tr>
<td>Pioneer 9</td>
<td>+14°</td>
<td>0.77 AU</td>
<td>1900 UT</td>
<td>2.5</td>
</tr>
</tbody>
</table>

* Θ is the Earth-Sun-Probe angle with positive being towards the west. R is the Sun to spacecraft distance.

...observe the solar particles directly from the active region. However, as shown by Figure 35, the particle flux observed by Pioneer 9 was almost an order of magnitude less than that observed by Pioneer 8.

The time intensity plots for the Pioneer 8 and 9 spacecrafts are shown in Figure 35. 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 ≈34 hours. During the
Fig. 35—The temporal variations of the 7.5-21 MeV cosmic ray fluxes observed by Pioneers 8 and 9 during the flare effect of March 12, 1969.
early phase of the event the decay time constant at Pioneer 8 was \( \approx 8 \) hours, however, during the later part of the event (after \( \approx 1200 \) UT, April 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 36 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 (\( \approx 90\% \) during the first two hours of the event), with the anisotropy aligned with the nominal interplanetary field lines. 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 37 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 spacecrafts is \( \approx 1 \) hour. Hence the time interval between the flare occurrence and maximum cosmic ray flux, expressed relative to this minimum time of flight, is three for Pioneer 8 and nine for
ANISO TROPY VECTOR DIAGRAM
(7.5–21.5 MeV)

U.O.F. T E X A S A T D A L L A S
SUN

PIioneer 9

18-19 UT
MARCH 12, 1969

04-05 UT
MARCH 13

07-08 UT
MARCH 13

PIioneer 8

18-19 UT
MARCH 12, 1969

22-23 UT
MARCH 12

05-06 UT
MARCH 13

NOMINAL
INTERPLANETARY
FIELD

ANISOTROPY SCALE
30 %

Fig. 36—The anisotropy vector diagram for the March 12, 1969 event.
Fig. 37--Illustrating the great difference in the rise times observed by Pioneers 8 and 9.
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 through the solar flare; (2) that the particles observed at Pioneer 8 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 VI 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 ~4 hours every 2-3 days, it is not possible 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 alternate 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.

It must be stressed 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 Archimedes 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 through 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 through the parent flare becomes apparent.

It is clear that a simple diffusive model based on a nominal Archimedes spiral magnetic field (Reid\textsuperscript{15}, Axford\textsuperscript{12}) 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\textsuperscript{16} or Jokipii and Parker\textsuperscript{13} could explain the observation. However, the deviations from the nominal field seem extreme, since Jokipii and Parker estimate that the fields may exhibit an rms deviation (i.e., standard deviation) of 15° from the nominal field line; Michell'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\textsuperscript{17}), and the fact that they can accelerate electrons to relativistic energies at points far away from the parent flare\textsuperscript{17}, suggests that the ion acceleration might be occurring at a point far removed from the parent flare. Dodson Prince\textsuperscript{18} 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\textsuperscript{14,20}. A shock wave of typical velocity (1000 km sec\textsuperscript{-1}) would travel \approx 40\degree in solar longitude in 13 minutes; however, the radio emission shows no evidence of a second enhancement 13 minutes after the first. It must be concluded 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\degree to the east of the parent flare (Newkirk and Altschuler\textsuperscript{21}). 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\degree 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 wider 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.

3.8 Anomalous Temporal Variations in the Cosmic Ray Flux

In the previous sections it was shown that the observed temporal variation of the cosmic ray flux at a given point in the interplanetary region is determined (a) by the temporal variations on a given set of field lines and (b) by the longitudinal gradients in the particle density. Under normal circumstances the temporal and corotational effects can be separated only by the use of the analysis described
previously. However flare events occasionally exhibit anomalous temporal variations which can be attributed to only one of two effects. Since the events provide valuable insight into the propagation processes, this section will describe examples of each type of variation.

The events described here were obtained prior to the launch of the Pioneer 9 spacecraft so that the data described below are from the Pioneer 8 spacecraft and the cosmic ray detector aboard the Explorer 34 Earth-orbiting spacecraft. The Explorer 34 cosmic ray detector is basically similar to the Pioneer detector, however with slightly different energy ranges.

1. **The Corotation of Solar Flare Electrons.**

Figure 38 illustrates the average hourly counting rates during the period July 6 through July 17, 1968. It can be seen that at some time shortly before 2100 UT on July 12 a well-defined enhancement in the > 13.5 MeV flux was observed at Pioneer 8. This event was short lived, rising to a maximum value at ≈0030 UT, July 13 and decaying back to the ambient value some 15 hours later. A similar enhancement was observed at Explorer 34 starting shortly after 1600 UT on July 13 and reaching maximum value at ≈2230 UT. The
Fig. 38--The temporal variations of the solar cosmic ray fluxes observed by Pioneer 8 and Explorer 34 during the period July 12-15, 1968. The location of the two spacecrafts during this period is shown in the inset.
time delay between the peak flux observed at Pioneer 8 and Explorer 34 was 22 hours.

On the basis of the observations shown in Figure 39 it is apparent that this event is an example of a corotating enhancement of the type discussed by Bryant et al., Lin et al., and Ahluwalia. For a corotating event, Explorer 34 would have recorded the event later than Pioneer 8 by a time $T_c$ given by

$$T_c = \left(\frac{d\psi}{dt}\right)^{-1} v \psi - \frac{1}{V_p} \Delta R$$

where $\Delta \psi$ and $\Delta R$ are the differences in solar longitude and radial distance, respectively, between the two spacecraft. At the time of this event $\Delta \psi$ and $\Delta R$ were $15^\circ$ and $1.2 \times 10^7$ km respectively. A plasma velocity of $660 \pm 50$ km/sec (as determined from the $K_p$ index) yields a value for $T_c$ of $22.6 \pm 0.4$ hours, in good agreement with the observed 22 hour delay.

In Figure 39 the hourly averaged count rate from the scintillation counters and the solid state telescopes of the two spacecrafts are plotted for the time interval July 6 - July 17. The scintillation data are identical to those depicted in Figure 38. It is clear that the scintillation counters and solid state detectors exhibit significant
Fig. 39—The temporal variations of the cosmic ray fluxes observed by Pioneer 8 and Explorer 34 during the period July 6-17, 1968.
differences in their time profiles. Since the solid state detectors are insensitive to electron fluxes, these differences in time profiles can be attributed to the recording of relativistic electrons by the scintillation detectors (13.5 MeV for Pioneer 8 and 2 MeV for Explorer 34). This conclusion has been supported by McCracken et al.\textsuperscript{27} and by Simnett\textsuperscript{28}.

From the symmetry of the event at Explorer 34 it must be concluded that the time variation was due predominately to the corotation of the electron stream. The situation at Pioneer 8 is somewhat more complex since the rise time is considerably faster than the decay. Thus a part of the temporal variation, at least during the first several hours of the event, is due to time variation in the density of particles along the field lines. This contention is supported by the anisotropy at Pioneer 8 shown in Figure 40. It can be seen that the anisotropy was 100\% for the first five hours of the enhancement. This indicates a strong gradient along the field lines and subsequently a large increase in the count rate. The anisotropy dropped quickly to a quiescent value of 10 to 20 \% during the later phase of the event.

From the duration of the event as recorded by Explorer 34, the angular extent of the electron stream can be
Fig. 40--The magnitude and direction of the cosmic ray flux observed by Pioneer 9 during the period July 12-13, 1968.
estimated to be only about 10° wide. This would indicate that the longitudinal spreading of the electron stream was negligibly small during the 22 hour corotation time between Pioneer 8 and Explorer 34 and as a result would require that the diffusion coefficient perpendicular to the field line be negligibly small compared to the diffusion coefficient parallel to the field lines (i.e., $K_\perp / K_\parallel \ll 1$). This observation is in good agreement with the theoretical predictions of Parker\textsuperscript{29}, Jokipii\textsuperscript{30}, and Roelof\textsuperscript{31} and with the observations of Lin et al.\textsuperscript{24}, who find that the transverse diffusion coefficient is at least two orders of magnitude less than the parallel diffusion coefficient.

2. Near Sun Modulation

The characteristic time-intensity profile of solar cosmic ray events has resulted in several models for the propagation of the solar particles in which a diffusive mechanism plays a predominant role in determining the character of the events. These models can be divided into two general classes which differ mainly in the region in which the diffusion occurs. The first class of models assumes that the propagation is controlled by scattering in the inhomogeneities which are present in the interplanetary
magnetic field\textsuperscript{32-34}. The important features of such interplanetary diffusion models are that the source of the cosmic ray injection is very short lived and that the character of the event is determined entirely by the scattering within the interplanetary field.

The second class of models assumes that the time profile is determined predominately by the conditions near the sun, with the particles being released over an extended period of time. Several processes have been proposed to produce such an extended source of particles. These include the following: (a) The continuous and/or secondary injection of particles\textsuperscript{35,36}. (b) "Diffusive" storage in which the propagation is inhibited by scattering in the solar magnetic fields\textsuperscript{12,15}, and (c) the "adiabatic" trapping of particles in the magnetic structure near the sun\textsuperscript{37}. There are no formal models corresponding to cases (a) and (c) above since the description of each event would require a much more detailed knowledge of the solar magnetic fields at the time of the events than is currently available.

Reid\textsuperscript{15} has proposed a diffusive model in which the particles diffuse across the surface of the sun in a thin isotropic layer with subsequent leakage onto the
interplanetary field lines. This model was later expanded by Axford to include the effects of propagation in the interplanetary field. Since both the interplanetary diffusion models and the Reid-Axford model provide a reasonable fit to the time profiles of the solar flare events, some basis other than the usual time profile must be used in evaluating the relative appropriateness of the different models. In this section two events will be described which display non-diffusive variation that would imply a strong influence of near-sun processes in determining the characteristics of solar flare events at early times.

Figure 41 illustrates the observation of the solar flare effect of September 29, 1968, by the detectors aboard Pioneer 8 and Explorer 34. The parent flare for this event was identifiable as a 3B flare which started at 1634 UT, September 29 at solar coordinates N17°-W50°. The two spacecrafts were separated at this time by ~21° of solar longitude. The upper curve of Figure 41 is the omnidirectional flux in the energy range 21.5 to 64 MeV recorded by Pioneer 8, while the lower curve illustrates the omnidirectional flux >10 MeV for the same event recorded by Explorer 34. Basically the event shown here displays a normal time intensity profile, i.e., a relatively fast rise followed by a slower
Fig. 41—The temporal variations of the cosmic ray fluxes observed by the Pioneer 8 and Explorer 34 spacecrafts during the flare effect of September 19, 1968.
exponential decay. However the decay profile at Pioneer 8 is interrupted by a sharp reduction in counting rate commencing about 1800 UT, September 30, which persisted for approximately twenty hours before returning to the decay rate established during the fifteen hours prior to the reduction.

Explorer 34, however, recorded this same event with a different time intensity profile than did Pioneer 8. Although the rising phase and early decay phase of the event as observed at Explorer 34 follows very closely that observed by Pioneer 8, Explorer 34 did not observe the sharp reduction in the count rate, but rather, during this same period of time recorded a disturbance in the decay rate which also lasted for about twenty hours.

At this point, the possibility of the disturbance being caused by a corotating structure, such as a very large filament or a sector boundary can be ruled out, since a corotating structure would have reproduced the reduction observed at Pioneer 8 some 36 hours later at Explorer 34. Since the diffusion of particles across the interplanetary field lines is negligibly small there appears to be only two probable explanations for this event. If the particles are not being stored near the sun, then the event could be the result of a
region of low cosmic ray density which moves radially outward from the Sun. If the Reid-Axford model is applicable, then the event could result from a disturbance in the solar diffusion layer which prevents the particles from moving out onto the interplanetary field lines.

The second event was recorded during the solar active period from October 31 to November 6, 1968, with many of the features of the September event. The omnidirectional particle flux during this period is shown in Figure 42. In this event the count rate at Pioneer 8 dropped off sometime between 1800 UT, November 2 and 0300 UT, November 3 and remained depressed for about 36 hours before returning to a normal decay. On this occasion, however, Explorer 34 recorded the same reduction as was recorded by Pioneer 8. This event is not as well defined as the September event since (a) the onset of the reduced phase occurs during a period of non-tracking of Pioneer 8 and (b) there was a 2B solar flare ($S15^\circ-W90^\circ$) which occurred at 0515 UT, November 4 that could possibly account for the recovery of the count rate on November 4. However, it is evident that both spacecrafts did record a sharp reduction in count rate at approximately the same time. This would again rule out the possibility of the event being the result of corotating structure in the
interplanetary field.

Although it was shown in Section 3.6 that the Reid-Axford model was inadequate in describing some solar flare events, it does illustrate the connection between the propagation effects near the sun and those in the interplanetary field in determining the time intensity profile as seen at 1 AU. The Reid-Axford model is shown in Figure 43. The density of particles in the solar diffusion layer as a function of time and distance, \( \rho \), from the flare is given by

\[
U(\rho, t) = \frac{A}{t} \exp \left( -\frac{\rho^2}{4kt} - \beta t \right) \quad (12)
\]

where \( k \) is the diffusion coefficient in the solar layer, \( A \) is a constant and \( \beta \) the fraction of particles per unit time and unit area which leak out onto the field lines from the solar layer. On the assumption that upon injection into the interplanetary magnetic field the particles experience isotropic diffusion, the "response function" \( R(x, t) \) of the interplanetary medium can be written as

\[
R(x, t) = \frac{1}{(4\pi Dt)^n} \exp \left( \frac{x^2}{4Dt} \right) \quad (13)
\]

where \( x \) is the distance from the solar surface, \( D \) is the diffusion coefficient for the interplanetary field and \( n \) is generally taken to be 1.5

The cosmic ray particle
SCHEMATIC OF THE REID-AXFORD MODEL

Fig. 43--A schematic illustration of the Reid-Axford model for the propagation of solar cosmic ray particles.
intensity as measured at the orbit of Earth \((x = X)\) will be
given as the convolution of the source function \(U(\rho, t)\) and
the field response function \(R(x, t)\), i.e.,

\[
I(t) = \int_0^t U(\rho, \xi) R(x, t - \xi) \, d\xi .
\] 

(14)

The anomalous temporal variations in the cosmic ray flux
during the September and October events can be fitted into
the Reid-Axford model if it is assumed that \(\beta\) is a func-
tion of time and solar position. Figure 44 shows the pos-
sible configuration of the solar conditions during the two
events. For simplicity a discrete confining layer with
transparency \(\beta\) is shown separating the two diffusion re-

gions, however, it is meant only to represent some mechanism
which controls locally the rate at which particles move out
of the diffusion layer into the magnetic field. Figure 44(A)
represents the prevailing solar conditions during the reduced
intensity phase of the September event. The shaded region
represents an area in which the transparency is low so that
particles are inhibited from moving onto the field line
rooted in this location. During the rise and early decay
phase of the event this opaque region was not present, but
rather developed at about 1800 UT, September 20, causing the
reduction in the Pioneer 8 counting rate. This region did
Fig. 44--Possible configuration of solar conditions; (A) September event, (B) November event.
not include the field lines which connect to Explorer 34, so that it would not see a reduction in counting rate. However, the presence of the opaque region would tend to reduce the total loss rate from the diffusion layer so that one might expect the decay rate to be reduced, as is observed by Explorer 34. In the November event, the situation is much the same except that both spacecrafts were on field lines which connected into the opaque region, so that when the transparency of the area decreased, both spacecrafts observed a reduction in counting rate.

One important feature of equation (14) is that if one of the functions is narrow in time, the particle time intensity profile will be determined predominantly by the form of the other. For example, if \( U \) were to approach a delta function (as in the case of a purely impulsive source), then the particle intensity observed at Earth would be given simply by \( R(x,t) \), corresponding to the interplanetary diffusion model. In the normal solar flare events, the time intensity profile reflects the combined effects of the source and interplanetary response functions. The interrupted decay profile, however, provides an opportunity to perform a first order separation of these effects. If the models sketched in Figure 44 are applicable and the particles are being suddenly
blocked at the sun, then it follows that the abrupt decay at
the onset of the reduced phase of the events must represent
the decay of particles in the interplanetary field. Since
the response function \( R \) at 1 AU is determined by \( D \), a lower
limit on the value of \( D \) can be obtained using equation (14)
by assuming that the source function \( U(\rho, t) \) in the
September 30 event was given by

\[
U(\rho, t) = \begin{cases} 
N_0 & \text{for } t < 0 \\
0 & \text{for } t > 0 
\end{cases} 
\quad (15)
\]

where \( t = 0 \) sets the onset time of the reduced phase and \( \rho_0 \)
the location of the Pioneer 8 field lines.

Equations (13), (14), and (15) give for \( t > 0 \)

\[
I(t) = \frac{1}{(4\pi D)^n} \int_{-\infty}^{0} \frac{U(\rho, \xi) \cdot \exp(-x^2/4Dt)}{(t-\xi)^n} \, d\xi \\
+ \int_{0}^{t} \frac{U(\rho, \xi) \cdot \exp(-x^2/4Dt)}{(t-\xi)^n} \, d\xi \\
= \frac{N_0}{(4\pi D)^n} \int_{-\infty}^{0} \exp\left(-\frac{x^2}{4D}(t-\xi)\right) \frac{1}{(t-\xi)^n} \, d\xi 
\quad (16)
\]

Making the variable substitution \( w = \frac{t-\xi}{t-\xi} \), equation (16)
becomes

\[
I(t) = \frac{N_0}{(4\pi D)^n} \int_{0}^{1/t} \exp\left(-\frac{k^2w}{4D}\right) \cdot w^{n-1} \, dw
\]
= \frac{N_0}{(4/D)^n} x^{-2(n-1)} \Gamma(n - 1, \frac{k^2}{4Dt}) \quad (17)

where \( \Gamma(n, x) \) is the incomplete gamma function. Assuming that (a) \( n = 1.5 \) and (b) that the intensity had dropped by a factor of 2 after 5 hours, equation (17) yields a value for \( D \) of 0.2 (AU)^2/hour. Equivalently, the mean free path, \( \lambda \), for a 10 MeV particle would be 0.6 AU. \( (D = \lambda v/3 \) where \( v \) is the velocity of the particle.\)

If it is assumed that the interplanetary diffusion model is valid and the reduced phases represent only local disturbances in the cosmic ray flux then the diffusion coefficient \( D \) can also be calculated by writing equation (13) in the form \( \ln(t^n \cdot I(t)) = \text{constant} - \frac{x^2}{4D} \cdot \frac{1}{t} \).

Thus if \( \ln(t^n \cdot I(t)) \) is plotted vs. \( 1/t \), the result should be a straight line with slope \( x^2/4D \). The data for the September 29 event is shown in Figure 45 which yield a value for the diffusion coefficient of \( D = 0.01 \) (AU)^2/hour or equivalently a mean free path of 0.03 AU at 10 MeV. Clearly, there is a discrepancy of about a factor of 20 in the results obtained by each of these calculations. It is evident that the appropriate expressions for \( U \) and \( R \) are required for a definitive model of the propagation of particles, thus it
ISOTROPIC DIFFUSION MODEL

SEPT. 29, 1969
t0 = 1540 HRS. U.T.
7.5 MEV. < E_p < 21.5 MEV.

\[
\frac{\Delta \left[ \log (I \cdot t^{3/2}) \right]}{\Delta (1/t)} = \frac{r_0^2}{4D} = -24.7 \text{ HR.}
\]

\[D = 0.01 \text{ AU}^2/\text{HR.}\]
\[\lambda = 0.03 \text{ AU.}\]

Fig. 45--The plot of \(\ln(I \cdot t^{3/2})\) vs. \(1/t\) for the solar flare event of September 29, 1968.
is important that the extent of particle storage near the surface be determined.

In the discussion above, the effects of convection of the solar particles have been neglected. It was shown in the previous sections that convection does, however, play an important role in determining the movement of particles. The fact that the convection was shown to move the particles out of the inner solar system within a period of 1 to 2 days will limit the influence of coronal conditions in determining the characteristics of solar events at late times. It would appear that a complete description of the solar flare effect will require the solution to two problems: the description of the early phase of the event in terms of the coronal conditions and the description of the event at late times in terms of the interplanetary parameters, with the initial conditions set in the early phase.
CHAPTER BIBLIOGRAPHY


19. Helen Dodson Prince, (private communication).

20. A. Maxwell, (private communication).


CHAPTER IV

CONCLUSIONS

The following summarizes the properties of the solar cosmic ray flares which have been derived from the Pioneer data.

1. **Anisotropy**

1.1 At $0 < T \lesssim 1$ day, the anisotropy at $E \sim 10$ MeV tends to be large and directed along the magnetic field lines.

1.2 At $1 \lesssim T \lesssim 4$ days, the anisotropy at $E \sim 10$ MeV tends to be directed radially away from the sun.

1.3 At $T \gtrsim 4$ days, the anisotropy at $\sim 10$ MeV is directed from a direction $\sim 45^\circ$ east of the satellite-sun line.

1.4 It is suggested that the anisotropy is parallel to the vector $\vec{E} \times \vec{B}$ at late times ($T \lesssim 4$ days).

2. **Convective Removal Processes**

2.1 Properties 1.2 and 1.3 imply the dominance of convection as compared to diffusion in the escape of solar cosmic rays from the solar system at late times ($T \lesssim 1$ day).

2.2 A positive radial cosmic ray density gradient, $\frac{\partial U}{\partial s}$, exists at very late times ($T \gtrsim 4$ days) near the orbit.
of Earth. This drives a diffusive current along the interplanetary field lines toward the Sun.

2.3 The effective convective removal velocity will be \( 0.5 V_p \) at very late times. It approximates \( 0.5 V_p \) at such times as the anisotropy is from \( 45^\circ \) east of the sun.

2.4 An anisotropy normal to \( B \) implies an equilibrium between the convective current \( V_p, U \), and the diffusive current \( K, \frac{dU}{ds} \) along the interplanetary field lines, where \( V_p \) is the component of the solar wind velocity parallel to the interplanetary magnetic field.

3. **Spatial Gradients**

3.1 As noted in 2.2, the properties of the cosmic ray anisotropy imply a positive radial gradient of cosmic ray density at very late times (\( T \leq 4 \) days).

3.2 Direct measurements indicate the persistence of strong gradients in heliocentric longitude at very late times (\( T \leq 4 \) days). \( e \)-folding angles of \( \psi_0 \approx 30^\circ \) have been observed.

3.3 At very late times (\( T \leq 4 \) days) the relative gradient \( \frac{1}{U} \frac{dU}{d\psi} \), in heliocentric longitude is invariant with respect to time.
4. **Temporal Decay**

4.1 The observed temporal variation of the cosmic ray flux is due to two major effects (a) convective removal of the cosmic radiation, and (b) the "co-rotation" of the cosmic ray population (see equation 3).

4.2 The observed time rate of change of cosmic ray flux is critically dependent upon the local value of the gradient in heliocentric longitude (for $E \approx 10$ MeV). When the observer is to the west of the centroid of the cosmic ray population, the gradient has been observed to result in the almost complete cancellation of the temporal decay which is due to the expulsion of the cosmic radiation by the solar wind. When the observer is to the east of the population centroid, the effect is to hasten the decay by a factor of $\sim 2$.

4.3 The properties of the cosmic ray spectra indicate that the influence of the longitude gradient upon the observed temporal decay increases towards lower energies. For example, for the flare event of 29 March 1969, the gradient term at about 5 MeV exceeds the convective removal term in equation (6). In this case, an observer on the western side of a cosmic ray population sees a
flux that increases with time.

4.4 The convective component of the decay time constant, $\tau$, is expressible in terms of the characteristics of the anisotropy (equation 10).

4.5 The convective time constant, $\tau$, increases by a factor of $\sim 2$ between the epoch when the anisotropy is directed from the sun, to the epoch at which it is directed from $45^\circ$ E.

4.6 At late times, when the anisotropy is directed from the sun, ($1 \leq T \leq 4$), the convective time constant varies as the reciprocal of the solar wind velocity. At very late times, ($T \leq 4$ days) it is essentially independent of $V_p$.

4.7 The observed time constant $T$ is a function of the position of the observer relative to the centroid of the cosmic ray population.

5. Cosmic Ray Spectrum

5.1 At late times, ($T \geq 1$ day), the spectral exponent near 10 MeV is dependent on the longitude of the observer relative to the centroid of the cosmic ray population injected by the flare. This effect results in a variation in spectral exponent over the range $2.0 < \gamma < 4.5$. 
5.2 At a given point in the frame of reference of the cosmic ray population, the spectral exponent is invariant with time.

6. Cosmic Ray Distribution at Early Times

6.1 In the March 12, 1969 event:

(a) The distribution of particles was not a simple decreasing function of distance from the nominal field lines through the flare.

(b) The most favorable propagation path through the solar system was along the lines of force some 40° to the east of those to be expected on the basis of the generally accepted models.

6.2 The radio and optical data for this event do not indicate the secondary acceleration of particles at points far away from the parent flare.

6.3 The anomalous distribution of particles at early times appears to be due to either (a) the stochastical wandering of the interplanetary field lines or (b) the redistribution of particles in the coronal magnetic field. The stochastical wandering of 40° from the nominal field line would have a probability of ~2% for chance occurrence.
7. **Anomalous Temporal Variations**

7.1 The event of July 12-13, 1968 provides an example of the corotation of a well defined stream of cosmic ray electrons between the Pioneer 8 and Explorer 34 spacecraft.

7.2 The negligible spreading of the electron stream during the 22 hour corotation time between Pioneer 8 and Explorer 34 requires that $K_{\perp}/K_{\parallel} \ll 1$.

7.3 The events of September and November 1968 suggest strong modulation of cosmic rays near the surface. Calculation of the diffusion coefficient in the interplanetary magnetic field based on the Reid-Axford model and the interplanetary diffusion model differ by a factor of $\sim 20$. 
APPENDIX I

THE DIFFERENTIAL RESPONSE FUNCTION
OF THE SCINTILLATION TELESCOPE

The "differential response" $A(\theta)$ of a detector system is defined by

$$A(\theta) = \frac{dN(\theta)}{J(\theta)d\theta}$$

where $dN(\theta)$ is the count rate which would result from an incident flux $J(\theta)$ from within the differential solid angle $\theta$ to $\theta + d\theta$. To determine the differential response of the Pioneer scintillation telescope it is useful to consider an equivalent detector composed of two thin disks. The configuration of the two disks is shown in Figure 46. The spacing $(S)$ between the disks is dependent on the range $(r)$ of the particles in the CsI crystal since any particle which enters the chamber at an angle greater than $\theta_m$ will be rejected by the anticoincidence. The distance $h$ is given by

$$h = \frac{d \cdot r}{(S_0 + h)^2 + d^2}$$

This equation can be solved by an iteration method by allowing

$$h_0 = \frac{d \cdot r}{(S_0^2 + d^2)^{1/2}}, \quad h_n = \frac{d \cdot r}{(S_0 + h_{n-1})^2 + d^2}^{1/2}$$

Thus $h$ is the limit of $h_n$ as $n$ becomes large. The range of

136
Fig. 46—Showing the actual telescope configuration (A) and the equivalent detector made up of two disk (B).

Fig. 47—The relative differential response of the telescope and octants.
a 90 MeV proton in the CsI crystal is ~2.65 cm, which corresponds to h = 2.13 cm.

The differential response of the detector as a function of the zenith angle, measured relative to the axis of the telescope, is given by $A(\theta) = (2\varphi - \sin 2\varphi)\cos\theta \cdot (d/2)^2 (\text{cm})^2$

where $d$ is the diameter of the detector and $\varphi$ is defined by

$$\cos \varphi = \frac{S}{d} \tan \theta.$$ 

A plot of the differential response function at energies of 1 MeV and 90 MeV are shown in Figure 47. For the purposes required here the function can be accurately fitted by

$$A(\theta) = A_0 \left(1 - \frac{\theta}{\theta_m}\right) \quad (\theta < \theta_m) \quad (1)$$

with $A_0 = 12.56$ (cm$^2$) and $\theta_m$ being 0.610 and 0.454 radians at 1 and 90 MeV respectively.

The geometric factor of the detector ($G_d$), defined as the integral of the differential response function, is given by

$$G_d = \int_0^{2\pi} d\varphi \int_0^{\theta_m} A(\theta)\sin\theta d\theta \quad (\text{cm}^2\cdot\text{steradians}). \quad (2)$$

The integral (1) yields geometric factors of 4.8 and 2.9 (cm$^2$·steradians) at 1 and 90 MeV respectively.

ANISOTROPY MEASUREMENTS

To provide a quantitative description of the cosmic ray flux as a function of direction, a harmonic series of the
form \( N_i = N_0 \left( 1 + \delta_1 \cos(\theta - \theta_1) + \delta_2 \cos(\theta - \theta_2) \right) \) (3) is fitted to the data from the eight octants. In the equation above \( N_0 \) is proportional to the omnidirectional flux and \( \delta_1 \) and \( \delta_2 \) are the amplitudes of the first and second harmonics, while \( \theta_1 \) and \( \theta_2 \) represent their phase.

If \( n_i \) \((i=1,\ldots,8)\) is the number of counts accumulated in the octant \( i \) then

\[
N_0 = \sum_{i=1}^{8} \left( \frac{1}{8} \right) n_i \quad \delta_1 = \frac{\left( A_1^2 + A_2^2 \right)^{1/2}}{N_0} \quad \delta_2 = \frac{\left( A_3^2 + A_4^2 \right)}{N_0}
\]

\[
\theta_1 = \tan^{-1}\left( \frac{A_1}{A_2} \right) \quad \theta_2 = \tan^{-1}\left( \frac{A_3}{A_4} \right)
\]

where

\[
A_1 = \frac{1}{4} \sum_{i=1}^{8} n_i \sin \theta_i \quad A_2 = \frac{1}{4} \sum_{i=1}^{8} n_i \cos \theta_i
\]

\[
A_3 = \frac{1}{4} \sum_{i=1}^{8} n_i \sin 2 \theta_i \quad A_4 = \frac{1}{4} \sum_{i=1}^{8} n_i \cos 2 \theta_i
\]

and \( \theta_1 \) is the mean viewing direction of octant \( i \) \((i=1,\ldots,8)\) (see Figure 6, Chapter 2). Equation (1) does not always represent the true particle flux distribution for two reasons.

1. If there exist higher harmonics \((>2)\) in the particle distribution, these harmonics will not be reflected in
140

equation (1). This error is usually small and can be
neglected, except when the particles are strongly columni-
ated, i.e., unidirectional.

2. The magnitude of $N_o$, $\delta_1$, and $\delta_2$ are reduced due to
the finite width of the octants and the detector opening
angle. If the particle flux is given by

$$J = J_o \left(1 + \alpha_1 \cos(\theta - \theta_1) + \alpha_2 \cos^2(\theta - \theta_2)\right) \quad (6)$$

then the count rate observed in octant $i$ ($i=1,...,8$) will be
given by

$$N_i = \int_\theta A_o(\theta - \theta_i) J(\theta) \, d\theta \quad (7)$$

where $A_o$ is the differential response of the octants and $\theta_i$
is the mean viewing direction of octant $i$. $A_o$ is defined as

$$A_o = \int_\varphi A_d(\varphi) H(\varphi - \theta) \, d\varphi$$

where $H(\theta)$ is 1 if $\theta$ is less than the half width of the
count rate observed in octant $i$ ($i=1,...,8$) will be
given by

differential response of the octants relative to the
center of each octant. Substituting equation (6) into (7)
yields, after some simple manipulations

$$N_i = J_o G_o \left(1 + \alpha_1 \left(\frac{G_1}{G_o}\right) \cos(\theta_i - \theta_o) + \alpha_2 \left(\frac{G_2}{G_o}\right) \cos^2(\theta_i - \theta_o)\right), (8)$$
where $G_0 = \int_\theta A_0(\theta) \, d\theta$, $G_1 = \int_\theta A_0(\theta) \cos \theta \, d\theta$, and $G_2 = \int_\theta A_0(\theta) \cos 2\theta \, d\theta$.

(9)

Comparison of equations (3) and (8) reveals that the calculated first and second harmonics are given by

$$\delta_1 = \frac{G_1}{G_0} \cdot \alpha \quad \text{and} \quad \delta_2 = \frac{G_2}{G_0} \cdot \alpha_2.$$

Equations (9) have been integrated numerically yielding

$$\frac{G_1}{G_0} = 0.95 \quad \text{and} \quad \frac{G_2}{G_0} = 0.80.$$
BIBLIOGRAPHY

Books


Articles


Unpublished Material


Public Documents