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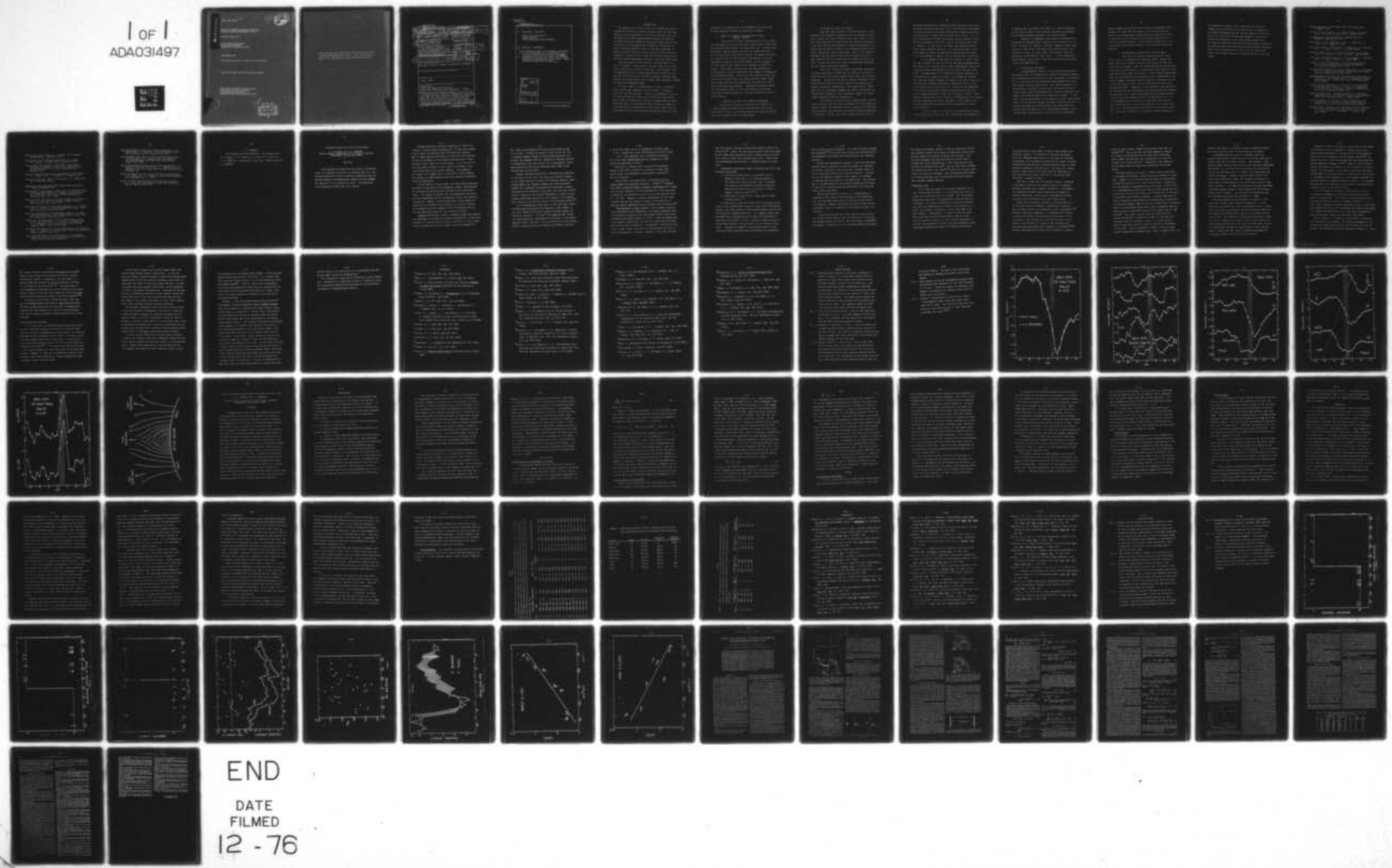

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STUDY OF COSMIC RADIATION NEAR THE EARTH'S NORTH GEOMAGNETIC POLE

Martin A. Pomerantz

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8 September 1976

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→ The nucleonic intensity observations at Thule, Greenland have established an apparently longer data base than any other station in either polar cap. During the brief period covered by this report, significant progress has been made toward understanding three important phenomena: (1) the origin (over) → next page

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of transient cosmic ray intensity variations; and (2) the mechanism that is responsible for producing north-south anisotropy and ~~accel-~~ acce leration of relativistic cosmic rays between converging interplanetary shock waves. These results are described in detail.

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1. INTRODUCTION

The objective of the work under this contract has been to monitor the intensity of cosmic radiation near the north geomagnetic pole, to analyze the intensity variations which are observed at the AFCRL Geopole Station, Thule, to correlate the data with those obtained at Antarctic cosmic ray stations and other solar and geophysical parameters, to maintain the cosmic radiation detectors, and to study new techniques for observing cosmic radiation such as neutron multiplicity measurements as a function of altitude and latitude; and the application these measurements may have to coupling coefficients

Since the results of this research are described in detail in a number of publications, the main body of this Final Report consists of a series of reprints. The principal lines of investigation will be summarized briefly in order to indicate the continuity of the scientific program initiated under Contract AF 19(628)-5200, and continued under Contracts F 19628-70-C-0190 and F19628-76-C-0047.

This final report is extraordinary in that, in contrast with previous ones extending over five years, it covers a period of less than one year. This is a consequence of the administrative decision within the Air Force to close Geopole Station and to terminate the scientific program that was being conducted there. At the present time, efforts are under way to arrange for the continuation of the crucial cosmic ray observations at Thule under different sponsorship, and Air Force cooperation in arranging for the implementation of this plan has been requested through the appropriate channels.

2. COSMIC RAY INTENSITY OBSERVATIONS AT AFCRL GEOPOLE STATION

The nucleonic intensity observations at Thule, Greenland (geomagnetic latitude 88°N) have established a longer data base than any other station in either polar cap. The data have been widely used by cosmic ray physicists around the world. During the period covered by this report, the records were sent on a regular basis to the four World Data Centers, to three other active groups in the United States, and to 19 groups in 17 other nations (the latter all in response to specific requests. Thule cosmic ray data have also been published on a current basis in Solar Geophysical Data (NOAA), and Geophysics and Space Data (AFCRL). Finally, the Thule neutron monitor was hard-wired in to the Space Environment Services Center (NOAA), and provided the real time observations required for surveillance and forecasting purposes. Recording at Geopole Station was terminated on June 13, 1976, and efforts are currently under way to resume operation in the new site at the earliest possible date.

3. ANALYSIS OF COSMIC RAY INTENSITY VARIATIONS

During the brief period covered by this report, important progress was made toward understanding a few of the many galactic cosmic ray intensity modulations and anisotropies upon which attention could be concentrated.

A. The Origin of Cosmic Ray Storms

Soon after the discovery of Forbush decreases, it was assumed by the scientific community that, in analogy with magnetic storms, the plasma released during solar flares is somehow responsible for transient cosmic ray intensity fluctuations. A few rare satellite observations of cosmic ray decreases suggested that the spatial extent of the modulating region can be large, indicating a broad plasma beam. Thus, it was generally accepted that even solar flares close to either the east or west limbs of the sun can modulate the terrestrial cosmic ray flux. In fact, on the basis of the aforementioned assumption, two well-known effects were deduced.

The first, called the center-limb effect, represents the claim that flares located near the center of the sun, in comparison with the limbs, produce larger cosmic ray intensity decreases. The second describes an apparent asymmetry in the modulating efficiency of flares located in the eastern and western hemispheres respectively. More specifically, flares that occur on the eastern segment are related to transient decreases more frequently, and, furthermore, appear to produce larger magnitude intensity diminutions.

Our analysis of the nucleonic intensity data from the polar stations, which are most appropriate for this purpose for several reasons, has revealed that for a majority of the transient decreases the heretofore universally accepted assumption is not valid. In fact, our initial study utilizing the new procedure of performing a superposed epoch analysis of the cosmic ray intensity during the epochs of all solar flares of importance ≥ 2 during an entire solar cycle (1964-1974) revealed that cosmic ray modulation is indeed associated with solar flares. However, when the epochs are divided into several groups characterized by the heliolongitude of the solar flares, a puzzling relationship is revealed. In some cases, the cosmic ray intensity decrease significantly precedes the flare. An identical analysis of an equal number of random selected epochs showed that this result is not attributable to chance, but is statistically significant.

In an attempt to delineate this effect, a similar analysis was conducted for 86 solar flares that were recorded during the transit of 24 regions that had been independently identified as among the most extraordinarily active during the same solar cycle. The magnitudes of the composite intensity decreases are increased by this selection process. This study has revealed that the time interval between the onset of the solar flares and the intensity decreases anomalously ranges from +5 to -5 days. Further analysis has shown that these results can be understood by ascribing the nucleonic intensity modulations to the solar active regions themselves rather than to specific flares. These results indicate that strict criteria are required for distinguishing the relatively few Forbush decreases of solar flare origin from the predominant modulation effects originating in solar active regions.

At this stage it is essential to reevaluate the center-limb and east-west effects and their theoretical interpretations.

It appears that the center-limb effect is a direct consequence of the fact that most of the transient decreases are produced by the central meridian passage of the active centers.

Analysis of geomagnetic data using the aforementioned procedure has revealed that, contrary to the situation with respect to cosmic ray intensity transients, magnetic storms begin a day (+1) after solar flare onset and maximum value of K_p is reached on +3 day. In other words, the planetary index K_p is positively correlated with solar flares. It has already been demonstrated by other workers that the active regions are negatively correlated with K_p.

b. North-South Anisotropy

A comprehensive analysis of the transient north-south anisotropy that is a characteristic feature of Forbush decreases has revealed that the direction of axial anisotropy is determined by the inclination of the associated interplanetary shock wave with respect to the ecliptic plane. The study included all recorded cosmic ray events (15) for which the sense of the anisotropy vector could be determined by a rigorous statistical procedure, and the associated shock orientation is known. In contrast, similar examinations of the same set of events showed that there is no correlation between the sense of the north-south anisotropy and either the heliolatitude of the associated solar flare or the inclination of the interplanetary magnetic field. An additional investigation of the collection of heretofore puzzling events during which the direction of anisotropy flips suddenly has shown that the reversal is associated with the arrival of a second shock, presumably with an inclination that is opposite to that of the earlier one associated with the onset of the Forbush decrease. These results provide new insight into the key role played by shocks in the transient modulation mechanism.

c. Interplanetary Acceleration of Cosmic Rays

The process of adiabatic acceleration of relativistic cosmic rays between two converging shocks, through the first-order Fermi mechanism, to which the unusual ground level event (GLE) of August 4, 1972, was attributed earlier was examined quantitatively, the nature of interplanetary shock waves and their propagation being taken into account. In the formal computational model the net evolution of the particle flux is determined by the balance between the acceleration of particles reflected from the moving shock waves and the loss of those particles which pass through the shocks. Comparison of the results of the theoretical calculations with the measurements has revealed that the observed abnormalities are a natural consequence of the proposed process. In particular, the computed times of maximum and the ratio of the enhancement at the mountain altitude South Pole station to that at the sea level polar neutron monitors are in good agreement, as is the rapid decay of the particle flux after the maximum. The initial growth of the nucleonic intensity appears to be delayed with respect to the prediction, but this discrepancy can be ascribed to the complexities in attempting to uniquely disentagle the GLE from the behavior of the total cosmic ray flux and to the late development of the particle reflection coefficient of the interplanetary shock fronts. An intensive search has revealed that the requisite conditions for observing GLE representing acceleration between converging shocks has occurred only twice over a period of two solar cycles, and on both occasions an abnormal GLE was in fact observed.

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5. PERSONNEL

The scientists who participated in this program were: S. P. Duggal, S. E. Forbush, D. W. Kent, E. H. Levy, and M. A. Pomerantz. The observers were John J. Dwyer and Robert J. Schroeder.

Transient Cosmic Ray Intensity Variations

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Abstract

A new approach to determining the origin of transient cosmic ray intensity variations has revealed that in a statistical sense solar flares, heretofore regarded as the predominant source of the modulation, actually do not precede the reduction in flux observed at Earth. The modulation is attributable to some other solar feature.

Although world-wide transient reductions in cosmic ray intensity, called Forbush decreases (or, if they occur sequentially, cosmic ray storms), were discovered four decades ago[1,2], their precise relationship to specific solar features, as well as the details of the modulation mechanism in interplanetary space, remain to be elucidated. In striving to attain this goal, research in this field has followed a very interesting course, with several detours. The purpose of this paper is to suggest that, on the basis of new evidence, the approach to understanding cosmic ray intensity variations should be redirected.

It was noted at an early stage that some Forbush decreases occurred in association with geomagnetic storms, characterized by a decrease in the horizontal intensity (H) of the Earth's field. This seemed to suggest that the geomagnetic variation could be responsible for the accompanying cosmic ray intensity fluctuation. However, since the magnitude of the Forbush decrease was not related to the change in H, a direct relationship between terrestrial magnetic field disturbances and cosmic ray storms was ruled out (see review by Elliot[3]).

Chapman and Ferraro's theory of magnetic storms (see details and references in the book by Chapman and Bartels[4]), in which the decrease in H during the main phase is acribed to a ring current which is formed by the solar streams, led to the suggestion that cosmic ray decreases could also be attributed to the ring current. Although the magnetic field inside the ring is reduced, thereby leading to the observed decrease in H, outside the external field as viewed by an incoming particle is reinforced by the ring current, as a consequence of which some cosmic rays that could previously enter might be deflected away from the earth.

However, detailed calculations indicated that, depending on the radius of the ring, the cosmic ray intensity change can be either positive or negative,[5,6] whereas magnetic storm related cosmic ray intensity changes are always decreases (except for a recently discovered brief pulse type increase associated with reflection of particles from the shock front[7]). Finally, studies of the latitude dependence of cosmic ray decreases established conclusively that changes in the geomagnetic field are not the main source of the observed effects[8,9].

It is interesting to note that, at the same time, attention was also being paid to the hypothesis that changes in the solar magnetic field could produce transient cosmic ray intensity variations. Vallarta[10] had suggested that cosmic ray storms might be a consequence of variations in the dipole magnetic field of the Sun. The so-called knee of the latitude effect of cosmic rays was ascribed to the Störmer cutoff imposed by this field, which, at geomagnetic latitude above about 50°, exceeded the cutoff determined by the earth's magnetic field. This hypothesis was subsequently discarded, and it was later demonstrated that the concept of a solar cutoff was completely invalid[11].

Similarly, a proposal that a positive electrostatic charge on the earth, producing a potential of about 10^9V, causes cosmic ray decreases by electrostatic repulsion[12] was also rejected.

Around 1950, a new generation of candidates for producing cosmic ray modulation was born. Alfven[13,14] proposed that solar corpuscular beams, presumably associated with flares, and carrying a magnetic field $\vec{B}$ perpendicular to the direction of motion $\vec{V}$, can decelerate cosmic rays via the electric field $\vec{E} = - \vec{V} \times \vec{B}/c$. However, a thorough examination of this model revealed that the net change in energy of the particles is zero and hence a decrease cannot be produced by this mechanism[15].

The corpuscular stream hypothesis led to several calculations (see details and references in the book by Dorman[16]) and an interesting suggestion that these beams contain large scale disordered and tangled magnetic fields[17]. Since the magnetized cloud expands rapidly away from the Sun, cosmic rays can reach the interior only by diffusion. Consequently, the particle density is lower inside, and when the cloud envelops the Earth, a transient decrease is observed. However, it was soon realized that this process requires extraordinary magnetic fields and velocities[18]. Later, the large scale knotted fields envisaged by this model were replaced by small irregularities and kinks in an overall large scale interplanetary field. These kinks are considerably more efficient in removing cosmic ray particles.

Contemporary theoretical models are based upon one of the following mechanisms:

1) Exclusion of particles by a re-entrant loop of magnetic field, such as is commonly observed in the corona over active regions, that is extended into space by the enhanced corpuscular radiation emanating from the center of activity, to form a magnetic tongue or bottle[19-22].
2) Deflection of particles by a shock wave in interplanetary space.[15]

In recent years, with the availability of in situ observations of the interplanetary medium by satellites, considerable attention has been devoted to seeking experimental verification of the various proposed mechanisms. For example, Barouch and Burlaga[23] have contended that most cosmic ray decreases are associated with magnetic "blobs" (regions of above average interplanetary magnetic field strength) in the vicinity of the Earth. Lockwood and Webber[24] have determined that in some cases the Forbush decrease modulating region was co-rotating, and in others radially expanding. The recent results of Duggal and Pomerantz[25,26] have confirmed directly the relationship of interplanetary shock waves to transient cosmic ray intensity decreases.

Despite the considerable progress in observing and interpreting specific features of transient cosmic ray intensity variations, conclusions concerning their ultimate origin at the sun have been contradictory and controversial. The purpose of the analysis reported in this paper is to attempt to identify the solar source of the modulation. The ultimate goal is to understand the relationship between the microcosm of short term variations and the macrocosm of the long term (solar cycle) modulation.

Before describing our results, it is appropriate to summarize briefly some of the highlights of the superstructure that has been constructed on the basis of the heretofore generally accepted assumption that solar flares are the predominant source of reductions in the galactic cosmic ray intensity.

It has been claimed that flares occurring near the center of the visible disk are the most efficient in producing the observed cosmic ray storms (see review paper, Lockwood[27]). Furthermore, in addition to this so-called center-limb effect, the eastern and western regions of the Sun appeared to contribute unequally toward the creation of modulation regions that produce cosmic ray intensity decreases at the earth. This east-west asymmetry has been explained as arising from an asymmetrical field configuration in the interplanetary space relative to the Sun-Earth line[28]. On the other hand, although the analysis by Ballif and Jones[29,30] could not rule out solar flares as sources of decreases, they hypothesized that almost all Forbush decreases can be associated with active regions near the Sun's central meridian.

SUPERPOSED EPOCH

In all previous studies of transient intensity variations, the Forbush decrease (i.e., the effect) was first selected, and a possible cause was assumed. The relationship between observed effect and hypothetical cause was then investigated. The converse procedure of assuming a possible cause and then determining the nature of the effect (i.e., a cosmic ray intensity variation), if any, would seem to be more rational. Consequently, in order to avoid the inevitable bias that results from assigning a specific solar flare or an active center to a given Forbush decrease, as has been the traditional practice, we have examined by superposed epoch analysis the cosmic ray intensity variations associated with a large number of solar flares without any selection criteria. The effects of long term variations, which can introduce complications in the study of transient fluctuations, are minimized by expressing the cosmic ray data as deviations from the mean intensity during 27 days (1 solar rotation) centered on the epoch day. The result of a Chree analysis comprising all 379 solar flares of Importance ≥ 2 that occurred during solar cycle 20 (11 year period from 1964-1974) is shown in Figure 1.

Note that a single day with multiple flares is regarded as one epoch, since the long recovery phase of a Forbush decrease precludes finer temporal resolution. Furthermore, this procedure affords a more conservative estimate of standard deviations. Contributions from enhanced diurnal variations are minimized by using daily mean values.

Comparison of the data recorded at north and south polar stations (Thule and McMurdo, respectively) indicates that no complications are introduced by axial anisotropy[31,32]. Although north-south asymmetry is a characteristic feature of cosmic ray storms, the magnitude and direction of axial anisotropy is not related to the position of solar flares. However, the direction is related to the inclination of the associated shock waves with respect to the ecliptic[25,26]. Although the duration of north-south differences is usually short ($\leq$1 day), several longer-lasting events have been recorded[31,32]. Thus, while the individual epochs in Figure 1 are likely to be characterized by north-south anisotropy, their random sense prevents the accumulation of a net anisotropy in any large data set. Consequently, the composite of 379 epochs does not reveal any significant north-south effect.

The Chree analysis in Figure 1 clearly reveals a decrease in the composite nucleonic intensity at polar stations of about 0.8%. However, it is striking that the onset of the decrease precedes the zero day (i.e., time of the flare). Furthermore, this discrepancy is exacerbated by the fact that a finite interval, corresponding to the transit time of solar plasma from the sun to the vicinity of the Earth, must elapse prior to the onset of the cosmic ray intensity decrease. A recent comprehensive study of spacecraft observations of interplanetary disturbances that occurred between 1968 and 1971 has revealed that the average speed of interplanetary shock waves, which presumably lead the piston plasma, is about 650 km/sec with a range of 400 to 1000 km/sec[33]. This result, coupled with the observations of Forbush decreases[27], indicates that both for slow and rapid decreases that are included in Figure 1, a plasma transit time of 2($\pm$1) days should be added to the time of occurrence of the flare. This is indicated in Figure 1 (and all other similar figures) by the shaded band. Thus, it appears that, on average, the cosmic ray decreases actually commenced several days prior to the arrival of flare ejecta at the earth.

In contemplating this puzzling situation, the first possible explanation is that the entire variation displayed in Figure 1 may have occurred by chance. Unfortunately, since the day-to-day intensity variations do not represent independent data points, it is not possible to estimate the standard deviation of individual points in Figure 1 by conventional statistical procedure. However, Figure 2 reveals that if 379 epochs are selected at random, the intensity variations, in five trials of Chree analysis, are significantly smaller than those in Figure 1. By comparing the pooled variance determined from Chree analyses based on random epochs with the variance of the curve in Figure 1, we find that the probability that the indicated result occurred by chance is <.0005.

Since the puzzling result displayed in Figure 1 is not fortuitous, we must seek a physical explanation. In the search for an alternative solar characteristic that is responsible for cosmic ray decreases, we have divided the 379 solar flare epochs into three groups based on the location of the solar flares. The resulting superposed epoch analysis, shown in Figure 3, reveals that whereas flares on the eastern hemisphere might be associated with cosmic ray decreases, the central (30°E-30°W) and western flares cannot be thus related, since in these cases the cosmic ray decrease preceded the arrival of plasma in the vicinity of the Earth.

Figure 4 is similar to Figure 3, except that the 86 epochs in this Chree analysis represent all visible solar flares (Imp ≥ 2) that occurred in a selected set of 24 extraordinary flare rich active centers during the period 1964-1974[34], excluding the active center associated with the record-breaking Forbush decrease of August, 1972[35]. Again, in this selected subset, the cosmic ray intensity is not related to the flares. However, for each group in this Figure, the central meridian passage (CMP) of the active region in which the flare occurred is indicated by the intersection of the diagonal (dotted) line with the respective composite intensity curves. It is apparent that the cosmic ray decrease in each group is associated with the CMP (± 1 day) of the active region.

It is of interest to conduct a similar test of the relationship of geomagnetic activity to flares and to active centers, respectively. The results of a Chree analysis of K_p data for the same 379 flares is plotted in Figure 5. It is clear that, regardless of whether the daily K_p sum is expressed as an absolute value, or as a percentage to normalize the epochs for changes during the solar cycle, the level of geomagnetic activity increases roughly one day after flare onset.

At this stage, it is essential to note that, in contrast with the cosmic ray intensity, the planetary geomagnetic index K_p does not always vary inversely with the level of solar activity. The positive correlation displayed in Figure 5 is quite well known for flares associated with geomagnetic storms[36]. However, when various manifestations of activity such as photospheric sunspots, chromospheric calcium plages, or coronal λ5303 are selected to define the epochs, a minimum in K_p follows CMP by three days[37,38]. The association of quiet geomagnetic conditions with active regions can be understood in terms of slow solar wind conditions (Figure 6) associated with the closed field lines of the active regions[38,39].

In view of the fact that, unlike the cosmic ray case, K_p is correlated either positively or negatively with solar activity extreme caution must be exercised in attempting to separate the flare effects from control by active regions. Thus, for our present purposes, further analysis of K_p is not warranted.

CONCLUSIONS AND DISCUSSION

It is clear from the aforementioned analysis that the majority of transient intensity variations of galactic cosmic rays are related to the passage of active center, and cannot be assigned directly to specific solar flares. Of course, it has long been thought that active centers play a limited role in producing both recurrent (27-day) and non-recurrent cosmic ray intensity variations[40-45]. The present work has revealed that, in fact, active centers do play a major role in the modulation process. However, in light of the statistical nature of this analysis, the direct production of Forbush decreases by some individual flares is not precluded.

In any case it appears that the well known center-limb and east-west effects require reevaluation. In fact the early conclusion, based on assuming a one-to-one correspondence between solar flares and transient decreases, that flares located near the center of the sun are more efficient in producing cosmic ray events (center-limb effect) can be understood in terms of the result presented here. Since most of the modulation is produced by the CMP of active regions, those solar flares that occur in the active regions when they are near the center of the visible disk would, at first sight, seem to cause larger and more frequent transient decreases.

The east-west asymmetry effect, according to which flares located on the eastern hemisphere of the sun are claimed to be more efficient producers of transient decreases than are western flares, can also be understood in terms of Figure 3. Compared to eastern flares there is a little chance that flares on the western hemisphere are likely to be associated with decreases since the modulation producers (active centers) create western solar flares <u>after</u> crossing the central meridian.

If flares are not responsible for day-to-day variations in cosmic ray intensity, what other phenomenon associated with active centers creates the modulation region in interplanetary space? Recent solar observations have revealed that active regions, over which the field lines are closed, are not the progenitors of high speed plasma streams. On the contrary, areas characterized by open field lines, i.e., coronal holes (see Figure 6), display almost a one-to-one relationship with high speed streams[46]. Since our preliminary investigation utilizing the procedure described above has revealed that coronal holes are not associated with cosmic ray storms, individual high speed streams do not appear to be promising as the modulating agent.

Recently, it has been demonstrated by Smith and Wolfe[47] that beyond 1 AU many interaction regions between adjacent solar wind streams are accompanied by either forward shocks, reverse shocks or shock pairs. In fact, their observations are consistent with the earlier proposals that the stream-stream interactions lead to the development of co-rotating interplanetary shocks. This apparent formation of co-rotating shocks beyond 1 AU signifies that the basic structure of the interplanetary medium in the outer solar system is different than that with which we are familiar near the orbit of the Earth. In principal, these interaction regions with relatively large and irregular fields, and associated with shock waves, can modulate cosmic rays. As more data regarding a larger volume of interplanetary space become available, it should become feasible to determine whether these interaction regions and the associated shock waves are the missing links in the relationship of the flare rich active regions with transient cosmic ray decreases. Finally, the importance of obtaining field and plasma measurements far beyond the plane of the ecliptic, for construction of a three-dimensional modulation model, cannot be overemphasized.

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FIGURE CAPTIONS

Fig. 1 Superposed epoch analysis of nucleonic intensity recorded at stations in the two polar regions with respect to all major solar flares that occurred during an entire sunspot cycle (No. 20). The zero day is the time of one or more sudden chromospheric eruptions, and the cosmic ray intensity is the percentage deviation from the mean during the 27 day interval (1 solar rotation) centered thereon. The shaded band indicates the time of the arrival near the earth of the plasma associated with the flare. The composite cosmic ray intensity decrease significantly precedes the epoch date.

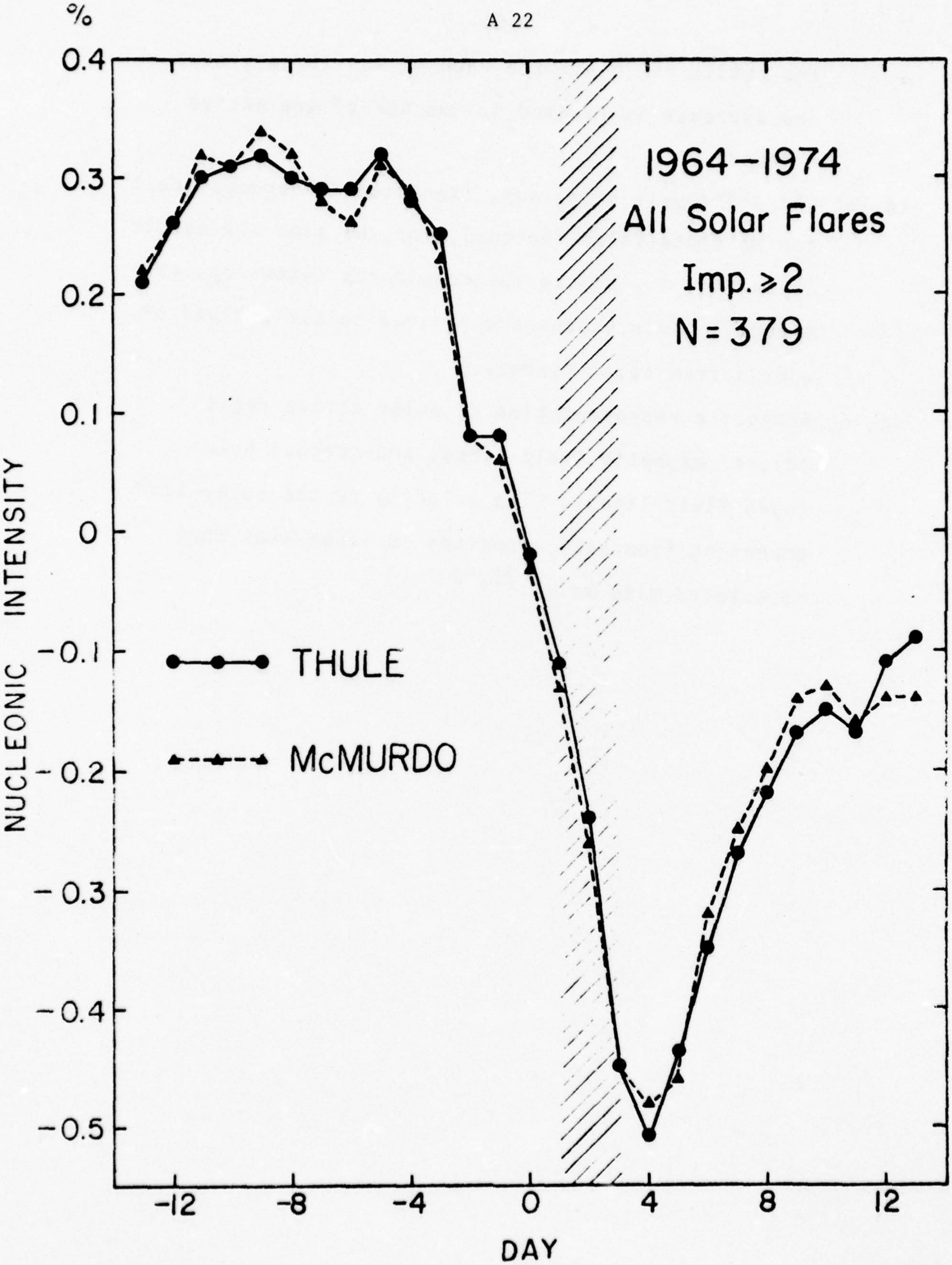
Fig. 2 Five trials of Chree analysis, each for the same number of epochs as in Fig. 1, but with randomly selected zero days. This procedure provides statistical confirmation that the effect has not appeared by chance.

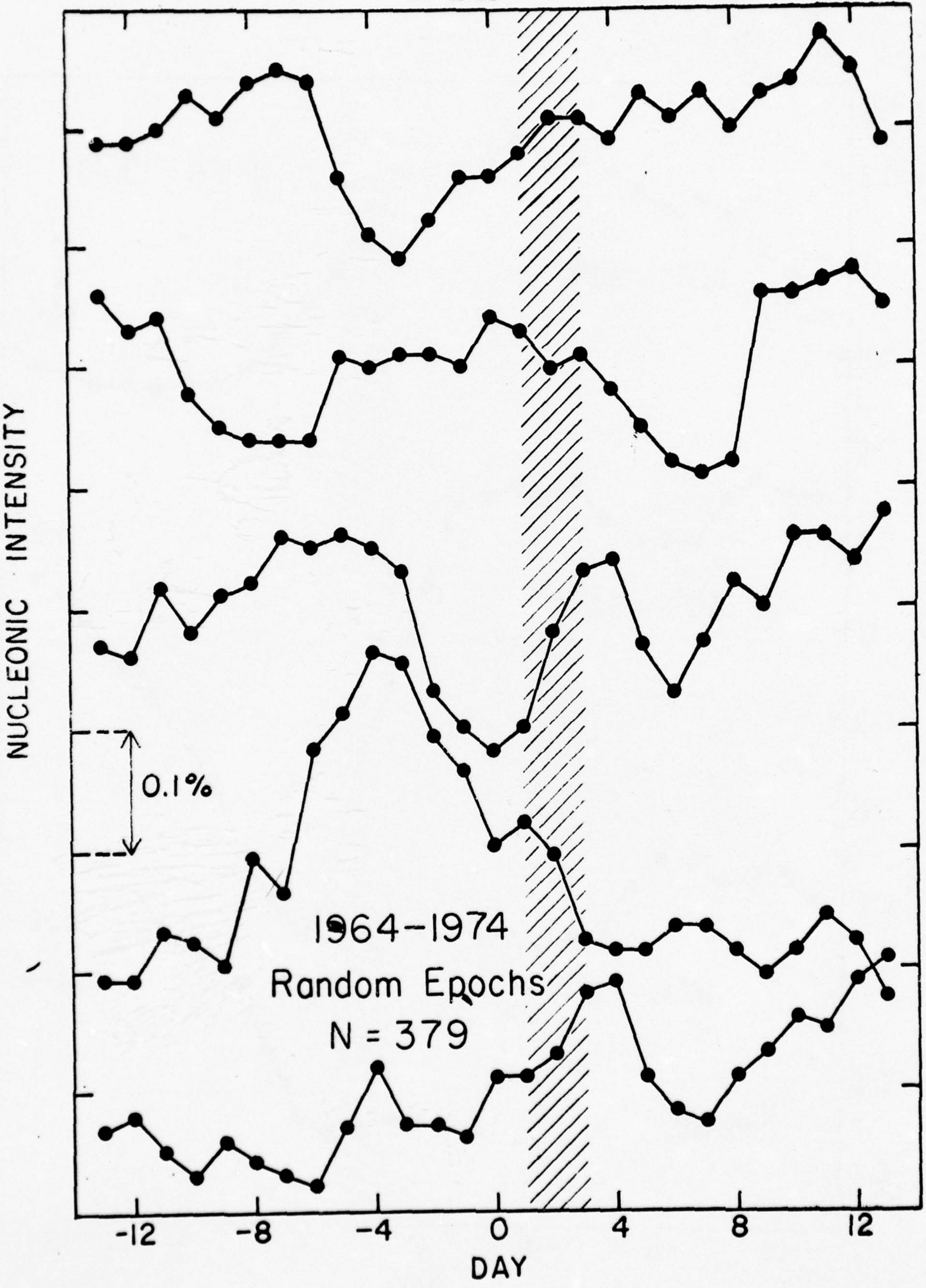
Fig. 3 Analyses of same data as in Fig. 1, but with epochs subdivided into three groups according to the location of the solar flares. The cosmic ray intensity decrease onset clearly precedes the flares occurring in the central and western segments of the solar disk.

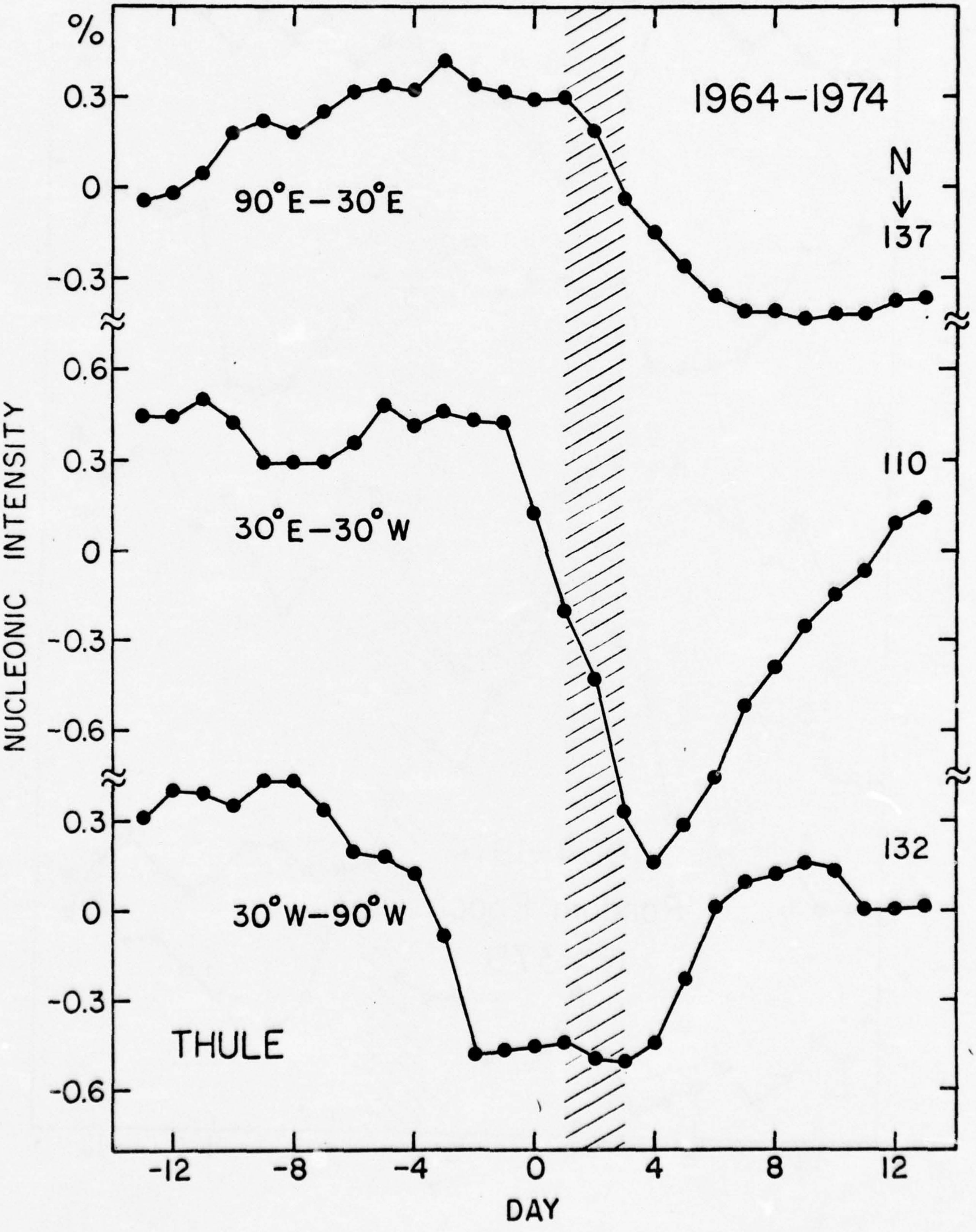
Fig. 4 Analysis similar to that in Fig. 3 for all days (86) on which major solar flares (Imp $\geq$2) occurred during the transit across the visible disk of 24 of the most extraordinary active centers that were observed during solar cycle 20. The intersection of the dotted line with the curves represents central meridian passage (CMP) of the active regions. For each of the three groups the decrease is related to the CMP of the active regions.

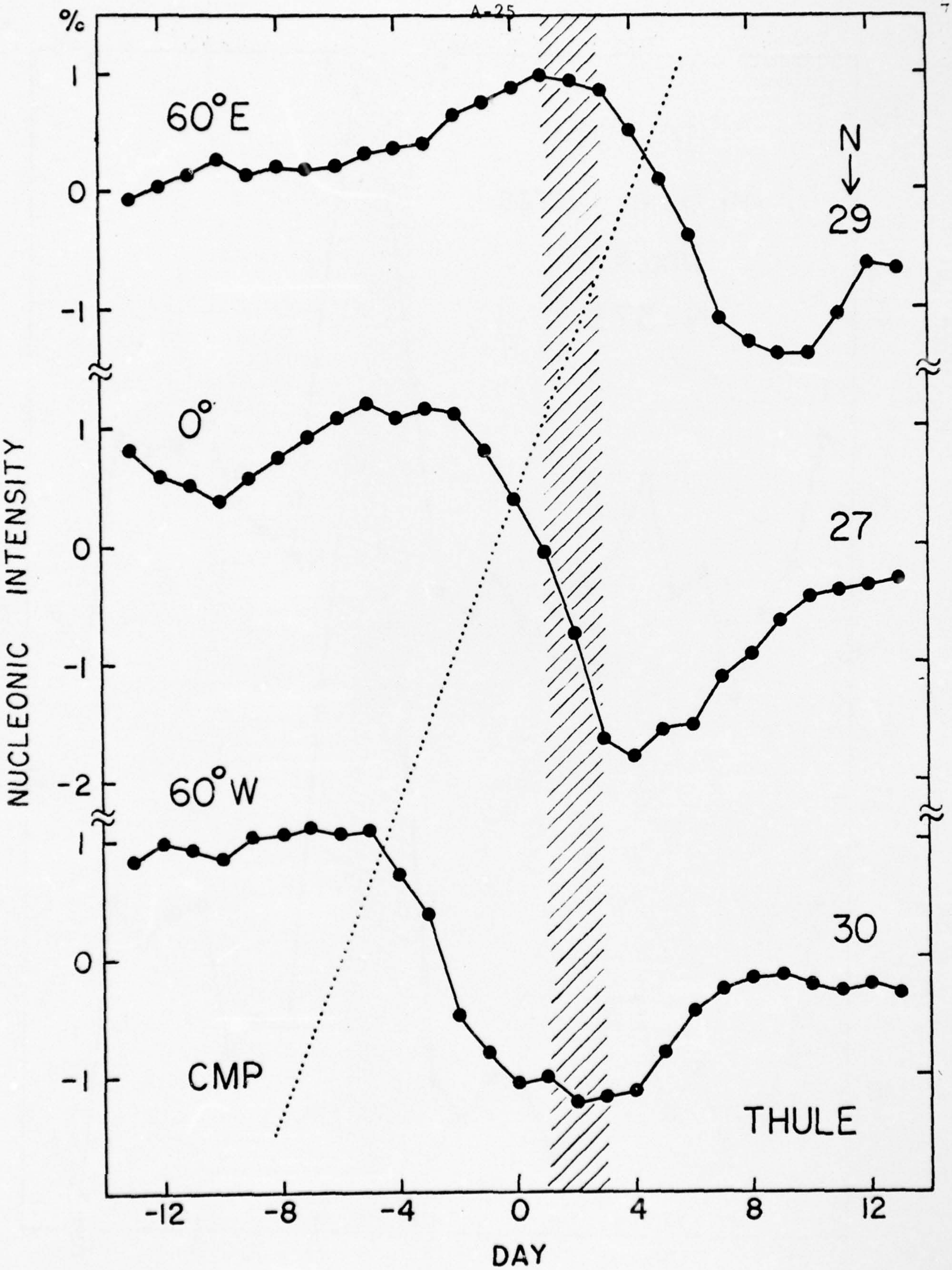
Fig. 5 Chree analysis of K_p sum, expressed as percent (top) and absolute value (bottom), for the same 379 epochs as in Fig. 1. Unlike the cosmic ray intensity, geomagnetic disturbances are related to the arrival of ejecta from solar flares.

Fig. 6 Schematic representation of solar active region (closed magnetic field lines) and coronal holes (open field lines). The velocity of the solar wind emanating from active regions is lower than that associated with holes.[38,39]


%
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
NUCLEONIC INTENSITY
1964–1974
All Solar Flares
Imp. ≥ 2
N = 379
THULE
McMURDO
-12
-8
-4
0
4
8
12
DAY


NUCLEONIC INTENSITY
0.1%
1964-1974
Random Epochs
N = 379
-12
-8
-4
0
4
8
12
DAY


%
1964-1974
N
137
110
132
90°E-30°E
30°E-30°W
30°W-90°W
THULE
0.3
0
-0.3
0.6
0.3
0
-0.3
-0.6
0.3
0
-0.3
-0.6
NUCLEONIC INTENSITY
-12
-8
-4
0
4
8
12
DAY


%
1
0
-1
1
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1
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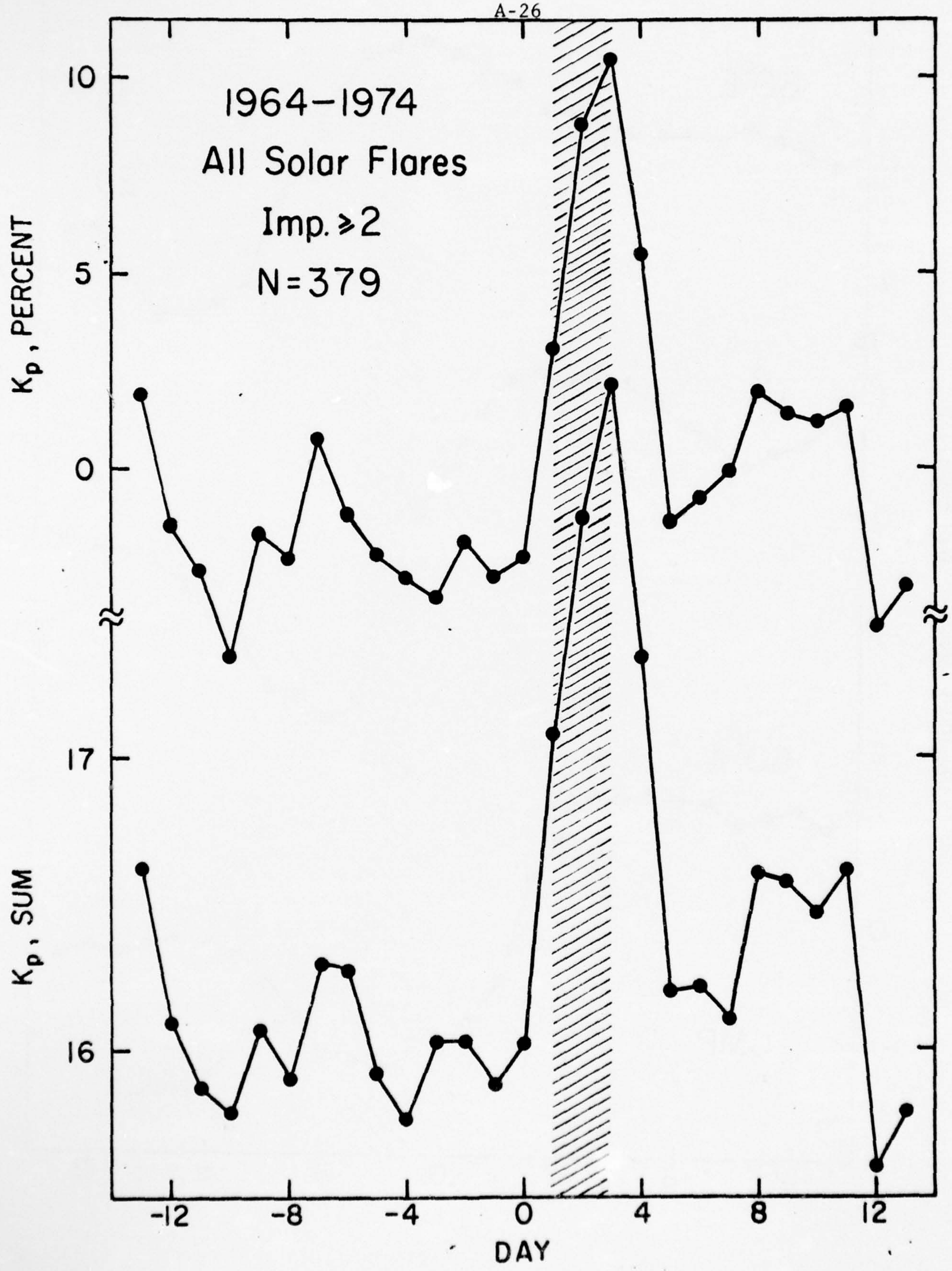
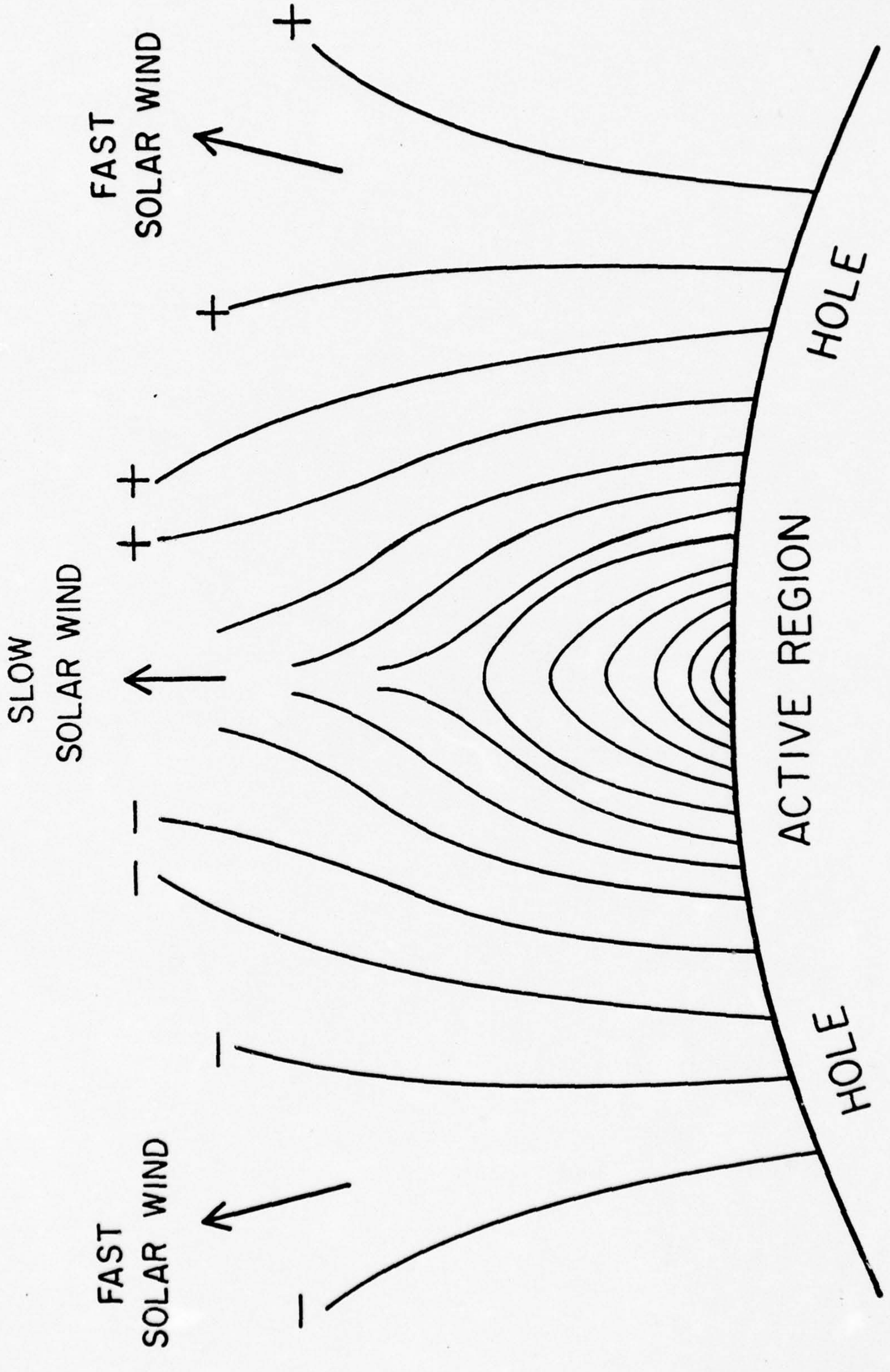
60°E
N
↓
29
0°
27
60°W
30
CMP
THULE
NUCLEONIC INTENSITY
-12
-8
-4
0
4
8
12
DAY


1964–1974
All Solar Flares
Imp. ≥ 2
N=379
Kp, PERCENT
10
5
0
Kp, SUM
17
16
-12
-8
-4
0
4
8
12
DAY


FAST SOLAR WIND
+
+
+ +
+ +
SLOW SOLAR WIND
− −
− −
−
−
FAST SOLAR WIND
HOLE
ACTIVE REGION
HOLE

Origin of Transient North-South Anisotropy of Cosmic Rays

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ABSTRACT

A comprehensive analysis of the transient north-south anisotropy that is a characteristic feature of Forbush decreases has revealed that the direction of axial anisotropy is determined by the inclination of the associated interplanetary shock wave with respect to the ecliptic plane. The study included all recorded cosmic ray events (15) for which the sense of the anisotropy vector could be determined by a rigorous statistical procedure, and the associated shock orientation is known. In contrast, similar examinations of the same set of events showed that there is no correlation between the sense of the north-south anisotropy and either the heliolatitude of the associated solar flare or the inclination of the interplanetary magnetic field. An additional investigation of the collection of heretofore puzzling events during which the direction of anisotropy flips suddenly has shown that the reversal is associated with the arrival of a second shock, presumably with an inclination that is opposite to that of the earlier one associated with the onset of the Forbush decrease. These results provide new insight into the key role played by shocks in the transient modulation mechanism.

INTRODUCTION

Because of the dynamic character of the mechanisms that produce transient fluctuations in the cosmic ray intensity, it is exceedingly difficult to comprehend them in any detail. It is clear that the observed properties of Forbush decreases are attributable to specific features of the interplanetary magnetic field (IMF) which may occur individually or in combination. These include:

a) Magnetic irregularities—rapid or slow fluctuations in the direction or magnitude of the IMF;

b) Magnetic bottles or tongues—extended structures of intense magnetic field;

c) Shocks or blast waves and tangential discontinuities.

The phenomena under a) are contained in the convection-diffusion approximation of the transport equation that describes the streaming of cosmic rays in the interplanetary medium. Some of the observed transient intensity variations can be ascribed to rapid changes in the parameters that determine the net anisotropy or modulation. Both b) and c) are manifestations of the motion of boundaries, and, in effect, the relevant theoretical analysis describes the sweeping up of particles by a moving semi-permeable membrane. Combinations of these departures from equilibrium conditions undoubtedly play a role in many of the observed transitory modulations and anisotropies.

Over the years, a number of models of the configuration of interplanetary plasmas resulting from solar disturbances have been proposed to account for various features of cosmic ray storms, including enhanced diurnal waves (Lockwood, 1971). With the acquisition of direct observations of the IMF, further studies of the observed characteristics of transient intensity decreases have been conducted, and additional explanations of their origin have been put forth (Pomerantz, 1975).

Recent developments indicate that anisotropies perpendicular to the ecliptic plane can provide a powerful diagnostic tool for understanding the mechanisms that produce the transient intensity variations. In the present paper, we report the results of an investigation of the relationship of the axial anisotropy to solar and interplanetary phenomena in an effort thereby to elucidate the basic modulation mechanism.

It has been established that anisotropy perpendicular to the plane of the ecliptic is a characteristic feature of cosmic ray storms (Duggal and Pomerantz, 1971; Mercer et al., 1971). The sense of the north-south (N-S) anisotropy varies from event to event. In fact, during a single Forbush decrease, the sign can change several times (Duggal and Pomerantz, 1971).

As a point of departure for the study described here, it seemed plausible to start from the hypothesis that, in cases where the dominant mechanism producing the Forbush decrease is (c), i.e., interplanetary shock waves, there might be a relationship between the direction of the observed north-south anisotropy and the inclination of the associated shock normal with respect to the ecliptic plane. The parameters needed for an analysis designed to test this possibility have been determined for a group of interplanetary shock waves (Chao and Lepping, 1974). Although the number of events for which the required comparison can be made is small, it comprises the only statistically significant currently available set for which the parameters have been determined by consistent procedures. Consequently, a similar search for other possible relationships of the north-south anisotropy to, for example, the location of the associated solar flare, or the direction of the IMF, must be confined to the same set of events. Furthermore, a comparison of the results obtained by following identical procedures serves to put the final conclusion into its proper context.

DATA ANALYSIS

Determination of North-South Anisotropy

The method for determining the direction of the north-south anisotropy vector has been described elsewhere (Nagashima et al., 1968; Duggal and Pomerantz, 1970). Briefly, for periods in which the magnitude of the longitudinal anisotropy is small, the fractional change in the cosmic ray intensity I at station i is given by:

$$\left(\frac{\Delta I}{I}\right)_i = A + B \sin \lambda^*(\gamma, i) \qquad (1)$$

Where $B = a \sin \lambda_j$.

Here, a, A and B are constants, γ is the variational spectral index, λ_j is the latitude defining the direction of the total vector of anisotropy, and λ^*, the effective asymptotic latitude of viewing for station i, is given by:

$$\sin \lambda^*(\gamma, i) = \int_{P_i}^{\infty} R(P) P^{-\gamma} \sin \lambda(P) dP \Big/ \int_{P_i}^{\infty} R(P) P^{-\gamma} dP \qquad (2)$$

where R(P) is the neutron monitor response function, P_i is the threshold rigidity, and λ is the asymptotic latitude for particles with rigidity P. Thus a least squares fit of the data from several stations to (1) yields the magnitude and direction of the north-south anisotropy vector. Note that since we are interested only in the sign of the north-south anisotropy, an approximate value of the spectral exponent γ, which could be determined more precisely by an iterative procedure, is adequate. Finally, it should be cautioned that, in contrast with this objective analytical procedure, the direct comparison of the intensities at a north and a south polar station can lead to grossly erroneous conclusions regarding the north-south anisotropy (Duggal and Pomerantz, 1971).

Determination of Shock Normal

Solar plasma observations with satellites make it possible to recognize the passage of a shock wave, and to determine its characteristics (Sonnett et al., 1964; Hirshberg, 1968; Taylor, 1969; Hirshberg et al., 1970; Hundhausen, 1970; Burlaga, 1971; Lepping, 1972; Bavassano et al., 1973; Dryer, 1974). When pre- and post-shock magnetic field vectors ($\vec{B}_1$ and $\vec{B}_2$, respectively) are known, the shock normal $\hat{n}_s$ can be assumed to be parallel to $\overrightarrow{\Delta B} \times (\vec{B}_1 \times \vec{B}_2)$, where $\overrightarrow{\Delta B} = \vec{B}_2 - \vec{B}_1$, on the basis of the magnetic coplanarity theorem. On the other hand, the normal to a tangential discontinuity $\hat{n}_t$ should be parallel to $\vec{B}_1 \times \vec{B}_2$. Thus the normals $\hat{n}_s$ and $\hat{n}_t$ can be evaluated for any event regardless of whether the field disturbance is associated with a shock or tangential discontinuity. Data from two or more spacecraft have been employed for distinguishing between a shock and tangential discontinuity (Chao and Lepping, 1974). In this case, the relative position vector with respect to a pair of spacecraft, $\overrightarrow{\Delta R} = \vec{R}_2 - \vec{R}_1$, is related to the propagation speed of the discontinuity, V_d, and to the time difference, Δt, between observations of the disturbance at the two points in the following manner:

$$\overrightarrow{\Delta R} \cdot \hat{n}_d = V_d \Delta t \qquad (3)$$

where $\hat{n}_d$ is the normal to the discontinuity. Also, since the normal component of the magnetic field is continuous across any type of discontinuity, then $\overrightarrow{\Delta B}$ is parallel to the surface of the discontinuity, i.e., for any type of discontinuity the following relationship holds:

$$\overrightarrow{\Delta B} \cdot \hat{n}_d = 0 \qquad (4)$$

It is important to note that both the shock (for a scale of .01 AU) and tangential discontinuity (.002 AU) can usually be considered as planar and, furthermore, in general, it can be assumed that they propagate at a constant speed (Burlaga and Ness, 1969; Chao, 1970). The simultaneous solution of (3) and (4) yields both V_d and $\hat{n}_d$. When data from three or more spacecraft are available, the redundancy improves the precision of $\hat{n}_d$.

By comparing $\hat{n}_t$ and $\hat{n}_s$ obtained from single spacecraft magnetic field measurements with $\hat{n}_d$ computed from multiple spacecraft and by using other techniques such as the signatures of different types of discontinuities in the IMF, Chao and Lepping (1974) have been able to differentiate the tangential discontinuities from shock waves. Furthermore, by using both single and multiple spacecraft methods they have deduced shock normals with uncertainties of approximately ±10°. They have divided the 38 shocks that were found during the period 1968-1971 into two groups. The first, which we shall designate C, comprises 22 shock waves for which the determined orientations are relatively more accurate. Each of these was assigned to a specific solar flare. Some of the remaining 16 shocks were not assigned to a specific solar flare.

RESULTS

Interplanetary Shock Waves

It is well known that not all storm sudden commencements (SSC) are accompanied by a Forbush decrease, i.e., not every interplanetary shock wave that reaches the earth produces an observable cosmic ray intensity decrease. Only 18 out of the aforementioned 38 shock waves are associated with Forbush decreases in which the intensity change exceeds 2%. To ascertain the association between shock wave and the cosmic ray storm and to minimize the complications from stream-stream interactions, the following two criteria have been applied to the 18 events: a) The time interval ΔT between the onset of the SSC (T_1) and the onset of Forbush decrease (T_2) should not exceed ±6 hours; b) no other SSC should occur during the time interval ($\Delta\tau$) between the arrival of the primary shock wave that presumably initiated the Forbush decrease and the end of the epoch of north-south anisotropy. Thus, three of these 18 events have not been included because the association of a Forbush decrease with the listed shock wave cannot be unambiguously established. Hence this study concentrates on the north-south anisotropy observed during the remaining 15 Forbush decreases (Table 1).

Data from eight stations (Table 2) were analyzed in terms of (1) to determine the sense of the north-south anisotropy. In accordance with the conventional definition, we here define the direction of the cosmic ray anisotropy vector as that from which the greater flux of cosmic rays arrives, rather than the direction of maximum intensity depression (Duggal and Pomerantz, 1975).

To determine the correlation between the directions of the shock waves and the north-south anisotropy, it is essential to convert all the angles to the same coordinate system. If the shock inclinations, available in solar-ecliptic coordinates, are converted into the geographical system, several complications arise. Note that in this conversion the universal time (UT) is quite important. However, to eliminate the longitudinal anisotropy (see section 2) and to achieve the necessary statistical precision, the north-south anisotropy cannot be evaluated over too short an interval of time. Since beyond a basic statistical limit the choice of the interval of anisotropy is arbitrary, the comparison of the directions of north-south anisotropy and the shock wave becomes subjective.

Furthermore, it is found that the onset of the north-south anisotropy does not necessarily coincide with either the arrival of the shock wave or the onset of the Forbush decrease (cf. Table 1). Hence, a similar complication arises in specifying the universal time.

Fortunately, because the angle between the rotational axis and the plane of the ecliptic (66.5°) is invariant, the sense of north-south anisotropy is the same in geographic and ecliptic coordinates. The results of the analysis of the 15 events for which the required data are available are plotted in Figure 1. Here the abscissa refer to the inclination of the shock normals with respect to the ecliptic, as determined by Chao and Lepping (1974) and the symbols S and N represent -66.5° and +66.5° rather than ±90° as explained above. The shock parameters for the circled point are regarded by these authors as being relatively more reliable (C).

It is clear that, in most cases, a south-pointing anisotropy vector is associated with a shock arriving from north of the ecliptic, and vice versa. From the binomial distribution (assuming two modes for shock wave inclination, positive and negative with respect to the ecliptic, and two modes for N-S anisotropy; i.e., P = 0.5), the probability that the agreement in Figure 1 occurs by chance is 0.0032.

Solar Flares

By following a similar procedure, it is of interest to ascertain whether the correlation of the anisotropy direction with shock wave orientation may merely be a consequence of the location of the solar flares associated by Chao and Lepping with the events in Figure 1. Figure 2 shows the relationship of the direction of the anisotropy to the heliographic location of the flare. In this case, there is not a statistically significant correlation, since the probability of the observed distribution occurring by chance (P=0.5) is not small (0.18). This is in agreement with our earlier suggestion that there does not appear to be a relationship between the locations of associated solar flares and the directions of N-S anisotropy (Duggal and Pomerantz, 1970).

IMF Direction

It is of interest to inquire whether the sense of the anisotropy vector is related to the direction of the IMF. For this study, the 3-dimensional vector averages of IMF, for those epochs during which the occurrence of north-south anisotropy has been confirmed by the data from eight stations, were evaluated. The direction of the resultant vector is plotted as the abscissa in Figure 3, and the ordinates are the same as in the previous figures. Since IMF data for two events are not available, only 13 cases remain. There does not appear to be a significant correlation between the anisotropy and the IMF. From the binomial distribution the observed result can easily occur by chance (probability =0.21).

The lack of a correlation between the IMF and N-S anisotropy directions is not surprising since the latitudinal angle θ of the IMF vector shows a large variability compared to the variations in the direction of N-S anisotropy. This is evidenced in Figure 3 by the large fraction of uncircled points for which the inclination with respect to the ecliptic is opposite to that shown in the figure during more than 25% of the observed interval.

Figure 4 shows an alternative and somewhat more detailed presentation of data relating to this point. Here, although the north-south anisotropy direction was constant for five days (July 10-15) during the well known long duration anisotropy event of 1968 (Pomerantz and Duggal, 1972), the sense of the

IMF direction was exceedingly variable. The regression plot in Figure 5 reveals that there is no correlation between the magnitude of the polar cosmic ray intensity difference Δ_{NS} and the IMF direction.

DISCUSSION

It is well known that anisotropy in the plane perpendicular to the ecliptic can arise from the particle drift produced by a radial cosmic ray density gradient, $\vec{\nabla}n$, in the presence of the IMF, $\vec{B}$. However, in view of the recent Pioneer X and XI observations, indicating that the radial gradient is small, $\lesssim 3\%/AU$ in the vicinity of the earth (Van Allen, 1973; McKibben, 1975; McKibben et al., 1975; McDonald et al., 1975; Axford et al., 1976), the particle drift proportional to $\vec{B}\times\vec{\nabla}n$ is expected to be negligible. It has been estimated, from data provided by the worldwide network of neutron monitor stations as well as by inclined meson telescopes at a single station, that changes in the direction of $\vec{B}$ produce a N-S anisotropy of the order of only 0.1% (Bercovitch, 1970; Kondo et al., 1975). Since the present study has been restricted to magnitudes exceeding 0.2%, the finding that there is no significant correlation between the inclination of $\vec{B}$ from the ecliptic and the direction of anisotropy is not incompatible with the earlier conclusion. Furthermore, it should be remarked that an out of ecliptic field component $\vec{B}_0$ will, on the basis of $\vec{B}_0\times\vec{\nabla}n$ drift, contribute to the azimuthal anisotropy only.

The original model of north-south asymmetry envisaged a relationship between the flare location and the sense of the anisotropy (Nagashima et al., 1968). However, in the simple picture that appeared to account satisfactorily for the first observation of this phenomenon, no allowance was made for the fact that the solar plasma beams can change their characteristics in interplanetary space. Furthermore, the later observation of events in which the direction of the N-S anisotropy flips rapidly cast doubt on the hypothesis that the heliolatitude of the solar flare is a relevant parameter. Thus, the conclusion that the direction of N-S anisotropy is unrelated to the flare heliolatitude is in accord with the present state of our knowledge.

In contrast to more or less continuous observations of the field and the solar flares, the parameters of interplanetary shock waves are available for a few events only. Bavassano et al. (1973) have evaluated the parameters of 16 interplanetary shocks during 1968 with data from a single spacecraft (Pioneer 8). Nine of these shocks are unambiguously associated with the anisotropy in cosmic ray storms of magnitude $\geq 2\%$. Since seven of these shocks are already included in Figure 1, no further conclusion can be drawn from these data. Only one event associated with a Forbush decrease and satisfying the criteria of section 3 is available from the small number of shocks listed earlier by Chao (1970) and Ogilvie and Burlaga (1969).

Despite the fact that the total number of events for which the requisite data are available is small, this study (section 3) has revealed that there is a significant relationship between the direction of anisotropy and the inclination of the associated shock wave. It is of interest to determine whether the characteristics of events during which the direction of anisotropy reverses suddenly are also consistent with the attribution of the sign of the anisotropy to the shock wave inclination. Thus, if the relationship indicated by the present study is indeed real, we expect, ignoring complicated events involving stream-stream interactions, that a) the phase inversion is associated with a second shock wave and b) the inclination of this shock is opposite to that of the earlier one associated with the onset of the Forbush decrease.

Although there are no cases for which the information required to establish b) is available, among the cosmic ray storms that have been analyzed there are a number of events in which the first condition a) holds. Figure 6 shows an example of a cosmic ray storm with which a pair of SSC was associated. The onset of the Forbush decrease on March 31, 1970, can be attributed to the shock wave that produced the SSC recorded at 0529 U.T. The onset epoch shows a north-south anisotropy (from north direction) of about 2% (Figure 7a). On the other hand, a 1% anisotropy with the opposite phase was observed during the recovery portion of this storm (Figure 7b). This reversal of the direction of the anisotropy appears to be associated with the SSC at 2153 U.T. on April 1, 1970 (Figure 6). Although the inclinations of the shocks that produced the two SSC are indeterminate, we expect that in the absence of spatial complications in the configurations of solar plasma and the associated shocks, they are likely to be opposite.

A thorough search for similar events (anisotropy reversal) covering 12 years for which high counting rate neutron monitor data are available yielded 5 events that are suitable for analysis (Table 3). Note that these include both small (3%) and large (8%) cosmic ray storms. For each event listed in Table 3, the direction of anisotropy was determined by least squares fit of the neutron monitor data to (1). Despite the fact that the magnitude of the anisotropy was small in some cases, the change in sense was statistically significant in every event that is cited. The onset of SSC is generally within ±10 hours of the onset of reversal. Because of statistical considerations, the estimated time of reversal is necessarily quite imprecise, with an uncertainty that can be of the order of four hours.

Several other examples (not listed in Table 3) in which the reversal of the anisotropy is associated with Si have been found. It has been suggested that some Si may be caused by tangential discontinuities (Burlaga and Ogilvie, 1969). Furthermore, it is quite possible that some Forbush decreases may be produced by tangential discontinuities (Quenby, 1971), in which case north-south anisotropy might also be related to these interplanetary disturbances. At this stage insufficient detailed information about the latter is available for conducting a statistical investigation.

It should be noted here that some events do occur in which a second or third SSC does not produce a change in the anisotropy direction, although in some of these cases the magnitude of the north-south anisotropy shows a variation associated with the SSC, which may be indicative of the arrival of a shock with different inclination. Events of this type may represent a train of shock waves that are similarly oriented with respect to the ecliptic plane. Conversely, there are some examples of anisotropy reversals that are unaccompanied by SSC. These latter events presumably belong to the same class of phenomena as those Forbush decreases which are not associated with sudden commencements (Lockwood, 1971).

It must be emphasized that the relationship between shock waves and anisotropy is statistical in nature rather than one-to-one, since other phenomena, such as stream-stream interactions, non-uniform plasma configurations, etc., can also control the cosmic ray density distribution. Nevertheless, despite the fact that the onsets of some Forbush decreases are not associated with shock waves, every Forbush decrease displays north-south anisotropy.

Finally, at this stage, the reason for the time difference between the arrival of the shock wave and the onset of the anisotropy that is sometimes observed is not clear. Detailed understanding of this effect probably requires information concerning the characteristics of the shock waves as a function of radial distance from the sun. Furthermore, knowledge of the complete geometrical configuration of the solar plasma is required to evaluate the relative roles played by shock waves, tangential discontinuities and the piston plasma in the observed evolution of the north-south anisotropy during a particular cosmic ray storm.

The inverse correlation between the inclination of the shock wave and the sense of the north-south anisotropy that has been revealed by our analysis indicates the key role played by shocks in producing Forbush decreases. Further progress in developing quantitative models that can account for all of their features will depend heavily upon the availability of multi-spacecraft interplanetary plasma and field data.

Acknowledgments. This research was sponsored by the National Science Foundation and by the Air Force Cambridge Research Laboratories, Air Force Systems Command, under contract F19628-76-C-0047.

TABLE 1

Nucleonic intensity decreases associated with interplanetary shock waves. On account of intensity fluctuations (e.g., increase before cosmic ray storm) near the storm onset and three dimensional anisotropies, extreme caution should be exercised in comparing the listed onset times with other data. The north-south anisotropy periods represent arbitrary intervals during the anisotropic epoch characterized by a sufficiently large N-S asymmetry for determining the sense unambiguously by the procedure described in the text.

	STORM SUDDEN COMMENCEMENT		COSMIC RAY STORM			NORTH-SOUTH ANISOTROPY PERIOD
No.	Date	U.T.	Date	U.T.	Duration, Days	
1	1968 Jan. 11	1251	Jan. 11	1400	>4	Jan. 11 1600 — Jan. 12 0400
2	1968 Jan. 26	1441	Jan. 26	1800	>5	Jan. 26 1800 — Jan. 27 0400
3	1968 May 7	0030	May 7	0200	∼1	May 7 0400 — May 7 1600
4	1968 July 13	1612	July 13	1800	$\gtrsim 1$	July 13 1800 — July 14 0400
5	1968 Nov. 16	0915	Nov. 16	1000	>2	Nov. 16 1200 — Nov. 16 1600
6	1968 Nov. 20	0904	Nov. 20	1000	>2	Nov. 20 1000 — Nov. 20 1600
7	1969 Feb. 10	2024	Feb. 10	1800	>6	Feb. 10 2100 — Feb. 11 0400
8	1969 Feb. 26	0158	Feb. 26	0600	>6	Feb. 26 0600 — Feb. 26 2400
9	1969 Mar. 17	0030	Mar. 17	0600	>2	Mar. 17 0800 — Mar. 18 0800
10	1969 Mar. 23	1826	Mar. 23	2200	>5	Mar. 24 0400 — Mar. 24 2000
11	1969 July 26	1153	July 26	1400	>3	July 26 1400 — July 27 2400
12	1969 Sept. 5	1333	Sept. 5	1400	>5	Sept. 5 1400 — Sept. 6 2400
13	1969 Sept.27	2125	Sept.27	2200	>2	Sept.28 0000 — Sept.28 0800
14	1970 June 17	0750	June 17	1000	>1	June 17 1200 — June 17 2400
15	1970 Aug. 16	2204	Aug. 16	2200	>6	Aug. 17 0000 — Aug. 17 0400

TABLE 2: Stations providing nucleonic intensity data utilized for evaluating the sense of the north-south anisotropy.

Station	Symbol	Latitude	Longitude, East	Altitude, Meters
South Pole	SP	90.0°S	0	2820
McMurdo	Mc	77.9°S	166.7°	48
Swarthmore	Sw	39.9°N	284.7°	80
Deep River	DR	46.1°N	282.5°	145
Goose Bay	GB	53.3°N	299.6°	46
Inuvik	In	68.4°N	226.3°	21
Thule	Th	76.6°N	291.6°	260
Alert	Al	82.5°N	297.4	66

TABLE 3: Cosmic ray storms, observed since the establishment of the high counting rate neutron monitor network (1964-1975), for which reversals in the direction of north-south anisotropy can be confirmed by a statistical procedure and during which an associated SSC was observed.

Event	Forbush Decrease Onset		Magnitude %	Anisotropy Reversal UT		Shock Wave Arrival UT		Geomagnetic Classification
1)	1968	Feb. 1	3	Feb. 2	0600	Feb. 2	1037	SSC
2)	1969	Mar. 16	3	Mar. 17	1000	Mar. 17	0030	SSC
3)	1970	Mar. 31	4	Apr. 1	1400	Apr. 1	2153	SSC
4)	1971	Dec. 16	8	Dec. 17	1800	Dec. 17	1418	SSC
5)	1975	Jan. 6	3	Jan. 7	1800	Jan. 7	2322	SSC

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FIGURE CAPTIONS

Fig. 1 Sense of the north-south anisotropy plotted as a function of the inclination of the associated shock wave for the 15 cosmic ray events for which the shock configuration has been determined by a consistent procedure. The circled points here and in Figure 2 represent cases in which the deduced shock parameters are considered to be relatively more reliable (Chao and Lepping, 1974). As explained in the text, N and S represent ±66.5° from the ecliptic plane.

Fig. 2 Plot similar to that in Figure 1, but with heliolatitude of the solar flare to which the shock designated by the corresponding number was ascribed as abscissa.

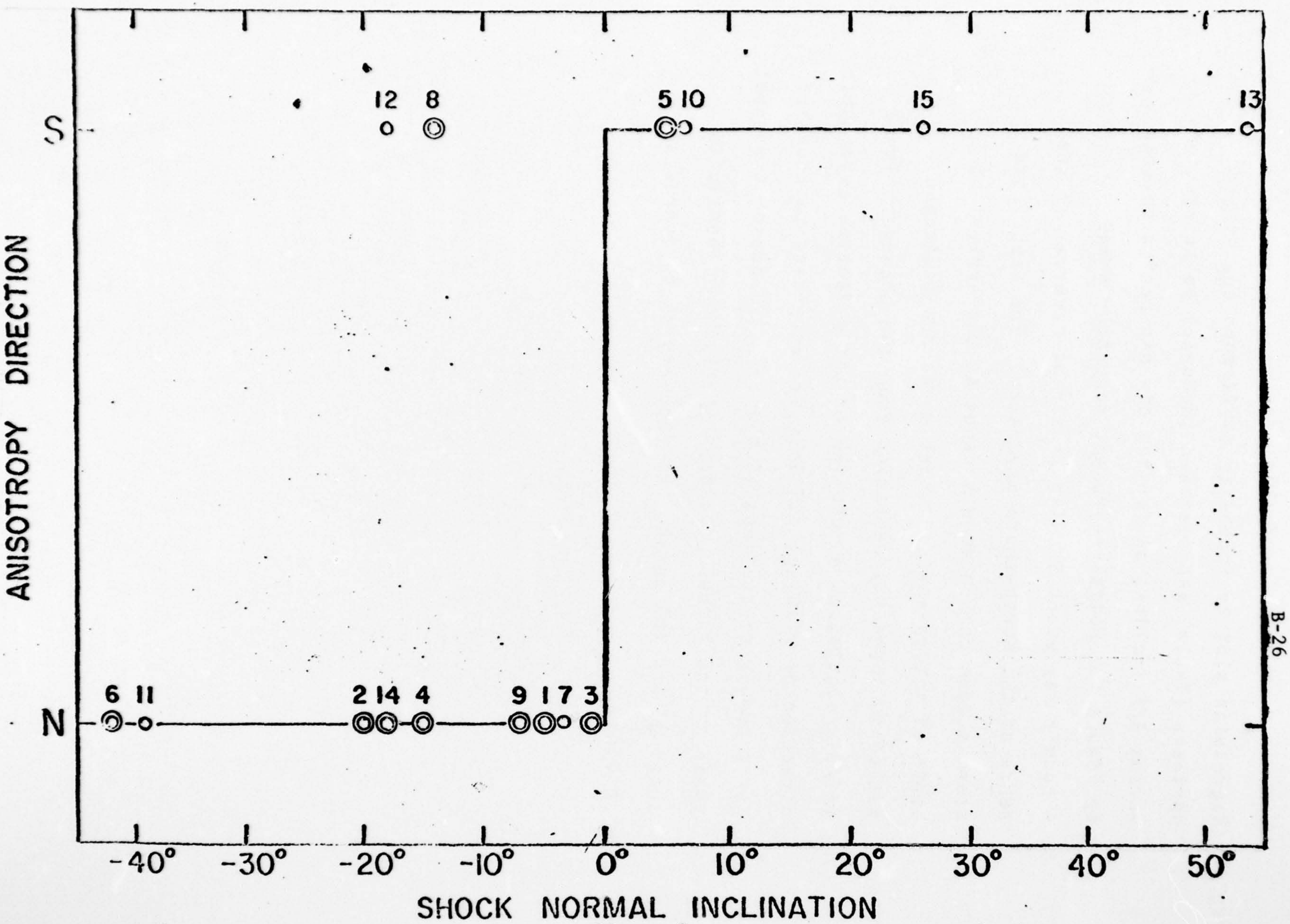
Fig. 3 Graphical representation similar to those in the two preceding figures, but with the inclination of the interplanetary magnetic field with respect to the ecliptic as abscissa. The circled points represent relatively stable field orientation during the epoch of north-south anisotropy. For the uncircled points, the inclination is opposite to that represented by the mean during more than 25% of the observed interval.

Fig. 4 Thule and McMurdo nucleonic intensities during an unusually long duration event in which the direction of north-south anisotropy remained constant for about six days. Despite this persistence, the IMF inclination displayed large fluctuations about the ecliptic plane.

Fig. 5 Regression plot of intensity difference Δ_{NS} between northern (Thule) and southern (McMurdo) polar stations versus IMF inclination for the six day period covered by Figure 4. Points represent four hour means.

Fig. 6 A cosmic ray event showing an abrupt reversal in the sense of the north-south asymmetry. The associated storm-sudden commencements denoting the arrival at earth of interplanetary shock waves are indicated.

Fig. 7 Nucleonic intensity deviation from the pre-event level $(\Delta I/I)_i$ plotted as a function of the effective asymptotic direction of viewing, sin $\lambda^*(\gamma,i)$, according to Equation 1, for a number of stations (Table 1); (a) during the onset phase of the Forbush decrease in Figure 6 (horizontal shading) and (b) during the recovery phase (vertical shading).


ANISOTROPY DIRECTION
S
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12
8
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15
13
6
11
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4
9
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7
3
-40°
-30°
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-10°
0°
10°
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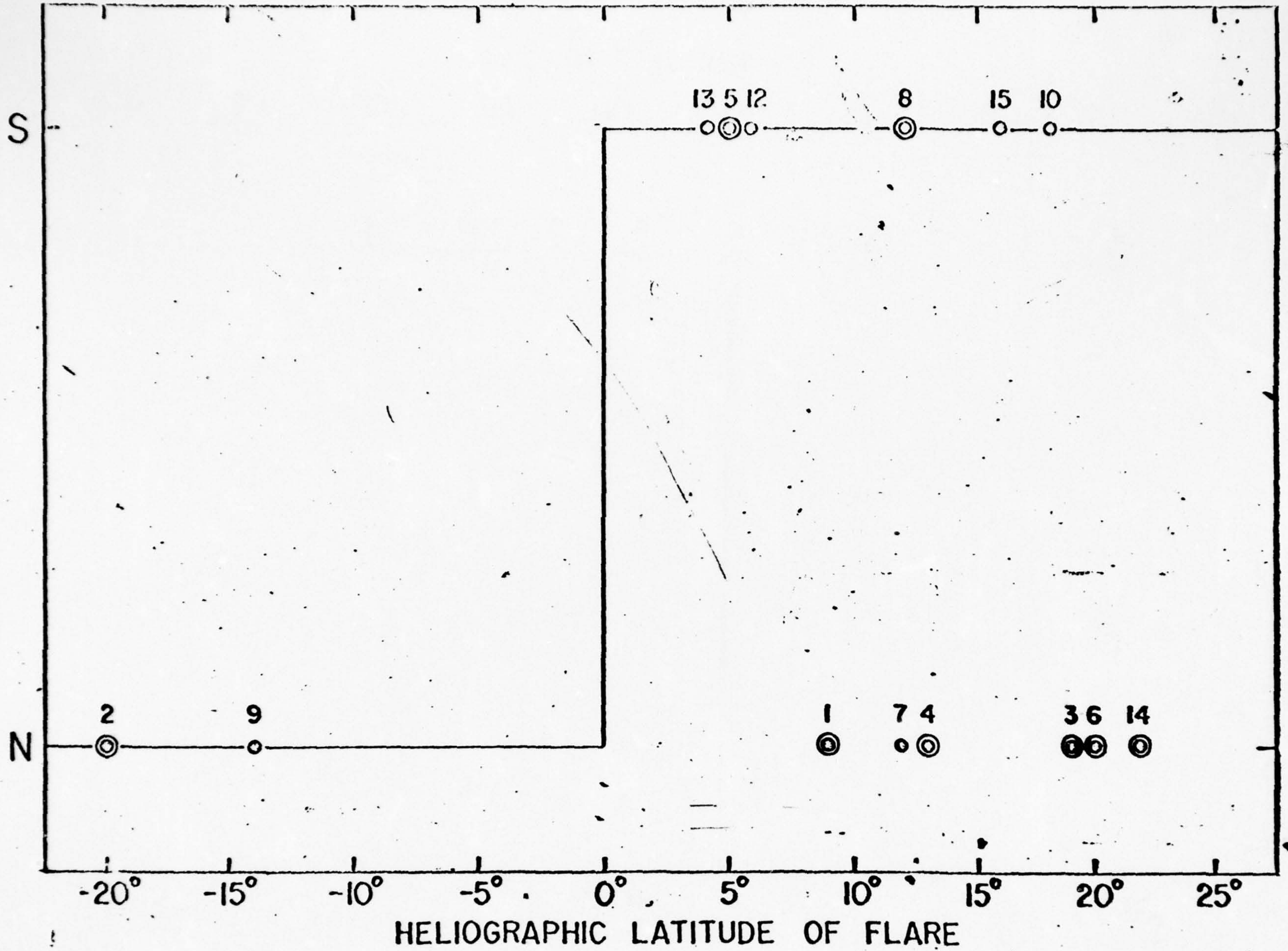
30°
40°
50°
SHOCK NORMAL INCLINATION

Figure 1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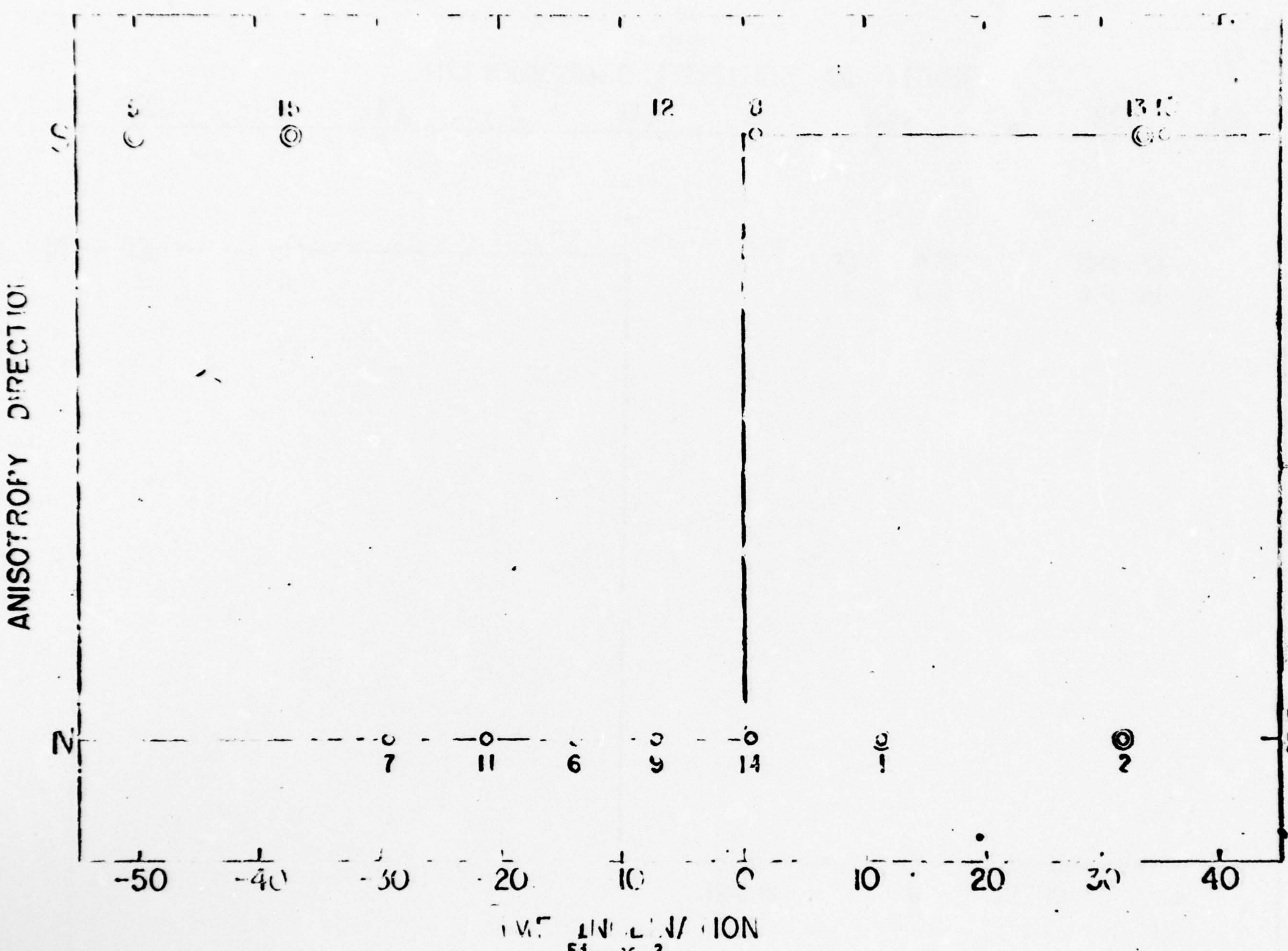
20°
25°
HELIOGRAPHIC LATITUDE OF FLARE

Figure 2


ANISOTROPY DIRECTION
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30
40
INCLINATION

Figure 3

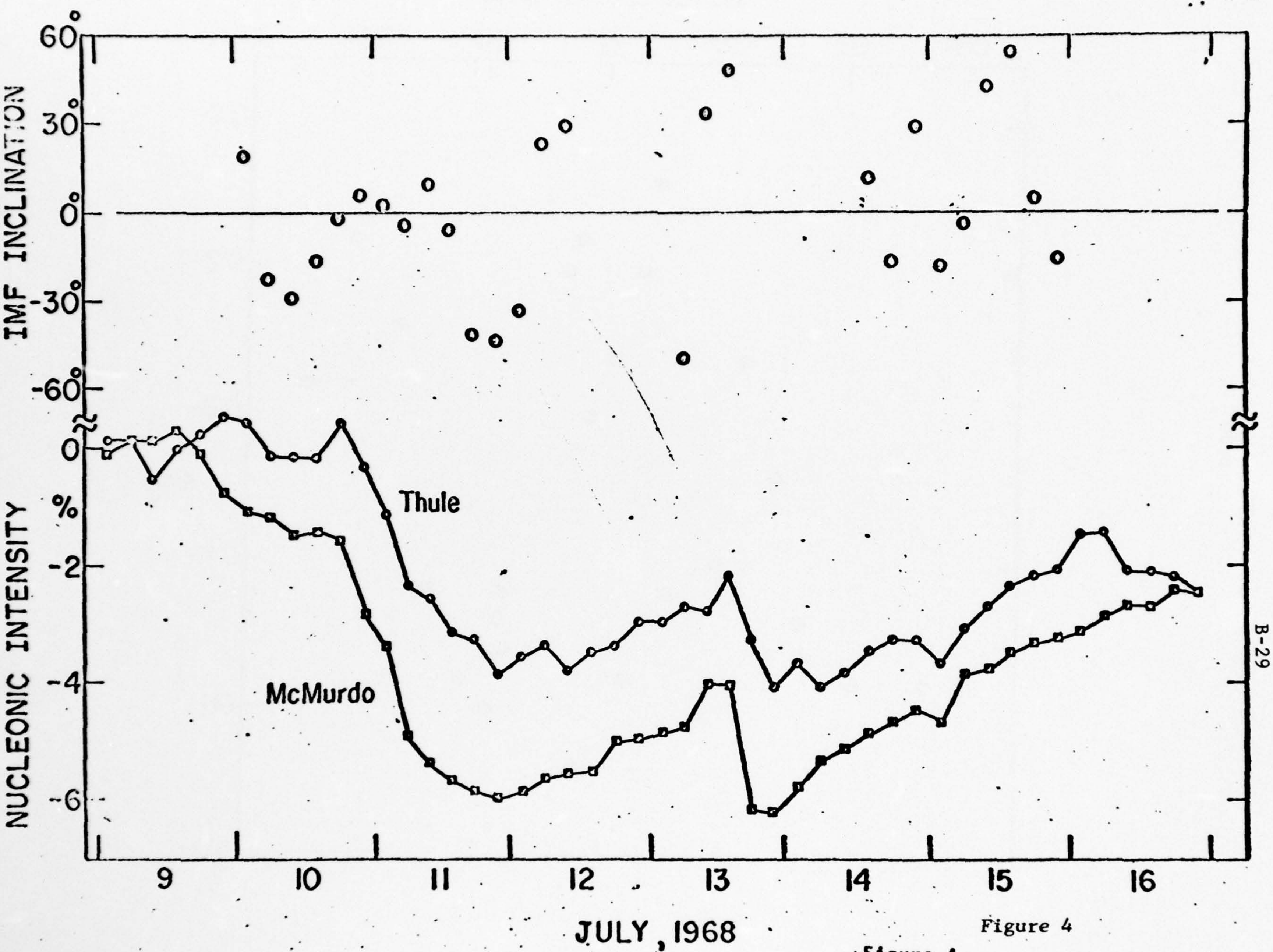


Figure 4

Figure 4

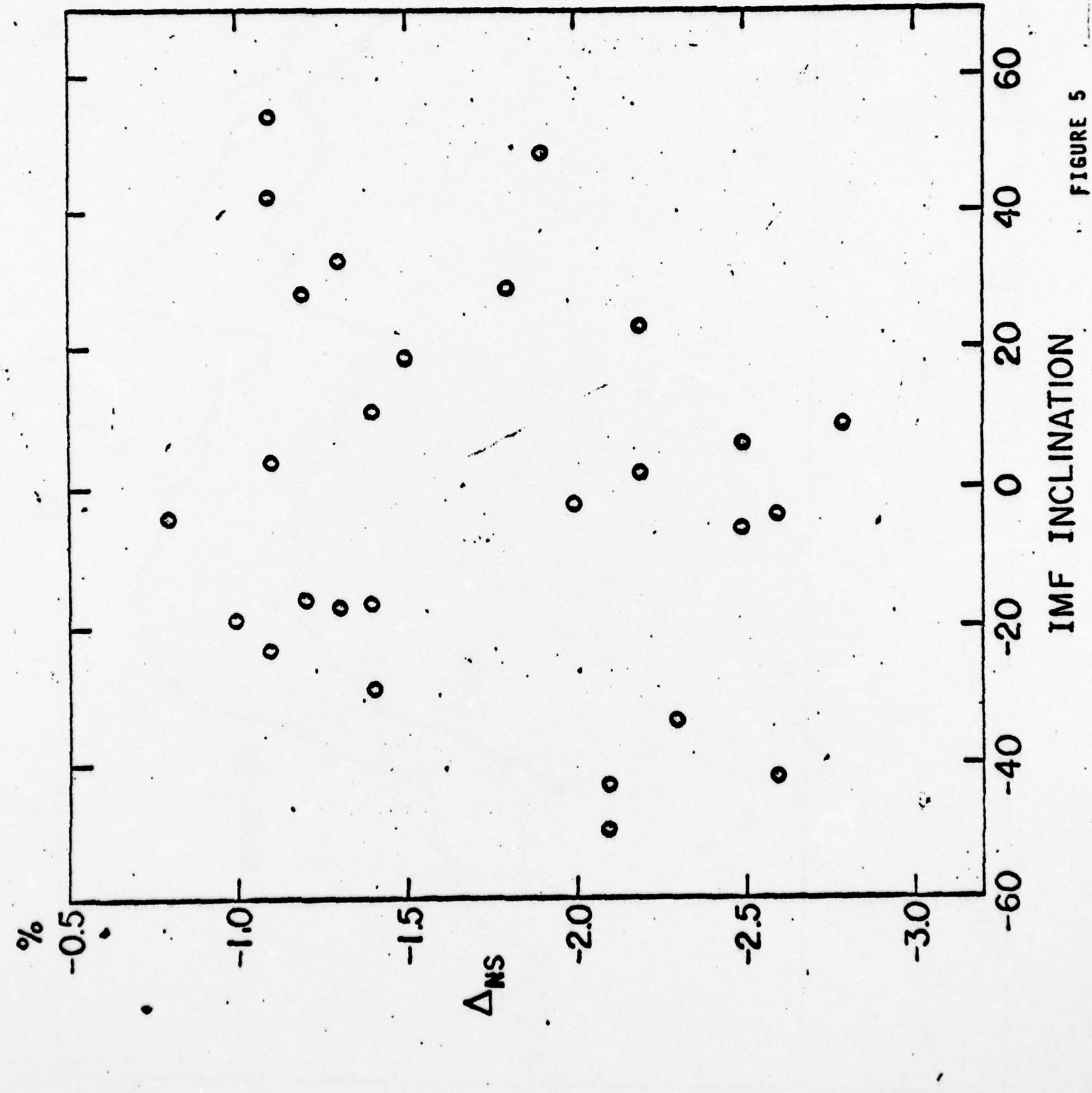
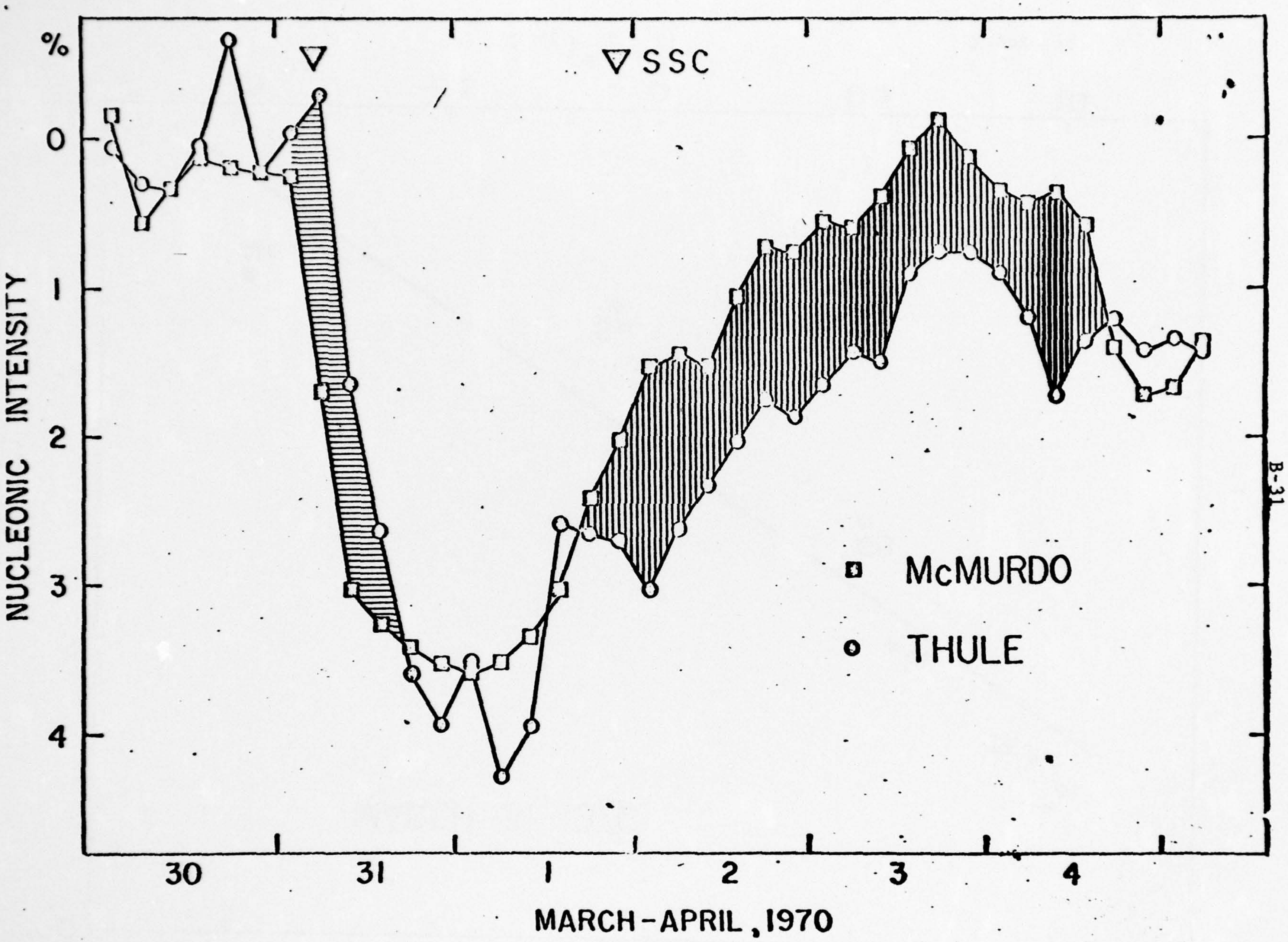


FIGURE 5


%
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1
2
3
4
NUCLEONIC INTENSITY
▽
▽ SSC
McMURDO
THULE
30
31
1
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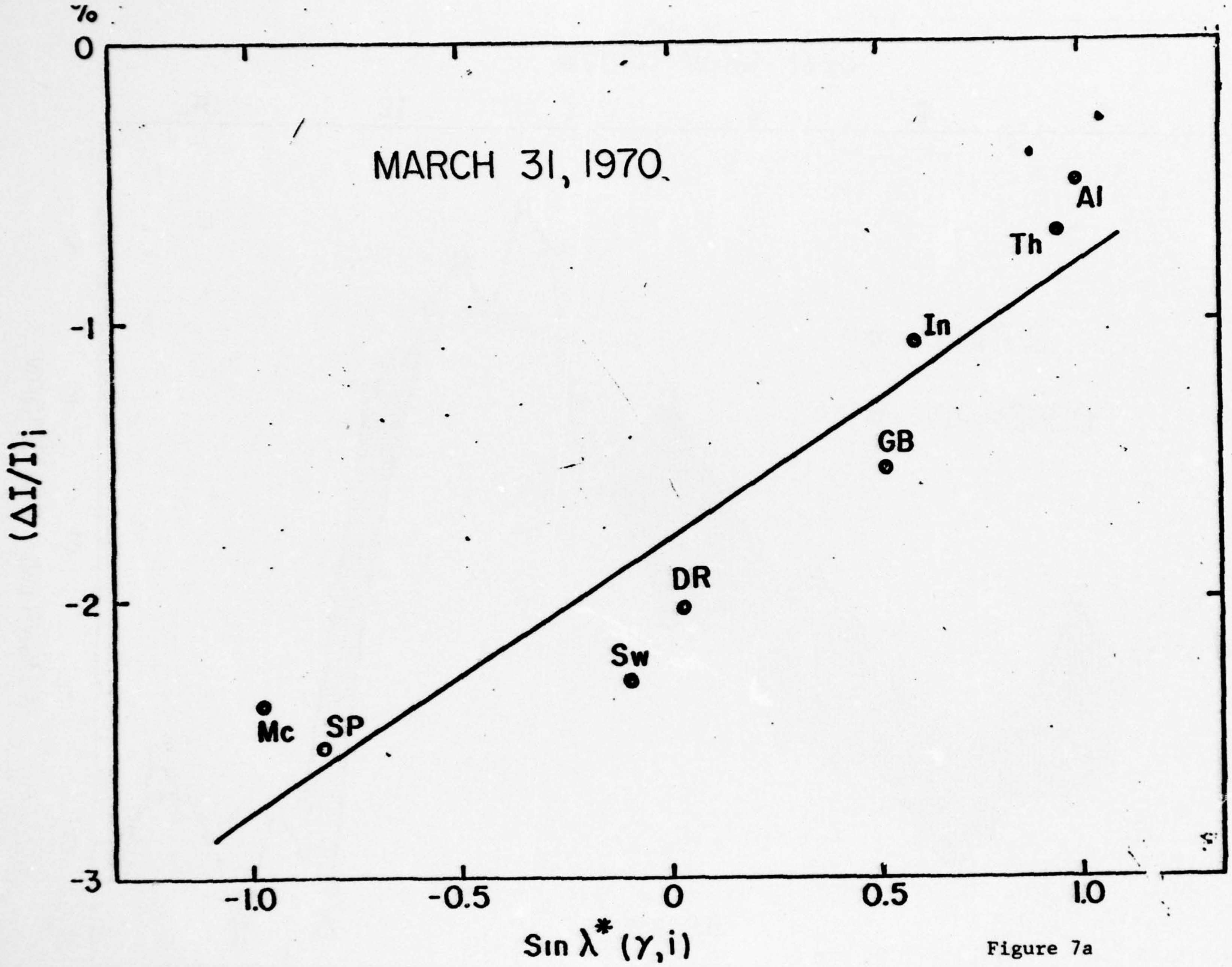
3
4
MARCH-APRIL, 1970

Figure 6


%
MARCH 31, 1970
$(\Delta I/I)_i$
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-1
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-1.0
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Th
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GB
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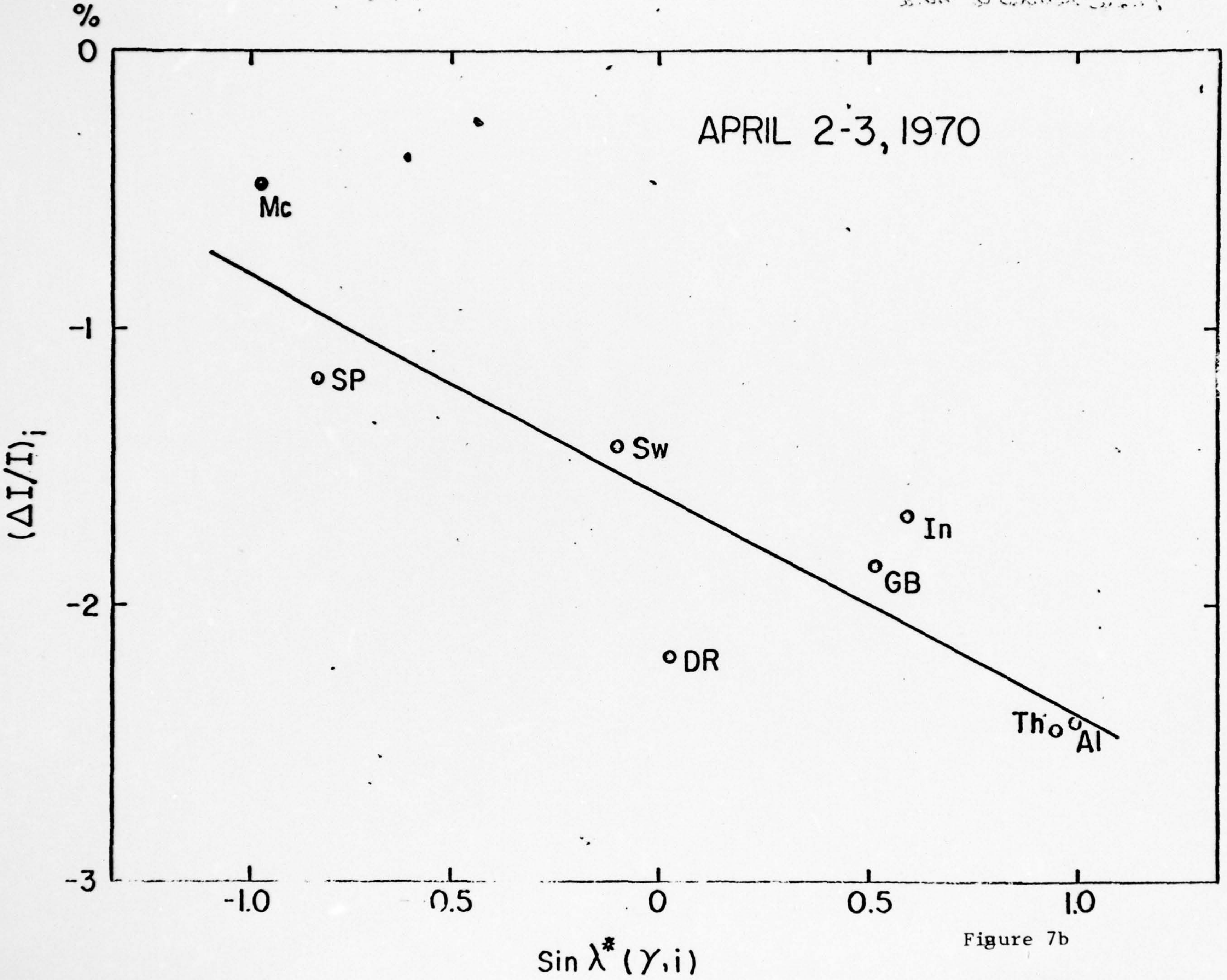
Figure 7a


APRIL 2-3, 1970
%
0
-1
-2
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(ΔI/I)ᵢ
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0
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Sin λ* (γ,i)
Mc
SP
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Al

Figure 7b

C-1

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Adiabatic Fermi Acceleration of Energetic Particles Between Converging Interplanetary Shock Waves

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The process of adiabatic acceleration of relativistic cosmic rays between two converging shocks, through the first-order Fermi mechanism, to which the unusual ground level event (GLE) of August 4, 1972, was attributed earlier is examined quantitatively, the nature of interplanetary shock waves and their propagation being taken into account. In the formal computational model the net evolution of the particle flux is determined by the balance between the acceleration of particles reflected from the moving shock waves and the loss of those particles which pass through the shocks. Comparison of the results of the theoretical calculations with the measurements has revealed that the observed abnormalities are a natural consequence of the proposed process. In particular, the computed times of maximum and the ratio of the enhancement at the mountain altitude South Pole station to that at the sea level polar neutron monitors are in good agreement, as is the rapid decay of the particle flux after the maximum. The initial growth of the nucleonic intensity appears to be delayed with respect to the prediction, but this discrepancy can be ascribed to the complexities in attempting to uniquely disentangle the GLE from the behavior of the total cosmic ray flux and to the late development of the particle reflection coefficient of the interplanetary shock fronts. An intensive search has revealed that the requisite conditions for observing GLE representing acceleration between converging shocks has occurred only twice over a period of two solar cycles, and on both occasions an abnormal GLE was in fact observed.

INTRODUCTION

Charged particle acceleration is an apparently universal feature of agitated plasmas as they relax to a more homogeneous equilibrium. It is generally thought that such acceleration in disturbed astrophysical plasmas is responsible for producing cosmic rays. The nearby occurrence of these processes in the solar system affords the only opportunity for a closeup view of their properties. Thus a full understanding of cosmic ray acceleration in the solar system has direct application to the general problem of the origin of cosmic rays.

It has become increasingly evident that the interplanetary plasma is a source of cosmic ray acceleration at low energies, particularly during disturbed times associated with increased solar activity [*Axford and Reid*, 1962, 1963; *Parker*, 1965; *Jokipii*, 1966; *Rao et al.*, 1967; *Lanzerotti and Robbins*, 1969; *Armstrong et al.*, 1970; *Ogilvie and Arens*, 1971; *Singer and Montgomery*, 1971; *Levy et al.*, 1974]. A recent observation by *Pomerantz and Duggal* [1973] of an unusual ground level enhancement (on August 4, 1972) in the relastivistic cosmic ray flux has been attributed by them [*Pomerantz and Duggal*, 1974*a*] to first-order Fermi acceleration of cosmic rays trapped between converging interplanetary shock waves. This suggests that even at relativistic energies some particle acceleration is an occasional feature of the solar wind.

In this paper we will explore quantitatively the process of adiabatic acceleration between two converging shocks through the first-order Fermi process, taking into account the nature of interplanetary shock wave propagation. We will then compare the results of the theoretical calculations with the observations. We will find that the peculiarities of the observations are a natural consequence of the adiabatic acceleration process in the solar wind.

Before proceeding with the analysis, we will discuss the main features of the cosmic ray observations and briefly review the relevant aspects of interplanetary shock wave propagation and particle trapping by hydromagnetic shock waves.

EXPERIMENTAL AND THEORETICAL CONSIDERATIONS

Cosmic ray observations. In a subsequent section, we discuss a search for instances of interplanetary acceleration of relativistic particles that covers the last 20 years. For the detailed discussion of the interplanetary acceleration phenomenon we will concentrate our attention on the very well studied ground level enhancement (GLE) which occurred on August 4, 1972 [*Pomerantz and Duggal*, 1973].

The main characteristics of this event are an approximately 10% increase in the count rate of neutron monitors at sea level polar stations having an effective atmospheric cutoff rigidity of about 1 GV and an approximately 30% increase at a mountain altitude polar station having an effective atmospheric cutoff which is fractionally lower (Figure 1). Stations with higher cutoff rigidities saw diminished enhancements, and the increase was not observed at stations with geomagnetic thresholds above about 1.2 GV. The rigidity spectrum of the particles producing the GLE is essentially indeterminable by the conventional procedure because of the very narrow range of rigidities over which it was observed and the vast uncertainties in detector response functions in the relevant energy region. However, an estimate of the lower limit of the spectral exponent γ obtained by considering the sensitivity of those stations at which the enhancement was not observed indicates $\gamma \gtrsim 9$ [*Lockwood et al.*, 1975]. Actually, if we take the data at their face value and consider the fluctuations in the recovery of FD-1 as indicated by high-rigidity cutoff detectors, a spectral index $\gamma \gtrsim 20$ is not inconsistent with the observations in the range between about 1.1 and 1.2 GV.

Bazilevskaya et al. [1973] have obtained spectral information at lower rigidities ($\lesssim 0.9$ GV) during short intervals of time before and after the ground level enhancement. Their measurements indicate a rigidity spectrum with $\gamma \approx 10$ [*Lockwood et al.*, 1975] in the range ~0.5–0.9 GV. In the

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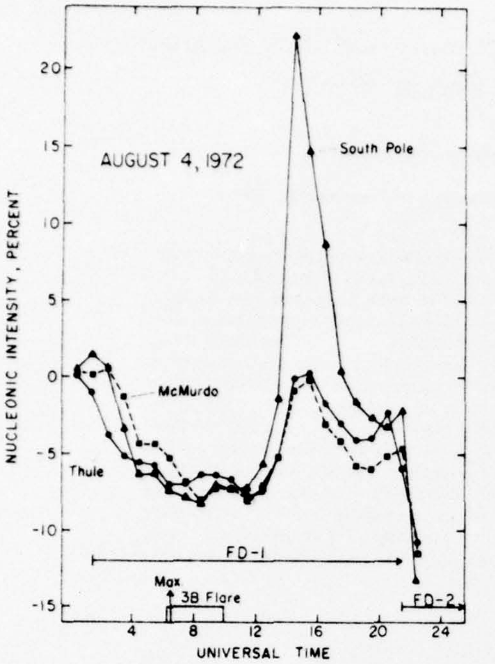

Fig. 1. Observations of the abnormal ground level enhancement on August 4, 1972, at the mountain altitude South Pole station and at two polar sea level stations, McMurdo, Antarctica, and Thule, Greenland. The points represent hourly mean percentage deviations from the quiet prestorm level at each location on August 3, 1972. [After *Pomerantz and Duggal*, 1974*a*].

absence of a rigidity dependent shock reflection coefficient for energetic particles the adiabatic acceleration process does not produce large changes in the spectral index of the particle flux. Thus the very soft spectrum of the particles producing the ground level enhancement reflects the steeply falling initial spectrum of the accelerated particles. In summary, it is clear that the spectrum steepened with increasing energy, γ increasing from a value of 9 or 10 below about 0.9 GV to greater than 20 by 1.2 GV.

The time dependence of the particle flux is shown in Figure 1. The enhancement peaks between 1400 and 1600 UT, 7 or 8 hours after the major solar activity which preceded it. The detailed morphology of this cosmic ray enhancement and of associated shock waves has been discussed by *Pomerantz and Duggal* [1974*a*].

Interplanetary shock waves. The feature of interplanetary shock wave propagation in which we are mainly interested here is the deceleration. Many questions about shock wave deceleration remain to be answered; several aspects of the problem have been surveyed by *Dryer* [1974].

Consider the relative speed of the fast overtaking shock S_2 on August 4 and the slower shock S_1 which preceded it, as illustrated schematically in Figure 2. The second fast shock was driven by a strongly decelerated blast wave [*Dryer et al.*, 1972] with an average sun-earth transit speed of about 2900 km s^{-1}, as reported earlier by *Pomerantz and Duggal* [1974*a*]. The initial speed of this shock was apparently in excess of 5500 km s^{-1}; by the time it had reached earth's orbit the speed had fallen to about 1000 km s^{-1}. The slower leading shock had an average sun-earth transit speed of about 1400 km s^{-1}. By the time such interplanetary shocks reach the orbit of earth their speeds fall to typically 500–700 km s^{-1} [see *Dryer*, 1974]. We will assume that the leading shock was moving at about 500 km s^{-1} as it passed earth and that the speed remained relatively constant over the next 15 or so hours which are of interest to us. On this basis we can estimate that during the ground level enhancement the leading shock was between 0.1 and 0.2 AU past earth and was moving at about 500 km s^{-1}. Altogether the relative closing velocity of the two shocks in question fell from an initial value of about 5000 km s^{-1} to about 500 km s^{-1} by the time the overtaking shock passed earth.

For the purpose of our later calculations it will be helpful to have a simple analytic expression for the motion of the second shock and for the relative closing velocity of the two shocks. The expression

$$V(R) = (5500 - 4550R) \text{ km s}^{-1}$$

where R is expressed in astronomical units, has the correct qualitative form for the deceleration, and is in reasonable agreement with the observations. It gives a sun-earth transit time of about 15.5 hours, in good agreement with the observed transit time for the overtaking shock. In the approximation that the leading shock is about 1/10 AU beyond earth, moving at 500 km s^{-1}, the closing velocity is

$$\Delta V(R) = (5000 - 4550R) \text{ km s}^{-1}$$

where R is the position of the overtaking shock. These approximations for the motion of the two shock waves will allow us to obtain simple analytic expressions for the evolution of the cosmic ray flux during the ground level enhancement.

Particle trapping. Magnetic field discontinuities reflect a fraction of the particles moving from the weak field side into the strong field. Such reflection of charged particles from hydromagnetic shock waves and similar magnetic field discontinuities has been examined in quantitative detail by several authors [*Wentzel*, 1964; *Rosenkilde*, 1965; *Hudson*, 1965, 1967]. *Parker* [1963] has explored the relationship of shock reflection of energetic particles to the Forbush decrease phenomenon. *Hudson* [1967] has calculated the reflection coefficient of a number of idealized shock transitions for an isotropic distribution of particles.

The particle reflection coefficient from a shock discontinuity depends on the magnetic field structure and on the pitch angle distribution of the particles. In general, the particles within a loosely defined loss cone pass through the magnetic discontinuity without reflection. The actual loss rate depends on the rate at which the loss cone is refilled. The loss cone is a function of the phase of the particle motion about the magnetic field lines as well as of the particle pitch angles. Thus reflection

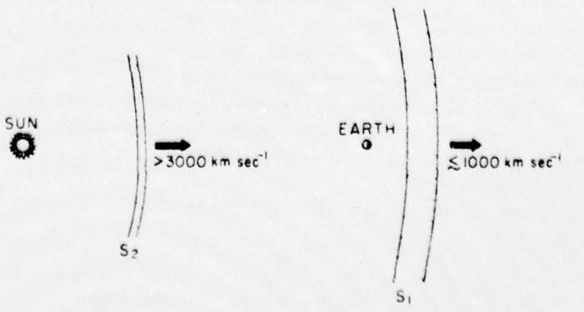

Fig. 2. Schematic diagram of the two interplanetary shocks on August 4, 1972.

C-3

from a shock discontinuity is analogous to reflection from a magnetic mirror but not completely equivalent to it.

Figure 3 depicts schematically two obvious possibilities for the topology of the magnetic field during the time of the August 4, 1972, GLE. Figure 3*a* shows distortions of the usual Archimedean spiral field under the influence of two successive blast waves. Particle confinement between the two shocks is possible because of the shell-like nature of interplanetary blast waves. Figure 3*b* shows the case in which flare ejecta driving the leading shock carries lines of force of the solar magnetic field to form a so-called Gold bottle. The front of the bottle moves away from the sun with the velocity of the leading shock. The dimensions of the bottle decrease at a rate given by the difference between the two shock velocities. In this second case, particle confinement is more efficient by crudely a factor of 2 because particles can be easily lost only once in a round trip between the two shocks rather than twice. We will eventually presume that the second case is applicable to the present discussion. This configuration is consistent with the limited available magnetic field data and provides efficient particle trapping.

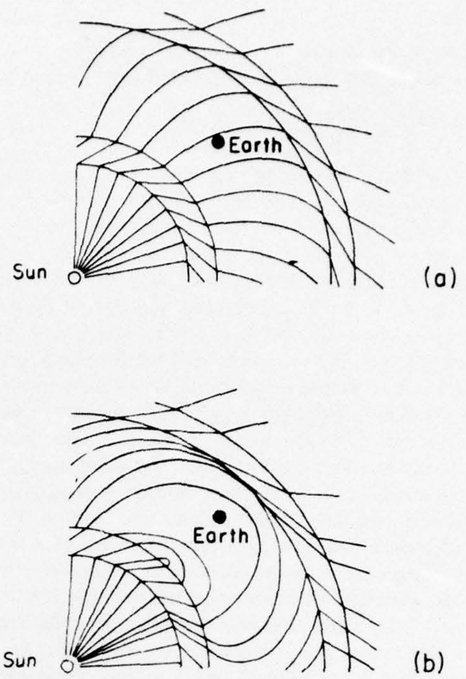

Fig. 3. Two alternative schematic representations of the topology of the interplanetary magnetic field at the time of the August 4, 1972, GLE. Although either could produce the particle confinement envisaged in the model, the more efficient Gold bottle configuration in 3*b*, which is consistent with the limited available magnetic field data, is presumed to be applicable to the present discussion.

It remains for us to estimate the particle reflection coefficient of the second shock discontinuity. In view of the complications and uncertainties involved in computing the reflection coefficient $(1 - k)$ from first principles it is preferable to take a crude phenomenological approach. The magnitude of the Forbush decrease produced by the second shock was about 20–25%. Making a very crude estimate of k on the basis of *Parker*'s [1963] analysis of the Forbush decrease, we estimate $k \sim 0.1$–0.15.

FORMAL COMPUTATIONAL MODEL

Acceleration of energetic particles trapped between two hydromagnetic shock waves or magnetic field discontinuities through the first-order Fermi process [*Fermi*, 1949] has been discussed previously for a variety of circumstances [*Parker*, 1958; *Axford and Reid*, 1962; *Wentzel*, 1963; *Jokipii*, 1966; *Hudson*, 1967]. In this section we will develop a simple model for the evolution of a population of relativistic particles trapped between two converging or overtaking interplanetary shocks. The net evolution of the particle flux is determined by the balance between the acceleration of particles reflected from the moving shock waves and the loss of those particles which pass through the shocks.

Particle transport equation. For highly energetic particles the acceleration by a moving shock wave is dominated by the reflection, cyclotron radius effects and gradient drifts along the shock electric field being generally less important. These latter effects, which dominate the motion of lower energy particles spending long times in the vicinity of the shock transition, have been recently discussed by *Sarris and Van Allen* [1974] and by *Chen and Armstrong* [1974]. In the present calculations we will include only the contribution to the acceleration due to reflection from the moving shock. The qualitative evolution of the particle flux is not changed by the inclusion of additional acceleration effects, which can be easily added should it become desirable to do so at a later time.

In order to avoid complications in the computational model we will consider particles moving along magnetic field lines between two semipermeable walls as shown in Figure 4. Suppose that at each encounter with a wall a particle has a probability k of passing through and being lost from the trapping region and hence a probability $(1 - k)$ of being reflected. If L is the distance between the walls, the rate of change of separation is $\Delta V = -dL/dt$. (Strictly, L is the distance along the field lines that a particle follows between its reflection points rather than the rectilinear distance between the shocks. While this may affect some numbers used in the subsequent calculations, it is easy to see that the conclusions are not changed in any substantial way.)

Assume for the purpose of computing the average albedo acceleration of the energetic particles that reflection preserves the component of motion parallel to the wall and reflects the normal component V_n. This assumption does not mirror the exact behavior of particles reflected from hydromagnetic shock fronts; indeed we will later use the fact that the reflected particles are scattered in pitch angle. However, the expression that we obtain for the average acceleration of the reflected relativistic particles is adequate for the present computation. The change in the total energy of a particle upon completion of one round trip between the closing walls is then $\delta E = 2E\Delta V V_n/c^2$ to first order in $(\Delta V/c)$. Since a particle makes

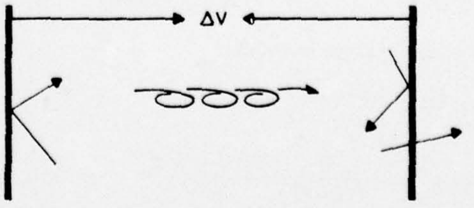

Fig. 4. Illustration of the basis for the computational model, in which the particles are assumed to move along magnetic field lines between the two semipermeable walls converging with velocity ΔV.

$(V_n/2L)\delta t$ round trips in a time δt, the rate at which a single particle gains energy through this first-order Fermi process is

$$\frac{dE}{dt} = \frac{-\mu^2}{L}\frac{dL}{dt}\frac{(E^2 - m^2c^4)}{E} \tag{1}$$

where μ is the pitch angle of the particle. Pitch angle scattering by magnetic field irregularities and at the shock transitions will keep the particle distribution nearly isotropic, and we will average (1) over an isotropic pitch angle distribution.

The details of the balance between the particles which are reflected and those which penetrate and are lost depend on the details of the shocked magnetic field. In the case where the magnetic field is essentially smooth except for the shock discontinuity itself the reflection is independent of rigidity in the broad range of rigidities corresponding to Larmor radii larger than the dimensions of the shock transition and smaller than the gross scale of the entire region of shocked solar wind. In the case of intermediate scale magnetic field irregularities the particle reflection coefficient may depend on rigidity. The reflection coefficient of real interplanetary shock waves is certainly rigidity dependent to some extent. However, the relatively small variation of Forbush decreases with rigidity [*Lockwood*, 1971] indicates that the reflection depends only weakly on rigidity. For this calculation we will presume a rigidity independent probability of loss k at each encounter with a shock discontinuity. If the spatial density of protons with energy E is $U(E)$, then the average rate at which these particles are lost from the trapping region is

$$Uv\langle\mu\rangle k/\alpha L \tag{2}$$

where v is the particle velocity and $\alpha = 1$ or 2 in the magnetic field configurations illustrated in Figures 3*a* and 3*b*, respectively.

Consequently, with $\langle\mu^2\rangle = \frac{1}{3}$ and $\langle\mu\rangle = \frac{1}{2}$, the transport equation for the trapped particle density is

$$\frac{\partial U}{\partial t} - \frac{1}{3L}\frac{dL}{dt}\frac{\partial}{\partial E}\left\{\frac{(E^2 - m^2c^4)}{E}U\right\} + \frac{1}{L}\frac{dL}{dt}U + \frac{kc}{2\alpha L}\frac{(E^2 - m^2c^4)^{1/2}}{E}U = 0 \tag{3}$$

EVOLUTION OF AN INITIAL PARTICLE POPULATION

Jokipii [1966] in a discussion of some aspects of particle acceleration at shock fronts has explored several properties of (3). Here we want to investigate the evolution of an initial population of energetic particles under adiabatic acceleration, and we will proceed directly to the solutions of (3).

In order to examine the basic properties of the particle equation we will first consider the case when $\Delta V = \Delta V_0$, where ΔV_0 is a constant. Multiplying (3) by $c(E^2 - m^2c^4)^{-3/2}$ and defining

$$F(E) = [c/E(E^2 - m^2c^4)^{1/2}]\,U(E) \tag{4}$$

we obtain after some manipulation

$$\frac{3L}{\Delta V_0}\frac{\partial F}{\partial t} + \frac{(E^2 - m^2c^4)}{E}\frac{\partial F}{\partial E} + \frac{3kc}{2\alpha\Delta V_0}\frac{(E^2 - m^2c^4)^{1/2}}{E}F = 0 \tag{5}$$

Defining the new variables

$$X \equiv \ln\,[(E^2 - m^2c^4)^{1/2}L^{-1/3}]$$

$$y \equiv -\ln\,[(E^2 - m^2c^4)^{1/2}L^{1/3}]$$

we obtain

$$\frac{\partial F}{\partial x} + \frac{3kc}{4\alpha\Delta V_0}e^{(x-y)/2}[e^{(x-y)} + m^2c^4]^{-1/2}F = 0 \tag{6}$$

whence

$$F(E) = \left[\frac{(E^2 - m^2c^4)^{1/2} + E}{mc^2}\right]^{3kc/2\alpha\Delta V_0} \cdot G[L^{1/3}(E^2 - m^2c^4)^{1/2}] \tag{7}$$

With $j(R, t) = R^2F$, where j is the omnidirectional particle flux and R is rigidity, (7) becomes

$$j(R, t) = R^2\left[\frac{(R^2 + m^2c^4)^{1/2} + R}{mc^2}\right]^{3kc/2\alpha\Delta V_0} \cdot G[L^{1/3}(t)R] \tag{8}$$

where G is an arbitrary function of its argument and will be chosen to satisfy an appropriate initial condition. In the following we will be concerned primarily with the integral flux above a cutoff rigidity R_c,

$$J(t) = \int_{R_c}^{\infty} j(R, t)\,dR \tag{9}$$

Ultimately, we will calculate the evolution of an initial distribution of energetic particles. But for the moment it is instructive to estimate the conditions necessary to produce a substantial increase in the particle flux. In general, cosmic ray spectra decline relatively rapidly with increasing rigidity, so that the largest part of the contribution to (9) is from particles with rigidities just above the threshold. Suppose that in the vicinity of the cutoff the initial particle distribution is a power law in rigidity

$$j(R, 0) = AR^{-\gamma} \tag{10}$$

Combining equations (8), (9), and (10), we obtain

$$J(t) = A\left[\frac{L_0}{L}\right]^{(\gamma+2)/3}\int_{R_c}^{\infty} R^{-\gamma} \cdot \left\{\frac{[(L/L_0)^{2/3}R^2 + m^2c^4]^{1/2} + (L/L_0)^{1/3}R}{[R^2 + m^2c^4]^{1/2} + R}\right\}^{3kc/2\alpha\Delta V_0} dR \tag{11}$$

where L_0 is the initial separation between the two shocks and $L = L_0 - \Delta V_0 t$. Consider the behavior of $J(t)$ for short times, such that $\epsilon \equiv \Delta V_0 t L_0^{-1} \ll 1$, by expanding (11) to first order in ϵ.

$$J(t) = A\frac{R_c^{-\gamma+1}}{\gamma - 1}\left[1 + \frac{(\gamma + 2)\epsilon}{3}\right] - \frac{Akc}{2\alpha\Delta V_0}\epsilon\int_{R_c}^{\infty}\frac{R^{-\gamma+1}}{(R^2 + m^2c^4)^{1/2}}\,dR + O^2(\epsilon) \tag{12}$$

It will suffice to consider the case when $R_c \gg mc^2$; then $J(t)$ grows if

$$\Delta V_0/c > 3k/2\alpha(\gamma + 2) \tag{13}$$

The points we will make here are unchanged by a more exact evaluation of the integrals in (12).

Equation (13) expresses the relation between the closing velocity of the shock waves, the particle spectral index, and the leakage rate of particles through the shock discontinuities that must be satisfied if the particle intensity is to continue increasing through the adiabatic acceleration process. All of the qualitative features of the ground level enhancement that we are discussing follow from this relation. As we have noted, γ is not changed substantially by the acceleration process. We will make the simplifying assumption that while the shock is propagating toward the earth, the reflection coefficient k remains unchanged.

Consider the values of k and α specified above: $k = 0.15$ and $\alpha = 2$. Then (13) yields $(\Delta V_0/c) > 0.1125\,(\gamma + 2)^{-1}$. We have suggested that in the August 4, 1972, GLE the spectral index between 1 and 1.2 GV was of the order of $\gamma \approx 15$. Consequently, ΔV_0 must exceed 2000 km s^{-1} in order for the particle acceleration to overcome the leakage losses, thereby permitting the flux to continue to increase. In this way the time of maximum in the ground level enhancement is determined by the deceleration of the closing velocity between the two shocks. Note also that as γ decreases, the critical value of $\Delta V_0/c$ increases. As was mentioned above, the observations indicate that the particle spectrum of the August 4 event is abruptly terminated, i.e., the spectral index γ increases with increasing rigidity. For such a spectrum, it is a natural consequence of (13) that the peak in the enhancement observed with detectors with lower cutoff rigidity should occur somewhat earlier. In the next section we will compute an idealized representation of the adiabatic acceleration process which explicitly includes the deceleration, and we will see that this temporal dispersion is small, of the order of an hour. The observations are not inconsistent with this predicted effect. Unfortunately, however, many complications prevent a conclusive test of the temporal dispersion. Among these are the large, rapid short-period fluctuations in the nucleonic intensity at different stations and the difficulty of accurately determining effective atmospheric cutoffs when the particle spectrum is an unknown function of rigidity.

Before proceeding to an idealized model for the adiabatic acceleration process, which we will compare with the observations, it is worth making two additional points. First, it is instructive to determine how the acceleration process affects the cosmic rays of galactic origin. The spectral index of these particles is $\gamma < 3$. Using (13), we find that in order to produce an appreciable increase in the galactic component of the cosmic ray flux, ΔV_0 must exceed 6500 km s^{-1}. This is higher than the sustained propagation speeds of interplanetary shock waves. Hence galactic cosmic rays do not enter into the present discussion in a substantial way.

The second point concerns the boundary conditions which have been implicitly assumed in our calculations. The boundary conditions come into our accounting for the loss of particles from the acceleration region. We have not taken similar account of the particles which may enter the acceleration region from the outside. It is straightforward to rewrite (3) to include leakage of some particles back into the acceleration region and to reduce it to a formal solution. The solutions are relatively complicated, particularly when shock wave deceleration is included explicitly. We will argue that for our present purpose the effect of particles leaking into the acceleration region from outside is negligible. The main consideration in this study is the morphology of the ground level enhancement: growth and decay of the particle flux and particularly the time of maximum. As we will see, the particle event represents an enhancement of about an order of magnitude in the flux of the steep spectrum particles. Thus during the main part of the event the energetic particle density is much higher in the acceleration region than outside. The number of particles leaking out will always be much larger than the number leaking in, and the uncertainty in the appropriate boundary condition can affect the net leakage rate by no more than about 10% during most of the event. This will have very little quantitative effect on our conclusions. The leakage of particles into the acceleration region must be taken more completely into account if when (13) is not satisfied, the magnitude of the enhancement is small.

Effect of shock wave deceleration. We now proceed to compute an idealized model explicitly including the deceleration of the shock waves to display the characteristics of the temporal intensity profile of the GLE. We will use the idealized decelerated closing velocity defined earlier, which can be written

$$\Delta V = -\frac{dL}{dt} = 5000\left(1 - \frac{R}{1.1}\right) \text{ km s}^{-1} \qquad (14)$$

where R is measured in astronomical units. Equation (14) is not intended to fit the sparse data covering the propagation of the shock waves that produced the August 4, 1972, GLE. In choosing a functional form for the shock velocities we have attempted only to represent the qualitative features of shock wave deceleration. We have therefore presumed a function which gives the observed sun-earth transit times and which permits a straightforward solution of the cosmic ray equation.

Rewriting (14) as

$$dL/dt = -V_0 L/L_0 \qquad (15)$$

where L_0 is the initial separation of the shocks (1.1 AU) and $L = L_0 - R$ and using (3), (4), and (15), we obtain

$$\frac{3L_0}{V_0}\frac{\partial F}{\partial t} + \frac{(E^2 - m^2c^4)}{E}\frac{\partial F}{\partial E} + \frac{3kc}{2\alpha V_0} e^{V_0 t/L_0} \frac{(E^2 - m^2c^4)^{1/2}}{E} F = 0 \qquad (16)$$

Defining $\xi = (V_0 t/3L_0)$ and $\zeta = \ln (E^2 - m^2c^4)^{1/2}$, we obtain from (16)

$$\frac{\partial F}{\partial \xi} + \frac{\partial F}{\partial \zeta} + \frac{3kc}{2\alpha V_0}\frac{e^{3\xi + \zeta}}{(e^{2\zeta} + m^2c^4)^{1/2}} F = 0 \qquad (17)$$

Writing $x = \xi + \zeta$ and $y = \xi - \zeta$, we obtain

$$\frac{\partial F}{\partial x} + \frac{3}{4}\frac{kc}{\alpha V_0}\frac{e^{2x+y}}{(e^{x-y} + m^2c^4)^{1/2}} F = 0 \qquad (18)$$

Solving (18) and expressing the solution in terms of particle rigidity R yield the general solution for the isotropic particle flux,

$$j(R, t) = G[L^{1/3}(t)R] \exp\left\{\frac{kc}{\alpha V_0}\frac{L_0}{L(t)} \cdot \left[\frac{(R^2 + m^2c^4)^{3/2}}{R^3} - \frac{3}{2}\frac{(R^2 + m^2c^4)^{1/2}}{R}\right]\right\} \qquad (19)$$

where again the function G is determined by the initial spectrum of the particles. To determine G, we will assume an initial spectrum which reflects the cutoff behavior outlined earlier. Consider the initial spectrum

$$j(R, 0) = AR^{-15R} \qquad (20)$$

with the slope increasing smoothly from a value of about 9 at

0.8 GV to about 20 at 1.2 GV. Combining (19) and (20), we obtain

$$j(R,t) = A\left[\frac{L(t)}{L_0}\right]^{-5[L(t)/L_0]^{1/3}R-2/3} R^{-15[L(t)/L_0]^{1/3}R-2}$$

$$\cdot \exp \frac{kc}{\alpha V_0}\frac{L_0}{L(t)}\left\{\frac{(R^2+m^2c^4)^{1/2}}{R^3}[m^2c^4-\tfrac{1}{2}R^2]\right.$$

$$-\frac{\{[L(t)/L_0]^{2/3}R^2+m^2c^4\}^{1/2}}{R^3}$$

$$\left.\cdot\left[m^2c^4-\frac{1}{2}\left[\frac{L(t)}{L_0}\right]^{2/3}R^2\right]\right\} \qquad (21)$$

We should point out that the analytic spectral form given by (20) ceases to be applicable below about 0.8 GV, where the spectral index would continue to decrease in disagreement with the observations. In this discussion we will confine our attention to rigidities near 1 GV, where this discrepancy betweeen the spectrum measured at lower rigidities and our analytic representation is of no consequence. With a 10 or 15% loss probability very few particles undergo a total rigidity increase of more than 0.1 or 0.2 GV.

Using (21) and (9), we compute the evolution of the integral particle flux above an appropriate cutoff. In constructing Figure 5, we have assumed a coupling coefficient $C(R) \propto R^3$ to represent the propagation through the atmosphere. It is well known that coupling coefficients are not well determined near the atmospheric cutoff; the approximation we have used here is satisfactory for our present purposes.

Recognizing the limitations inherent in the approximations used in constructing our model, we can compare Figure 5 directly with the neutron monitor observations. The curves show the computed evolution of the particle flux measured with ground-based neutron monitors having cutoffs at 0.9 GV and 1.1 GV, as indicated. Time is reckoned by assuming that the shock wave set out from the surface of the sun at 0630 UT, the time of maximum activity of the flare which produced the overtaking shock. We have neglected the relatively slight motion of the first shock wave during the interval shown. The computed time of maximum is just after 1400 UT. Since this is to be compared with the observed maximum at about 1500 UT, the computations are in good agreement with the observations. Of course, one can tune the computational model more finely by slightly adjusting the shock velocity, the reflection coefficient, or the spectrum, but greater precision is obviously not warranted at the present time.

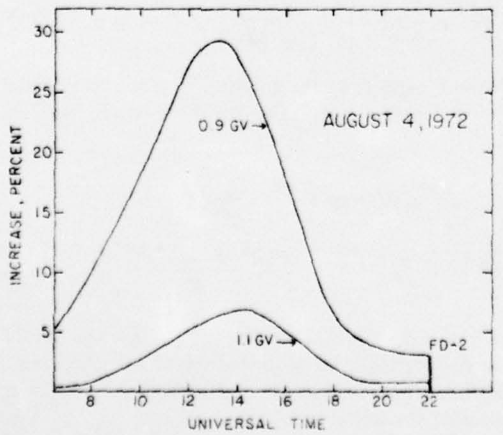

Fig. 5. Calculated evolution of the integral particle fluxes above two different effective atmospheric cutoffs, corresponding to the mountain (~0.9 GV) and sea level (~1.1 GV) polar stations in Figure 1.

We have chosen the nominal atmospheric cutoffs of 1.1 GV and 0.9 GV to compare the results of the calculations with polar observations at sea level and at high altitude, respectively (Figure 1). Note that the ratio of the computed maxima compares well with that of the observations.

The proper normalization of the curves in Figure 5 requires an estimate of the contribution of the ambient steep spectrum particles to the total solar particle flux prior to onset of the ground level enhancement arising from the adiabatic acceleration mechanism. This analysis is complicated by the complex conditions that prevailed at this time. In particular, the solar particle emission occurred during the initial phase of a Forbush decrease at a time characterized by significant anisotropy. Thus all of our attempts to evaluate objectively the intensity of the steep spectrum component prior to the rapid enhancement failed to lead to unambiguous results. Nevertheless, consideration of all relevant factors suggests that a contribution at the sea level polar stations by the steep spectrum solar component of the order of half a percent is consistent with the observations. With this initial intensity the calculations predict about an 8% enhancement, as is shown in Figure 5. Then with the initial spectrum (equation (20)), the calculations show that the initial contribution to the particle flux from the steep spectrum component above 0.9 GV should be about 5% (which also appears to be consistent) and the magnitude of the increase should be about 30%, which is in good agreement with the observations. Finally, we note that the rapid decay of the ground level enhancement is also in good agreement with the calculations. The particle flux has fallen to its preenhancement value some 3 or 4 hours before the following Forbush decrease, FD-2. This decrease in the particle flux, hours before the arrival of the second shock, is a direct consequence of rapid deceleration of the overtaking blast wave. When the closing velocity between the two shocks falls below 1500 or 2000 km s^{-1}, the leakage rate of particles from the confinement region becomes larger than the rate at which the flux is increasing as a result of adiabatic acceleration.

The computed growth phase of the ground level enhancement disagrees substantially with the observations. A detailed comparison is difficult because the observed particle flux is the sum of a decreasing galactic component due to the evolving first Forbush decrease and the increasing solar component. An unambiguous separation of these two components is not feasible. Nevertheless, it appears that the observed onset is delayed several hours with respect to the computed time of the initial enhancement. We suggest that this discrepancy is due to our necessarily idealized representation of the formation and propagation of interplanetary shock waves. As a particular example, consider the reflectivity, for energetic particles, of a quasi-spherical shock wave propagating outward in the Archimedean spiral magnetic field. Where the average field is nearly normal to the direction of shock propagation, no large magnetic discontinuity is produced. Thus near the sun the shock reflects very few particles, if any. It is only as the shock wave progresses further from the sun, where the obliquity of the field to the shock front increases, that the particle reflectivity becomes appreciable. On this basis, our estimate for the particle reflectivity of the shock discontinuity represents the average value during the transit from the sun to the earth. From the several hour duration of the delay, we can estimate that the shock front becomes well developed, with respect to cosmic ray reflection, at a few tenths of an astronomical unit from the sun. In addition, our one-dimensional model does not incorporate the effects of spherical or quasi-spherical geometry which characterizes the real solar wind. The spherical effects are most marked during the first few hours of propagation of the second shock, and they also depress the initial growth of the cosmic ray flux below that deduced from the one-dimensional computations.

Future attempts to produce fully quantitative models will have to take these and other additional effects into account. If highly detailed observations of particle enhancements due to adiabatic acceleration become available in the future, such models may serve as ground-based diagnostics of interplanetary shock wave formation and propagation. At present there are not enough observational data to warrent the construction of a more sophisticated model.

SEARCH FOR ADDITIONAL EVENTS

In the light of the above results we have conducted an intensive investigation to determine whether particle acceleration in interplanetary space was in fact observed in all cases where the requisite interplanetary conditions prevailed, as specified by our model. This study includes the entire period (1952–1973) for which continuous records of the arrival at the earth of low-energy solar particles is available.

The abnormal characteristics of the August 4, 1972, GLE provided an empirical basis for identifying particles accelerated by the converging shock mechanism [*Pomerantz and Duggal,* 1974*a*]. In particular, criteria for distinguishing protons accelerated to relativistic energies in interplanetary space from those normally accelerated in the immediate vicinity of the sun include [*Pomerantz and Duggal,* 1974*a*] (1) unusually long delay between the onset of flare activity and the GLE, (2) significantly steeper energy spectrum, (3) preexisting ambient low-energy solar protons, and (4) appropriate juxtaposition of two converging interplanetary shocks, the following shock moving appreciably faster than the leading shock. Starting from the third criterion, we have studied all periods during which either significant polar cap absorption was observed [*Bailey,* 1964; *Pomerantz and Duggal,* 1974*b*; A. J. Masley, private communication, 1973] or measurable fluxes of energetic solar particles were reported [*Van Hollebeke et al.,* 1974].

Since geomagnetic storm sudden commencements (ssc) are generally regarded as signatures of the impact of shock waves on the magnetosphere, these data (i.e., ssc recorded by ≥10 observatories) have been used to identify the shock pairs. It should be remarked here that several authors have suggested that some ssc are attributable to tangential discontinuities rather than shock waves [see, e.g., *Taylor,* 1969; *Chao and Lepping,* 1974]. This dual interpretation does not seriously affect the present study, since both shock front and tangential discontinuities are acceptable in our model. The physical causes of sudden impulses (si^+, si^-) are more complicated, although some of these can be produced by tangential discontinuities (see *Burlaga and Ogilvie* [1969] and references therein); hence in this study the shock information was derived solely from ssc data.

For the present purposes a double shock has been defined as a pair of shocks with onset times (T_1, T_2) at the earth that satisfy the following criterion:

$$\Delta T = T_1 - T_2 \qquad 60 > \Delta T > 1 \text{ hour}$$

The lower limit $\Delta T > 1$ hour recognizes that only hourly cosmic ray data are considered in this study; on the other hand, the upper limit is rather arbitrary since of course the distance between any two shocks depends on the velocities of the individual shocks. In general, this limit allows distances of the order of 1 AU between the leading and following shocks.

The results are summarized in Table 1. The ΔV criterion was satisfied when the velocity of the following shock S_2 unambiguously exceeded that of the leading shock S_1, as required for the mechanism to operate.

Our theoretical model requires a significant velocity difference between the following and the leading shocks (equation (13)). Direct satellite observations of shock velocities near the earth are available in only two cases. For the remaining events the mean velocities of the shocks between the sun and the earth were estimated by associating the ssc with solar flare observations. As Table 1 shows, there was an unambiguous determination of a significant relative velocity between the leading and following shocks in two events. In both cases, shock-accelerated particles were observed, and the relevant phenomenology has already been reported by *Pomerantz and Duggal* [1974*a*].

It is also important to investigate the converse question, i.e., have any of the previously recognized GLE been erroneously ascribed to direct particle acceleration at the sun? An up-to-date summary of all GLE observed since the start of systematic monitoring in 1936 has recently been published [*Pomerantz and Duggal,* 1974*b*]. Reexamination of these events has shown that the time delay between the onset of the flare and the onset of the relativistic particle increase is abnormal for only two events, namely, July 17, 1959, and August 4, 1972, which have been discussed earlier. Furthermore, studies of

TABLE 1. List of All Shock Pairs That Occurred Between 1952 and 1973 at Times When Low-Energy Solar Particle Fluxes Were Observed at the Earth

Event No.	Year	Leading Shock S_1 Date	Leading Shock S_1 UT	Following Shock S_2 Date	Following Shock S_2 UT	ΔT, hours	ΔV Criterion Satisfied	GLE Observed
1	1957	Sept. 2	0314	Sept. 4	1300	58	no	no
2	1959	July 15	0803	July 17	1638	57	yes	yes
3	1960	April 5	1300	April 7	1511	50	no	no
4	1960	April 27	2020	April 30	0132	53	no	no
5	1960	April 30	0132	April 30	1213	11	no	no
6	1968	Oct. 31	0859	Nov. 1	0916	24	no	no
7	1969	Feb. 27	0307	Feb. 28	0423	25	no	no
8	1972	Aug. 4	0220	Aug. 4	2054	19	yes	yes

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several workers have shown that except for these cases a diffusion model for the propagation of particles between the sun and the earth predicts the intensity versus time profiles of all major GLE observed with neutron monitors [*Meyer et al.*, 1956; *Duggal et al.*, 1971; *Lockwood and Shea*, 1961; *Pomerantz et al.*, 1961; *Dorman*, 1963; *Burlaga*, 1967, 1970; *Lockwood*, 1968; *Baird et al.*, 1967; *Fisk and Axford*, 1969; *Duggal and Pomerantz*, 1972, 1973*a*, *b*].

SUMMARY AND CONCLUSIONS

We have reviewed the main features of the anomalous cosmic ray ground level event that occurred during a widely studied remarkable series of solar, interplanetary, and terrestrial disturbances in August 1972 [*Coffey*, 1973]. In particular, we have examined quantitatively the original hypothesis by *Pomerantz and Duggal* [1974*a*] that the August 4 GLE resulted from adiabatic Fermi acceleration of cosmic rays trapped between a slowly moving interplanetary shock wave and a rapidly moving second shock which was overtaking the first during that time.

Several authors [*Bazilevskaya et al.*, 1973; *Lockwood et al.*, 1975] have proposed alternatively that exotic cosmic ray containment and propagation effects were responsible for the peculiar nature of the August 4 event. However, on the basis of the present calculations, it is clear that such effects need not be postulated. In the absence of a quantitative treatment of the proposed exotic mechanism, further discussion is not warranted at the present time.

Comparing computations based on the present simplified representation of relativistic particle acceleration, by overtaking interplanetary shock waves, with the observations, we find substantial agreement. The computed time of maximum particle flux agrees within an hour with the observed maximum in the ground level enhancement. The computational ratio of the maximum amplitude of the enhancement at the mountain altitude south polar neutron monitor to that of the sea level polar monitors agrees well with the observations. The rapid decay of the particle flux after the maximum and substantially before the following Forbush decrease is also a point of good agreement between the computations and observations. We note that the observed initial growth of the nucleonic intensity is delayed with respect to the computations. This delay is apparent despite the complexities involved in trying to uniquely disentangle the ground level enhancement from the behavior of the total cosmic ray flux. The several reasons for this discrepancy between the observations and the computations have been discussed. We have suggested that the predominant factor is the late development of the particle reflection coefficient of interplanetary shock fronts. This points up the possibility of using detailed models of such particle events as a diagnostic of interplanetary shock wave propagation.

Acceleration of relativistic particles by the mechanism discussed in this paper is a relatively rare phenomenon. In fact, an extensive search has revealed that the requisite conjunction of conditions for observing ground level enhancements representing acceleration by reflection between converging shocks has occurred only twice over a period of two solar cycles, and on both occasions GLE were in fact observed. Finally, it is worth mentioning that this observed solar wind acceleration process makes a negligible direct contribution to the overall galactic cosmic ray flux in the solar system. Some galactic cosmic rays may be accelerated in this way elsewhere on a far grander scale.

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