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Solar Protons and Magnetic Storms in July 1961

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Abstract. The State University of Iowa's satellite Injun 1 (1961₀₂) was launched at 0422 UT on June 29, 1961, and is in an orbit of 67° inclination with apogee 998 km and perigee 881 km. Among the Injun instruments are silicon p-n junction detectors sensitive to protons with energy between 1 and 15 Mev, and a Geiger counter sensitive to protons of energy above 40 Mev. These units detected solar protons during the period of considerable solar activity extending from July 11 to 28, an epoch containing twelve flares of class 2 or 3 and six major magnetic storms that can be divided into four distinct solar proton events. In this period the proton intensity varied widely, with a maximum unidirectional flux of 33,000 particles/cm² sec ster for 1- to 15-Mev protons occurring during the storm of 1115 UT, July 13, and a maximum omnidirectional flux of 900 particles/cm² sec for protons of energy above 40 Mev in the storm of 1121 UT July 13. In general, the energy spectrum varied from storm to storm and within a single storm. The temporal and spatial characteristics of the solar proton flux are correlated with details of geomagnetic storms and other solar-terrestrial phenomena such as polar-cap absorption. Some 1- to 15-Mev protons leak out of the main solar stream and enter the geomagnetic field many hours before the onset of a magnetic storm. These particles are observed only on magnetic shells of L with values between 4.8 and 6.1 earth radii, the range corresponding to the undisturbed geomagnetic cutoffs. A large influx of 1- to 15-Mev protons occurs during the last part of the initial phase of the storm and during the early part of the main phase, indicating their previous containment in the storm-producing plasma. A marked equatorial shift of the cutoff latitude occurs during the main phase of the storm. A sharp decrease in the flux in the main phase is followed by a slower exponential decay with a relaxation time of about one day for the 1- to 15-Mev particles. This decay begins after the peak of the main phase and extends through the recovery period of the storm, during which the geomagnetic cutoff gradually returns to its prestorm value. The possibility that the 1- to 15-Mev particles are geomagnetically trapped during the exponential decay is discussed. Considerable fluxes of protons with energy above 40 Mev were observed during only one of the four solar proton events reported. The storm-time cutoffs of these protons occurred at L values lower than the corresponding cutoffs observed with the 1- to 15-Mev protons. These observations and those reported for similar events by other workers are compared in detail. An over-all picture for such events is proposed.

1. INTRODUCTION

In recent years a considerable body of data has been accumulated concerning solar cosmic rays, their composition, energy spectrums, and time dependence. These characteristics have been established by studies of ionization pro-

duced in the lower ionosphere [Bailey, 1959, 1962; Little and Leinbach, 1958; Reid, 1961; Reid and Leinbach, 1959] and by direct observation of solar particles [Anderson, 1958; Anderson et al., 1959; Anderson and Enemark, 1960; Biswas and Freier, 1961; Brown and D'Arcy,

TABLE 1. Characteristics of Detectors

Detector	Symbol	Omnidirectional Characteristics			Directional Characteristics*		
		Shielding	Detectable Protons	Geometric Factor cm ²	Shielding	Detectable Protons	Geometric Factor cm ² ster
p-n junction detector	PNA	minimum of 3.5 g cm ⁻² of Al	55 to 57 Mev if incident normal to the depletion layer. Detectable energy range varies with angle of incidence; lower limit always >55 Mev.	Complex and energy dependent	2.6 mg cm ⁻² of mylar	1.4-17 Mev	2.8 × 10 ⁻²
p-n junction detector	PNB				Background monitor for PNA		
p-n junction detector	PNC				2.6 mg cm ⁻² of mylar	1.6-11 Mev	2.8 × 10 ⁻²
p-n junction detector	PND				Background monitor for PNC		
Spectrometer background							
Geiger counter	SpB	3.5 g cm ⁻² of Pb	>40 Mev	0.14	—	—	—
213 Geiger counter	213 GM	5 g cm ⁻² of Pb	>50 Mev	0.14	1.2 mg cm ⁻² of mica	>0.5 Mev	1.4 × 10 ⁻²

* The relative directions of the open-ended detectors are as follows: PNA points at right angles to both PNC and 213 GM, and PNC and 213 GM point at 135° to one another.

1959; Charakhchian *et al.*, 1960; Davis *et al.*, 1961; Earl, 1961; Freier *et al.*, 1959; Ney *et al.*, 1959; Rothwell and McIlwain, 1959; Van Allen and Lin, 1960; Winckler, 1960; Winckler, Bhavsar, Masley, and May, 1961; Winckler and Bhavsar, 1960; Yoshida and Wada, 1959]. It is of particular interest here that the behavior of the protons near the earth can be correlated with some details in related geomagnetic storms [Winckler, Bhavsar, and Peterson, 1961].

The purpose of this paper is to report satellite observation of solar cosmic rays in a low energy range, to make comparisons with other observations, and to present detailed data concerning the time dependence of these particle fluxes and their relation to solar, geomagnetic, and associated phenomena. These data make it possible for us to infer certain relationships between the various events observed, and to propose a general picture for the sequence of such events.

2. EXPERIMENTAL APPARATUS

The observations reported here were made by means of several particle detectors carried on the Injun 1 satellite. This satellite was designed and built as a radiation research vehicle at the State University of Iowa under the direction of

one of us (B. J. O'Brien). Injun 1 and the Naval Research Laboratory satellite, Solar Radiation 3 (SR 3), were launched at 0422 UT on June 29, 1961, under the direction of the Applied Physics Laboratory. An orbit was achieved of inclination 66.8°, with apogee altitude 998 km, perigee altitude 881 km, and period 104 minutes. Unfortunately, there was one failure in the launch process: the separation mechanism between Injun and SR 3 failed. As a result, the two payloads are now orbiting together as satellite 1961₀. The major effect of the nonseparation on Injun is that the planned magnetic orientation of the satellite cannot be achieved. It had been intended that the satellite should orient magnetically in the manner achieved previously by several Navy navigational satellites [Fischell, 1961a, b]. To this end, Injun contains a permanent magnet (6000 ergs/gauss) plus appropriate spin and oscillation damping rods. Calculations indicated that after initial damping the angle between the satellite's magnetic axis and the earth's field should never exceed a few degrees. The basis of these calculations was destroyed by the failure of the Injun-SR 3 separation mechanism. The larger, heavier SR 3 contributes significantly to the over-all moment of inertia and its magnets add also to the over-all magnetic

moment in such a way that a sluggish, rolling tumbling motion occurs with a period of several minutes. As far as Injun is concerned, the practical results of this whole situation have been the effective loss of one detector, the auroral photometer, and a very considerable complication in data reduction.

Although Injun 1 has a mass of only 40 lb, it contains 14 radiation detectors of various types, along with a digital data-handling system, transmitter, power system, and command receiver. The satellite has been described briefly by Pieper [1961a, b] and in detail by O'Brien and Whelpley [1962]. The present report deals only with some observations made in July 1961 by the APL package of four silicon p-n junction detectors, the spectrometer background Geiger counter, and the 213 GM module. The characteristics of these detectors are given in Table 1.

The spectrometer background Geiger counter is part of the magnetic electron spectrometer developed by Laughlin (unpublished). This device has recently been described elsewhere [O'Brien *et al.*, 1962].

The APL proton detector unit consists of two pairs of detectors mounted so that the pair consisting of PNA and PNB looks out at right angles to the direction seen by the pair PNC and PND. All four detectors are symmetrically mounted in an aluminum housing so that they are essentially identically shielded. The shielding is a complicated function of direction for a given detector, but in no direction is it less than 3.5 g cm^{-2} Al. Small Alnico 5 permanent magnets are mounted over the detectors to keep electrons of less than 250 kev from reaching them. Detectors PNA and PNC each have an opening of 0.21 ster through their magnets; detectors PNB and PND have their openings filled by 3.5 g cm^{-2} aluminum plugs so as to serve as background monitors for PNA and PNC. Each detector is 4 mm by 4 mm in area. The four detectors are made from the same resistivity silicon, they are operated at 18 volts bias, and they have depletion (plus diffusion) layers of 166 ± 12 microns. The proton energy thresholds for the detectors (with no absorbers) are set electronically at 0.92, 1.07, 1.28, and 1.00 Mev for PNA, PNB, PNC, and PND, respectively. Since the detectors are light-sensitive, PNA and PNC are covered by 2.6 mg cm^{-2} of heavily aluminized mylar foil. The thickness of this foil plus the

no-absorber threshold sets the lower limit of energy sensitivity at 1.4 Mev for PNA and 1.6 Mev for PNC. The upper limit is determined by the energy of a proton whose dE/dx multiplied by the thickness of the depletion layer just equals the no-absorber threshold (plus the energy loss in the mylar foil). The detectors were calibrated by means of high-energy protons obtained from the $d(\text{He}^3, p) \text{He}^4$ reaction at the University of Maryland Van de Graaff generator. The detectors are not temperature-compensated; the upper and lower limits to the energy of detected protons vary by about 30 per cent from -25°C to $+25^\circ\text{C}$. Although no temperature measurement of the p-n junction detectors is made in Injun, five other temperatures in the payload are measured and from these we can establish the p-n detectors' temperature to about $\pm 5^\circ\text{C}$. We estimate that during the observations reported here PNA responded to protons within the energy interval (1.4 ± 0.2) Mev to (17 ± 3) Mev, and PNC responded to protons in the energy range (1.6 ± 0.2) Mev to (11 ± 2) Mev. For brevity, both ranges are referred to throughout as 1-15 Mev.

The two background detectors PNB and PND are provided with built-in α -particle sources that give them mean counting rates of 30 and 24 per second, respectively. These counting rates are periodically checked from flight data when Injun is in the slot between the radiation zones.

The arrangement of the p-n detectors is such that they are insensitive to electrons. An electron incident normal to the depletion layer of an active detector and having a path length equal to the depletion layer thickness would have an energy of only 160 kev, well below the electronic bias of about 1 Mev. An electron of energy greater than 1 Mev has a small probability of scattering in such a way as to spend its entire path in the depletion layer. Assuming single nuclear scattering for 1-Mev electrons in a silicon layer $166\text{-}\mu$ thick, an incident flux of 10^5 electrons/cm² sec ster would produce about 2 counts/sec. Typical intensities of such electrons at Injun altitude are less than one per cent of this flux [O'Brien *et al.*, 1962]. On the other hand, an electron incident through the shielding would have to penetrate at least 3.5 g cm^{-2} Al and therefore would require a minimum energy of about 7 Mev to produce a count. Pileup of low-energy electrons in the active detectors is

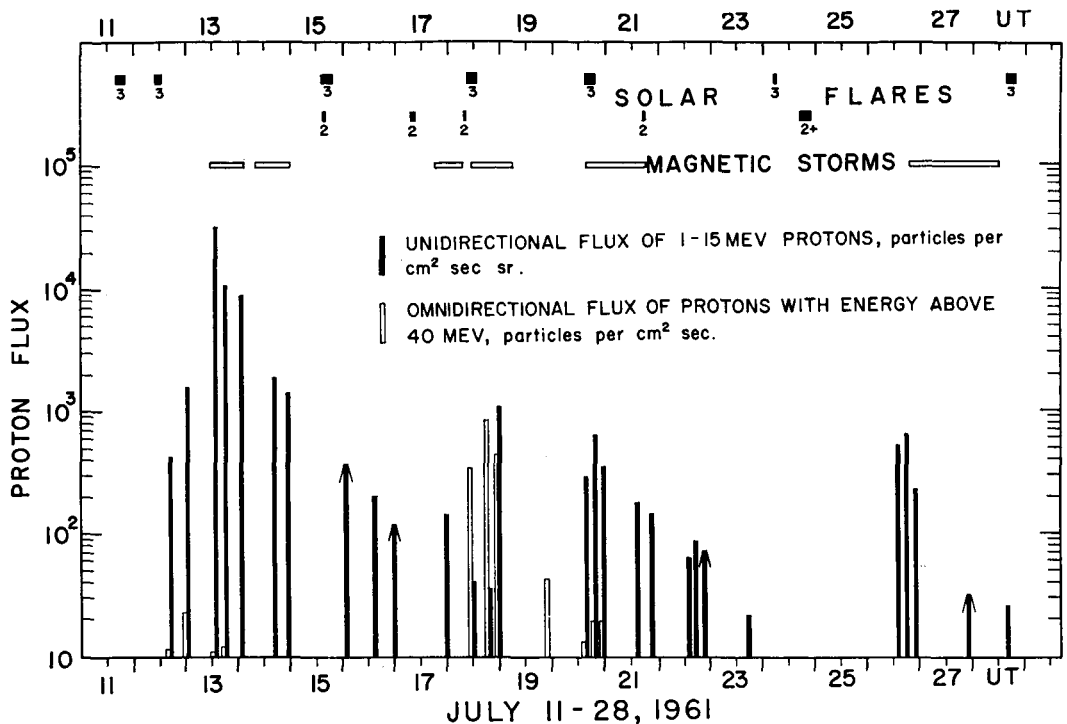


Fig. 1. Solar flares, magnetic storms, and some of the proton fluxes observed by Injun 1 in the period July 11-28, 1961.

prevented by the sweeping magnets that reject electrons of less than 250 kev.

These considerations concerning electron sensitivity have been verified in two ways. First, placing a 1-mc Tl^{204} source directly in front of an active detector produced no counts, whereas an unshielded 1-mc RaD source at sufficient distance in air to just stop the Po^{210} α particles gave only 10 counts/min. Second, in many passes through the horns of the outer Van Allen zone, the active detectors show no counts that cannot be accounted for by cosmic ray background, whereas the 213 GM measures > 40 -kev electron fluxes ranging up to more than 10^5 particles/cm² sec ster. It must also be added, however, that in 12 passes during early July, before the solar proton events to be discussed below, small numbers of counts were sporadically registered by PNA or PNC, at irregular intervals. These counting intervals were always in the region $3.0 \leq L \leq 4.2$. The counting rate was usually of the order of 2 to 3 per second (the largest rate was 12 per second), and the counting interval of the order of

a few seconds to a few tens of seconds. Whether these few counts indicate the electron sensitivity of the p-n detectors under certain conditions of satellite orientation (the 213 GM was *not* indicating a trapped electron maximum during any of these intervals of p-n counting, so either PNA or PNC *might* have been looking directly at the trapped electrons) or whether they are some of the trapped low-energy protons recently discovered by Davis [1962] is not clear.

Although the solar cosmic radiation is known to contain nuclei other than those of hydrogen, such as He, C, N, O [Fichtel and Guss, 1961; Biswas, Freier, and Stein, 1962; Biswas, Fichtel, and Guss, 1962], the flux of protons is much greater than the flux of all other nuclei. Accordingly, we have considered that we are dealing only with solar protons in the observations reported here, although the p-n detectors cannot distinguish protons from heavier nuclei and, indeed, have wider energy ranges for them; e.g., for α particles the sensitive range of detectors PNA and PNC is 3 to 350 Mev.

The counting rate of each of the Injun de-

tectors relevant to this report is telemetered once per second. The accumulation intervals vary for the various detectors, being 60/64 sec for PNC, 61/64 sec for PNA, SpB, and 213 GM, and 62/64 sec for PNB and PND. It was found that none of the phenomena relevant to this report required the use of time resolution as short as 1 sec, so the procedure of averaging over 10-sec periods was adopted in order to reduce statistical fluctuations. Data plotted in many of the figures below have been obtained in this manner; however, to avoid confusion on the graphs, data points are generally shown only at minute intervals.

The particle intensities observed by the Injun detectors on a given pass are a composite function of satellite position, orientation, and time. In addition to its several detectors, the satellite also contains a single axis Schonstedt fluxgate magnetometer, whose original purpose was to monitor the expected magnetic orientation. Because of the failure to achieve that orientation, the usefulness of the magnetometer was reduced to measuring one component of the magnetic field over a limited range. From this measurement, it is possible to calculate the pitch angle between the field direction and the velocity vector of those particles that enter directional detectors whose entrance apertures are parallel to the magnetometer's sensitive axis. Unfortunately, neither PNA nor PNC has this geometry, so detailed pitch-angle data concerning 1- to 15-Mev protons are impossible to obtain. Nevertheless, the fact that PNA and PNC look out at right angles to each other makes deviations from isotropy in the radiation very clear. We have not investigated this point in any detail up to the present time; but, generally speaking, at high latitudes PNA and PNC frequently show the same counting rates, indicating the isotropy of the solar protons in these regions over a solid angle of the order of π (and probably more) steradians. There are, however, occasional cases in which marked differences in the counting rates occur; in the discussions below, we have generally used the larger flux. The analysis given below is also based on the assumption of the quasi-stability of conditions in space over the duration of a pass.

Telemetry reception relevant to the present discussion was obtained at Iowa City, Iowa (SUI); at Silver Spring, Maryland (APL/JHU); and

at Prince Albert, Ottawa, and St. Johns, Canada (through the generous cooperation of the National Research Council of Canada).

3. OBSERVATIONS

Early July 1961 was a period of solar and magnetic quiet with no flares of importance 2 or 3 and with only one moderate magnetic storm between July 1 and July 11. During this period in many of the passes made by Injun at high latitudes over North America, detectors PNA, PNC, and SpB showed no counts that could not be accounted for by cosmic-ray background. On July 11 there began a period of considerable solar-terrestrial activity extending through July 28 that contained 12 flares of importance 2 or 3 [*National Bureau of Standards*, 1961] and four principal magnetic storm periods [*Lincoln*, 1961, 1962] which we here separate into six distinct storms.

During this period, Injun detected solar protons or more than 40 passes, many of which are shown in Figure 1. Here the flares and magnetic storm periods are indicated, as well as the plateau fluxes observed by the p-n detectors and the background Geiger counter. The term 'plateau flux' is used to indicate the fact that, as the satellite moves north, for example, the counting rate of a particular detector is observed to increase as the earth's magnetic field allows protons of progressively lower energy to penetrate to 1000-km altitude, the counting rate eventually reaching a constant or plateau value where the minimum energy detectable by the counter becomes either higher than the local geomagnetic cutoff energy or lower than the minimum energy in the primary solar proton stream. All the proton fluxes given in Figure 1 are such (high-latitude) plateau fluxes, with the exception of the four passes with arrowheads at the top of their vertical bars. For these fluxes the satellite's path and/or the end of telemetry reception prevented the reaching of a plateau.

It is clear from Figure 1 that the large number of solar and terrestrial events between July 11 and 28 make unambiguous relations between them difficult to define. Nonetheless, if one makes the common assumption that protons are emitted by the sun only during visible flares, the following relations are suggested:

1. The flares of 1615 UT July 11 and 1000 UT July 12 are responsible, respectively, for the geo-

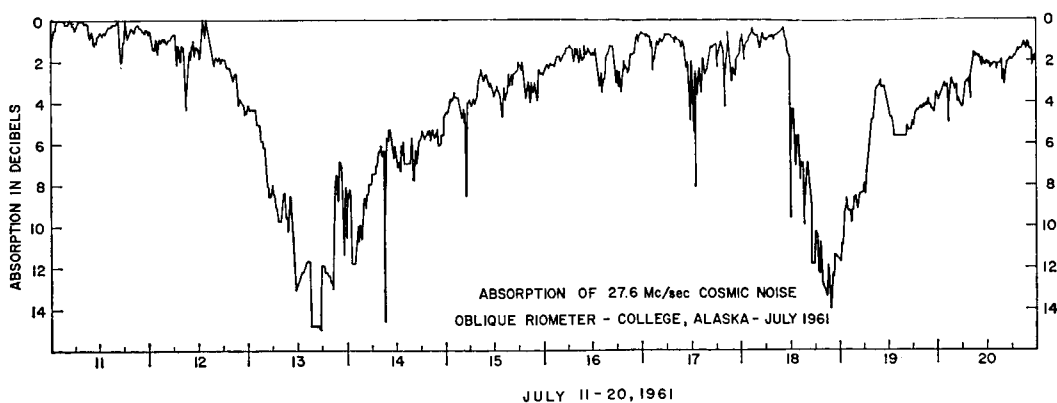


Fig. 2. Absorption of cosmic radio noise at 27.6 Mc/s by the oblique riometer at College, Alaska (after H. Leinbach, private communication, 1962).

magnetic storms beginning at 1115 UT July 13 and 0800 UT July 14. The particle fluxes observed between July 12 and 17 are directly related to these events.

2. The high-energy fluxes observed on July 18 were ejected by the flares of 0745 UT and 0921 UT that day. Some of the geomagnetic effects of that day, in particular the storm beginning at 1121 UT, are probably also associated with these flares and the high-energy fluxes; however, the earlier storm of 1826 UT July 17 may better be associated with an earlier flare, that of 1433 UT July 15, as may be the low-energy flux found late on July 18.

3. The period of geomagnetic activity between 0248 UT July 20 and 2400 UT July 21 may be best associated with a low-energy plasma ejected by the flares of July 18. The low-energy fluxes observed between July 20 and 23 are related to these events.

4. The major geomagnetic storm of 1950 UT July 26 to 1200 UT July 28 followed the flares of 0500 UT and 1722 UT July 24. Low-energy proton fluxes observed between July 26 and 28 are part of the plasma stream that produced this storm.

The relations suggested in (1) and (4) above seem straightforward; those in (2) and (3) are somewhat less clear-cut. However, the observations reported are, of course, not dependent on the flare-storm relations suggested, although some of the interpretation of these events given below does so depend. For convenience the intervals are referred to as the storms of July 13, 18, 20, and 26, respectively, although the events

connected with each extended on either side of the designated day.

In analyzing these data, we have been able to correlate changes in the observed geomagnetic cutoffs with events in the simultaneous magnetic storms. For this purpose, we define the geomagnetic cutoff for 1- to 15-Mev protons as that point (1) where the unidirectional flux is 10 protons/cm² sec ster and (2) beyond which there is a sharp rise to higher flux values. A similar definition is used for protons of energy greater than 40 Mev, when the omnidirectional flux reaches 10 protons/cm² sec. The geomagnetic dependence is expressed in terms of *McIlwain's* [1961] magnetic shell parameter L , measured in units of earth radii, with cutoff values of L denoted L_c . In addition, the dependence is also given in terms of geomagnetic latitude θ , based on a centered dipole approximation, to facilitate comparisons with earlier work in this field. It is recognized that geomagnetic latitude is not so useful a coordinate for expressing such dependence as the newer magnetic shell parameter; however, all data presented here come from a relatively restricted range of longitude (about 210° to about 350°E) which minimizes the difficulty inherent in the use of the geomagnetic latitude.

The accuracy with which we can determine the value of the geomagnetic cutoff L_c depends on the quality of the data in each case. It is usually in the range of 0.2 earth radii. Frequently, the two orthogonal detectors, PNA and PNC, observe the same value of L_c in a given pass within this accuracy, indicating the isotropy of the

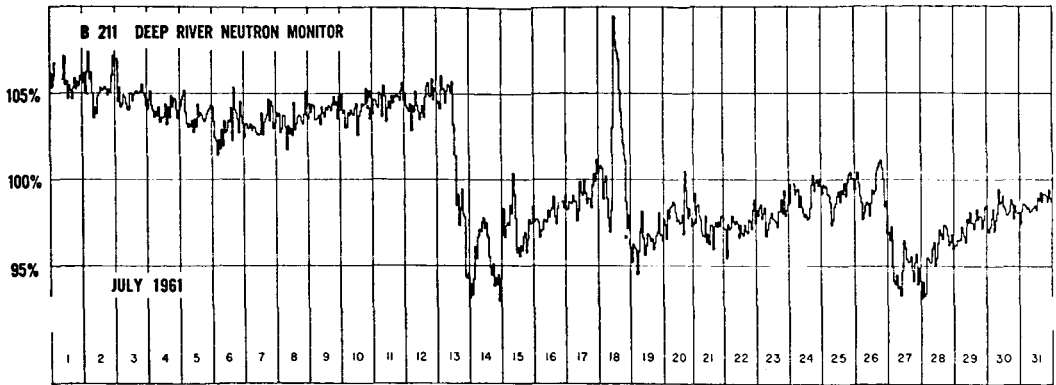


Fig. 3. Pressure corrected hourly totals from the standard neutron monitor at Deep River, Ontario, Canada; 55,500 counts per hour correspond to the 100 per cent level (after Carmichael and Steljes in *National Bureau of Standards*, [1961]).

radiation over a solid angle of at least π steradians. This observation is true especially after the beginning of the main phase of a geomagnetic storm. Before that time, wider spreads in the value of L_c seen by the two detectors are generally noted, a fact probably connected with the anisotropy of the radiation. We have selected the lower L_c in each case throughout this report.

It is sometimes assumed (for discussion see Bailey [1962]) that the solar-proton energy spectrum can be expressed in terms of a differential power law in energy of the form

$$N(E) dE \sim E^{-x} dE$$

This practice is followed here even though the totality of our data indicate that the spectrum (a) changes within a single solar proton event, and (b) varies from one event to another. By using plateau values of the fluxes in our two energy ranges, the exponent can be determined from

$$\frac{PN}{SpB} \cdot \Omega = \frac{\int_{1.5 \text{ Mev}}^{15 \text{ Mev}} E^{-x} dE}{\int_{40 \text{ Mev}}^{\infty} E^{-x} dE} \cong (27)^{x-1}$$

The results obtained in this manner are subject to uncertainty on two scores: (a) a lack of knowledge of the appropriate factor Ω to account for the different solid angles of the detectors and the anisotropy of the radiation (we have taken $\Omega = 2\pi$), and (b) statistical uncertainty due to the low counting rate in SpB in many cases. We later treat the general applica-

bility of the power-law spectrum, although its validity at a given instant of time cannot be examined by data relating to only two energy intervals.

Data from certain other sources concerning the July events have become available to us. As detected with the oblique riometer at College, Alaska, a large absorption of cosmic radio noise at 27.6 Mc/s began around 1900 UT July 12 and persisted until about July 21. (H. Leinbach, private communication 1962). Intervals of particularly pronounced absorption, reaching points 15 db below normal, occupied in the periods 1900 UT July 12 to 2100 UT July 13 and 1100 UT July 18 to 2200 UT July 18 as shown in Figure 2. Data from the Deep River neutron monitor, Figure 3, show that the neutron counting rate was generally reduced in the July period beyond 1100 UT July 13 with the exception of a short period around 1100 UT July 18, when an influx of high-energy solar particles penetrated the atmosphere. (The cutoff rigidity and energy for protons at Deep River are respectively 0.87 bv and 340 Mev in the formulation proposed by Quenby and Webber [1959].) Four Forbush decreases of primary cosmic rays were observed through the diminution of the secondary sea-level neutrons between July 13 and 28. Storm-time variations in the horizontal component of magnetic intensity, corrected for normal diurnal variations, have been derived from magnetograms from low-latitude observatories at Huan-cayo, San Juan, Honolulu, and Guam, as shown in Figure 4. The nomenclature for the characteristic phases of a typical magnetic storm as

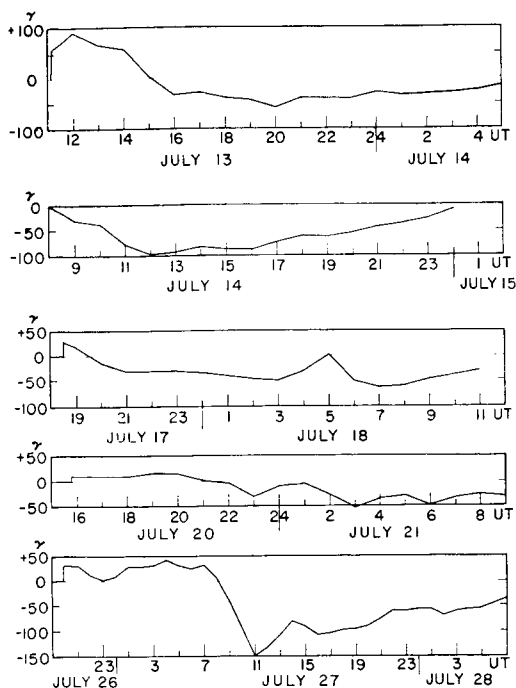


Fig. 4. Hourly means of variations in the horizontal component of magnetic intensity corrected for normal diurnal variations, during storms of July 1961 derived from observations at four low-latitude observatories: Huancayo, San Juan, Honolulu, and Guam.

described by Chapman and Bartels [1940] are used extensively here.

Storm of July 13. Two solar flares of importance 3 in the McMath plage region 6171, one at 1615 UT July 11 and the other at 1000 UT July 12, were followed by a period of magnetic disturbance extending from 1115 UT July 13 to about 2400 UT July 14. The magnetic interval may be subdivided into two principal storm periods: (1) a sudden commencement storm beginning at 1115 UT July 13 and extending to the early hours of July 14, with the characteristic main-phase field depression and at least a partial recovery; (2) a gradual storm starting at 0800 UT July 14, continuing until 2400 UT July 14, and consisting principally of a depression of the horizontal force. The gradual storm was followed by a relatively quiet period of about three days until 1826 UT July 17. The absorption of cosmic radio noise at College, Alaska, began to increase at 1900 UT July 12 and reached a point of maximum absorption,

more than 15 db below the normal level, at about 1400 UT July 13. A large Forbush decrease of cosmic rays began about 1100 UT July 13, practically coincident with the start of the first storm.

The first observation of solar protons by Injun occurred on the northward pass of 1717 UT July 12, 18 hours before the sudden commencement of 1115 UT July 13. As the dashed curves in Figures 5 and 6 show, protons of energy 1 to 15 Mev started to appear at $L_e = 6.1$ and $\theta = 63^\circ$, and they rapidly increased in number with increasing latitude, reaching a maximum unidirectional flux of 410 protons/cm² sec ster at $L = 13.3$ and $\theta = 73^\circ$. High-latitude proton counts existed also during the prestorm pass of 0034 UT July 13, beginning at about $\theta = 59^\circ$ and $L_e = 4.8$ and extending to a maximum intensity of 1500 protons/cm² sec ster at the highest point for which data are available. Telemetry for a pass at 0222 UT July 13, showed no 1- to 15-Mev protons in the range $34^\circ < \theta < 58^\circ$ and $1.8 < L < 4.1$. Since these three passes oc-

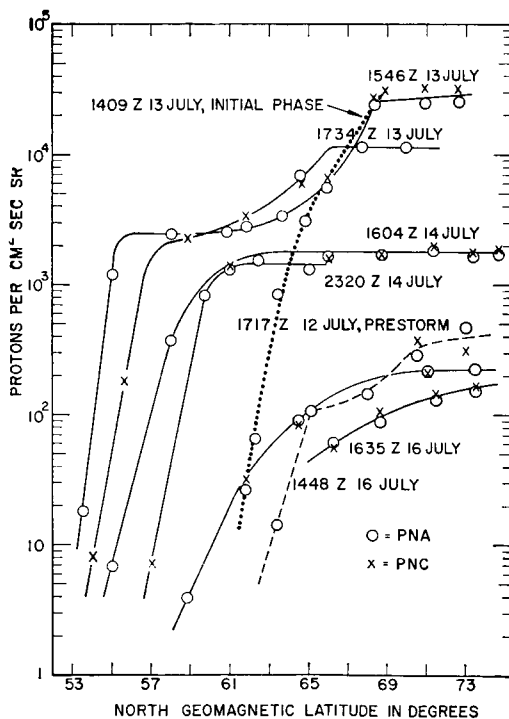


Fig. 5. Latitude dependence of 1- to 15-Mev solar protons observed by Injun 1 in relation to the storm of July 13.

occurred during the quiet magnetic period preceding the sudden commencement, the proton flux detected was the forerunner of the plasma stream producing the storm, and its spatial variation shows that the normal geomagnetic cutoff at 1000 km for 1- to 15-Mev solar protons lies in the range $59^\circ < \theta < 63^\circ$ and $4.8 < L < 6.1$.

The existence of prominent temporal and spatial variations of proton intensity marked the period when the magnetic storm was in progress. During the initial phase of the storm, which lasted from 1115 UT to about 1530 UT on July 13, proton fluxes were found on the passes of 1215 UT and 1409 UT. During the pass of 1215 UT July 13, solar protons started to appear at $L = 4.4$ and rose sharply to an intensity of 750 protons/cm² sec ster at $L = 4.7$, the northernmost point for which telemetry was available. On this pass in regions of $L < 4.4$, some sporadic counts were present, stemming we believe (as previously noted) from particles other than the solar particles here discussed: sporadic PN counts with rates between 0.1 and 3 counts/sec existed in the region $3.0 < L < 3.3$ and $3.6 < L < 4.0$, regions

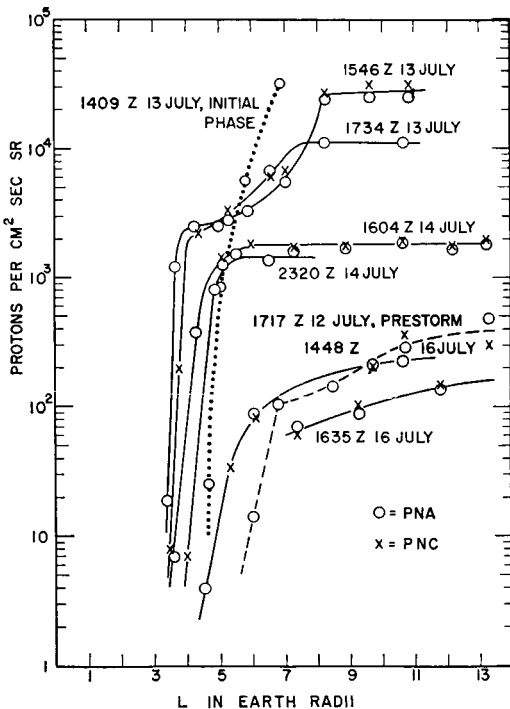


Fig. 6. L (magnetic shell parameter) dependence of 1- to 15-Mev solar protons observed by Injun 1 in relation to the storm of July 13.

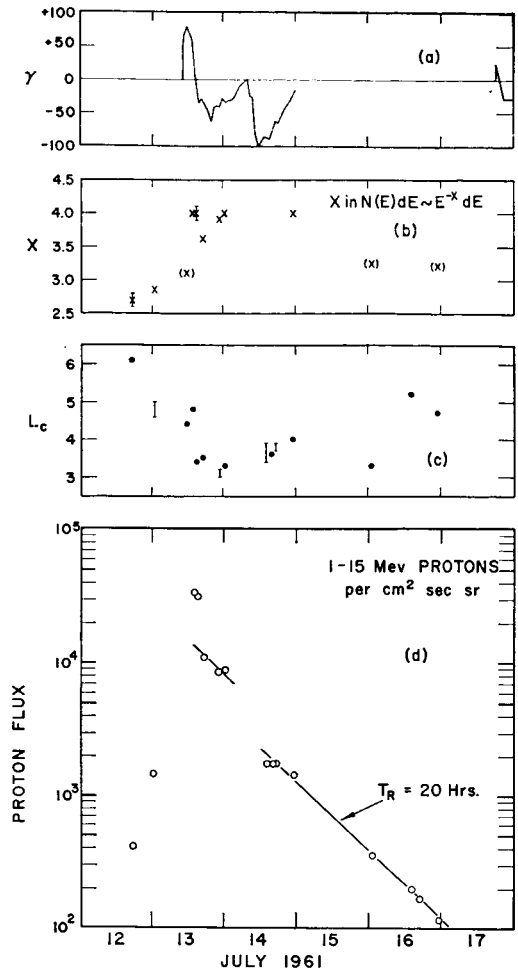


Fig. 7. Analysis of storm of July 13 for 1- to 15-Mev protons. (a) Variations in the horizontal component of magnetic intensity derived from observations at four low-latitude stations, measured in gamma (10^5 gauss). (b) Time variation in the exponent in power-law description of solar proton spectrum. (c) Time variation in geomagnetic cutoff L_c in earth radii. (d) Time dependence of plateau flux.

separated by one devoid of counts and followed by one extending to $L = 4.4$ which contained rates always less than 1 count/sec. On the pass of 1409 UT July 13, as is shown in Figure 6, the proton flux rose sharply beyond the cutoff of $L_c = 4.8$ to a maximum of 33,000 protons/cm² sec ster at $L = 6$. This peak flux was considerably in excess of the prestorm intensity maximums and strongly suggests that these protons were imbedded in the relatively low-energy solar

plasma causing the magnetic storm. It is noted here also that there are indications of temporal variations in flux along the flight path of the 1409 UT pass.

Soon after the beginning of the main phase of the storm, a pass at 1546 UT July 13 showed a cutoff of $L_c = 3.4$ and a plateau beyond $L = 8$ having an intensity of 32,000 protons/cm² sec ster, practically equaling the maximum found in the initial-phase pass. At 1734 UT July 13 the locations of the cutoff and knee were essentially unchanged, but the plateau value dropped to 11,000 protons/cm² sec ster, indicating a rapid decrease in the flux of 1- to 15-Mev protons during the early part of the main phase of the storm, while the depression in horizontal force was approaching or was at its maximum. In the recovery phases of the storm two (unplotted) data passes, at 2305 UT July 13 and 0048 UT July 14 gave very similar results: For each pass, $L_c \cong 3.2$ was followed by a rapid rise to a plateau value of 8700 protons/cm² sec ster in the range $4.6 < L < 8.3$. With the aid of Figures 7a and 7c, we note that in the main and recovery phase of the storm the proton cutoffs lie consistently in the L_c range 3.0 to 3.5, considerably below the prestorm range of 4.8 to 6.0, indicating a marked storm-time shift of the proton region toward the equator. For an aspect later treated, we note here that, as shown in Figure 7d for the three passes starting with 1734 UT July 13, the temporal variation of proton intensity in part of the main phase and in the recovery period of the storm can be described by an exponential with a relaxation time of 20 hours. A pass at 0239 UT July 14 showed no protons in the range $2 < L < 3$, a finding consistent with the cutoff positions existing at this time.

It thus appears probable that the 1- to 15-Mev protons detected between 1717 UT July 12 and 0048 UT July 14 were ejected during the class 3 flare that existed from 1615 UT to 2040 UT on July 11 the first July flare of importance 2 or more. At any rate, these protons formed part of the corpuscular stream producing the sudden commencement of 1115 UT July 13 and probably containing relatively large numbers of low-energy particles. (The 43-hour lapse between the onset of the flare and storm corresponds to a direct sun-earth transit time for 3-ev electrons and 5-kev protons.) As the stream moved through interplanetary space, some of the

1- to 15-Mev protons escaped confinement, moved ahead of the main body of the stream, and were geomagnetically deflected into the northern regions where they were detected by Injun in the prestorm passes of 1717 UT July 12 and 0034 UT July 13. (An alternative origin for the forerunner protons is discussed below.) When the storm-producing stream reached the geomagnetic field, large temporal and spatial changes in intensity occurred, as previously discussed.

The sudden-commencement storm of 1115 UT July 13 was followed by a gradual storm beginning at 0800 UT July 14 that produced principally a field depression without any preceding initial field rise. Because of the closeness in the time of the two storms, the gradual storm may have started while a residual of the preceding storm still existed. If this is so, then the particles of the second storm-producing stream may have been somewhat dispersed by the residual field of the preceding storm, so that the sharp front of the stream and related initial field rise did not develop. The gradual storm may have been produced by particles ejected from the sun during the class 3 flare of 1000 UT July 12. If this is true, the flare-storm lapse time is 46 hours, similar to that for the storm of 1115 UT July 13.

There are no Injun data for the part of the second storm when the decrease in H was approaching and ultimately reached its maximum. Beyond the time of maximum decrease, when the horizontal force was returning to its prestorm level, passes at 1419, 1604, and 1748 UT on July 14 gave practically identical results, many of the primary features being exemplified in the pass of 1604 UT July 14 in plotted Figures 5 and 6. The average cutoff was $L_c = 3.7$, a knee existed at $L = 5$, and a plateau flux of 1800 protons/cm² sec ster extended out to $L = 17$. At 2320 UT on July 14, near the end of the gradual storm, the plateau flux had diminished to 1500 protons/cm² sec ster and the cutoff increased to $L_c = 4.0$, while the position of the knee was practically unaltered.

The gradual storm ended about 2400 UT July 14 and was followed by a period of magnetic quiet that lasted for nearly three days. During this poststorm period, the proton intensity continued to decrease and there was a shift of the proton region to higher cutoff points, toward the prestorm condition, as shown in Figures 5

and 6 for the passes of 1448 and 1635 UT on July 16 and in the data presented in Figure 7c.

The diminution of the plateau intensity of 1- to 15-Mev protons for the period 1419 UT July 14 to 2348 UT July 16 can be represented by an exponential decay with a relaxation time of 20 hours; this period represents that part of the gradual storm beyond the peak field decrease and the bulk of the post-storm period. (It may also be significant that in the sudden commencement storm of 1115 UT July 13, the flux decayed with the same relaxation time from 1734 UT July 13 to 0048 UT July 14 an epoch also including part of the storm period beyond the time when the maximum H decrease occurred.)

With reference to Figure 7d, these intervals with similar decay times are separated by a period when the temporal decrease must have been much more rapid than that of an exponential decay with a relaxation time of 20 hours. Although there are no direct data to substantiate the following possibility, this rapid decay may have occurred during the period 0800 to 1200 UT on July 14 when the storm field was approaching the maximum depression. In a comparable period in the storm of 1115 UT July 13, a rapid dissipation took place in the interval between the passes of 1546 and 1734 UT as previously noted.

Further discussion of the exponential decay of proton intensity observed in the latter phases of these storms is deferred until section 4.

There is also shown in Figure 7b the temporal change in the exponent in the assumed power-law spectrum. It is observed that initially, in the prestorm period, the spectrum is relatively hard, having an exponent of about 3. In the main phase the spectrum softens to an exponent of 4, and during the poststorm period it appears to gradually return toward its prestorm value. Those exponents in parentheses in the figure refer to passes in which the PN flux reached a maximum but not a plateau.

In Figure 7c, which shows the cutoff as a function of time, those cutoffs not accurately obtainable from the data are indicated by vertical lines that cover the region of uncertainty.

Storm of July 18. The solar-terrestrial phenomena of July 18 were complicated by the overlapping of events due to low- and high-energy particle fluxes probably associated with flares of July 15 and 17, and of July 18, respec-

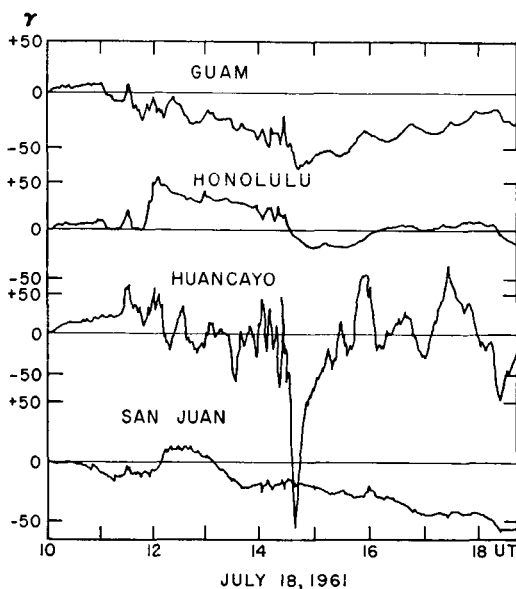


Fig. 8. Horizontal component magnetograms for part of the storm of July 18.

tively. A class 3 flare occurred from 1433 to 1929 UT July 15 in McMath plage region 6172; a class 2 flare occurred the same day from 1508 to 1549 UT in region 6171; and a class 2 flare occurred from 0720 to 0920 UT July 17 in region 6171.

On July 18 there were two solar flares reported, both in the McMath plage region 6171: one of importance 2 lasting from 0745 to 0835 UT and located at 7° to 8° S and 55° to 62° W; the second of importance 3 extending from 0921 to 1330 UT at 5° to 8° S and 55° to 63° W, the temporal sequence and the similarity in flare position suggesting that the second flare may have been a continuation and outgrowth of the first. The flares were followed by a number of terrestrial events that began practically simultaneously while the class 3 flare was still in progress. For example, as is shown in Figure 2, for the oblique riometer at College, Alaska, absorption of cosmic radio noise commenced between 1000 and 1100 UT July 18 and reached a maximum absorption 14 db below the quiet level at 2200 UT July 18. As is shown in Figure 3, the Deep River neutron monitor registered a 10 per cent increase in counting rate about 1100 UT superposed on a moderate Forbush decrease that occurred throughout the day of July 18.

The period of magnetic disturbance associated

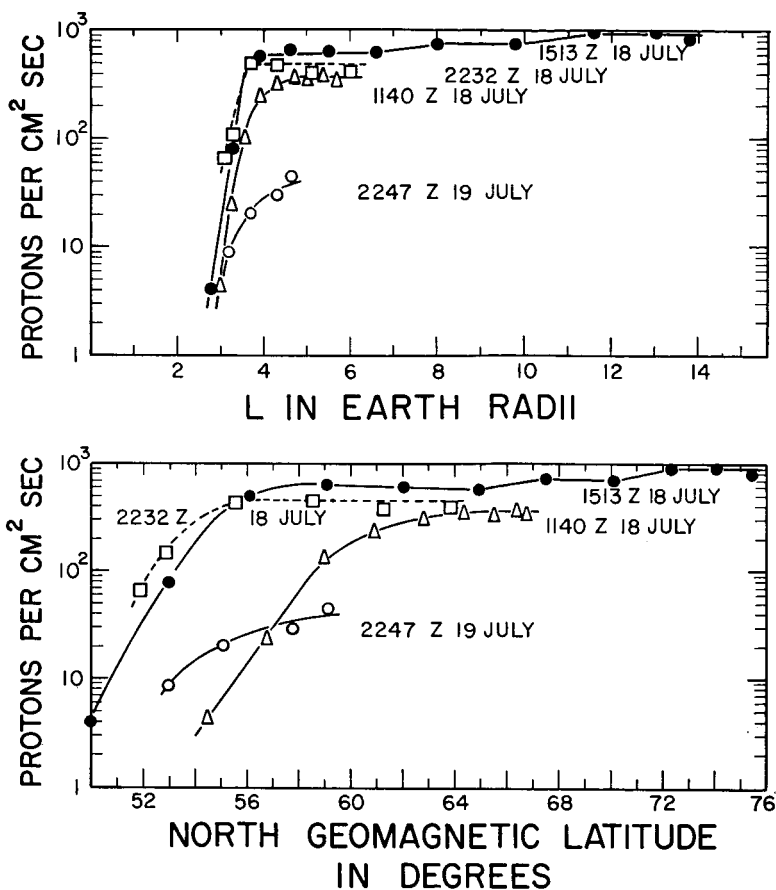


Fig. 9. Latitude and L dependence of solar protons above 40 Mev observed by Injun 1 in relation to the storm of July 18.

with these five flares extended from 1826 UT July 17 to 0600 UT July 19 and contained two storms: one began at 1826 UT July 17; the other started at 1121 UT July 18 in the recovery phase of the first storm. In the second storm, a sharp rise in the horizontal force occurred at 1121 UT July 18 and was followed by a sharp short decline. Before the increase, there had occurred a field decrease which started at 1100 UT July 18 and which, as is indicated in Figure 8, was more marked at the night-side stations, Guam and Honolulu, than at the day-side stations, Huancaayo and San Juan.

Only one Injun pass was observed between the sudden commencements of 1826 UT July 17 and 1121 UT July 18: at 2400 UT July 17 a pass which went as far north as $L = 6.2$ showed a plateau flux of 1- to 15-Mev protons of 150 particles/cm² sec ster above a cutoff of $L_0 = 3.7$

and knee of $L = 4.0$. There was no flux of protons above 40 Mev beyond the normal cosmic-ray background.

The first observation of solar protons on July 18 occurred in the pass of 1140 UT, which started 19 minutes after the sharp rise in H found at all low-latitude magnetic observatories, and 40 minutes after the beginning of the depression in H found principally at the night-side observatories. The Injun proton observations relevant to this storm period showed an energy spectrum as well as a temporal and spatial variation considerably different from those found in the other July storms: the storm of July 18 was marked by the appearance of relatively large fluxes of protons of energy greater than 40 Mev. Though the Injun instruments do not allow a further delineation of proton energies in the range above 40 Mev, the stream detected by Injun must

have contained at least some protons of energy of the order of magnitude 1 bev in view of the increase in counts at the Deep River neutron monitor. It is possible that the minimum proton energy in the primary beam was significantly above 40 Mev, and this possibility must be recognized in the following discussion.

As shown for the 1140 UT pass in Figure 9, the flux of protons with energy above 40 Mev passed the cutoff intensity of 10 protons/cm² sec at $L_c = 3.1$ and then rose to a plateau value of 350, with the knee at $L = 4$. The cutoff and knee found here are lower than those found for the 1- to 15-Mev protons on comparable passes during the initial phase of other storms; for example, on the 1409 UT pass on July 13, also occurring in the early stage of a storm, the cutoff for the 1- to 15-Mev protons was at $L_c = 4.7$, and, though the knee was not directly detected, the available data showed it was certainly above $L = 7$. Three closely spaced passes on July 18, at 1327, 1513, and 1659 UT gave similar results for the protons of energy 40 Mev and above, as exemplified in the plotted pass of 1513 UT (Figure 9), where the plateau flux reached 900 protons/cm² sec. The L cutoffs during these and later passes generally lie between 2.9 and 3.1, indicating that the spatial dependence of these protons was not markedly influenced by the changes in the storm field. At 2232 UT July 18, the plateau value of the flux was 400 protons/cm² sec; at 2247 UT July 19, 45 protons/cm² sec.

With regard to the 1- to 15-Mev protons during the storm of 1121 UT July 18, the maximum unidirectional flux was about 40 protons/cm² sec ster in the four passes preceding that of 2232 UT July 18, when the flux increased to 1100. On this pass a cutoff at $L_c = 3.5$ was noted, a value comparable with that found during the main phases of other storms. Though the next pass received, that of 2247 UT July 19, showed a short plateau in SpB, the PN flux reached a value of only 10 protons/cm² sec ster at $L = 4.6$, the northernmost point from which data were received, implying the retreat of the geomagnetic cutoff toward its prestorm value.

With regard to the array of events of July 18 it is worth emphasizing that a number of phenomena began around 1100 UT during a solar flare: Injun detection of protons with energy above 40 Mev, a magnetic storm, absorption of cosmic radio noise, and a striking increase in

counting rate at the Deep River neutron monitor. This temporal association indicates that at least the early stage of the magnetic storm that began at 1121 UT may well have been caused by energetic particles and that the Injun protons above 40 Mev may represent part of the storm-producing solar stream that penetrated to the 1000-km level in the northern regions on this occasion. (Alternatively, but we believe less likely, the 40-Mev protons were produced in the flares of July 18 and overtook a low-energy solar stream ejected by the flares of July 15 and/or 17, so that both the high-energy protons and the plasma arrived essentially simultaneously at the earth, with the plasma being responsible for the geomagnetic storm.) The earlier storm of 1826 UT July 17, however, must have been associated with the arrival of low-energy particles.

Storm of July 20. The storm period 0248 UT July 20 to about 0100 UT July 22 was one of relatively small magnetic disturbances, the composite of which was not even considered a principal magnetic storm by 6 of 17 magnetic observatories [Lincoln, 1962]. This storm period was preceded by the appearance of two flares on July 18, which were previously discussed and which we associated with the high-energy protons of the storm of that date. Thus, the disturbance beginning on July 20 was probably caused by a low-energy plasma ejected with the higher-energy protons observed on July 18.

Detailed analysis of magnetograms of middle- and low-latitude observatories yields the following characteristics. A small sudden commencement storm began at 0248 UT July 20 and lasted (complete with main phase and recovery) until about 0900 UT July 20 with a range in horizontal force of 30 γ or less. After 0900 UT July 20 the magnetic variations were principally those of the local diurnal variation until about 1600 UT July 20 when the major disturbance of this period began. We consider here only this latter disturbance, whose hourly means are shown in Figure 4 and which, primarily on the basis of the Huancayo records, we treat as a sudden commencement beginning at 1550 UT July 20. This storm ended around 2400 UT July 21 and was followed by a relatively quiet period of about four days, until 1950 UT July 26.

The prestorm passes of 1359 UT July 20, plotted in Figure 10, and 1541 UT July 20 showed

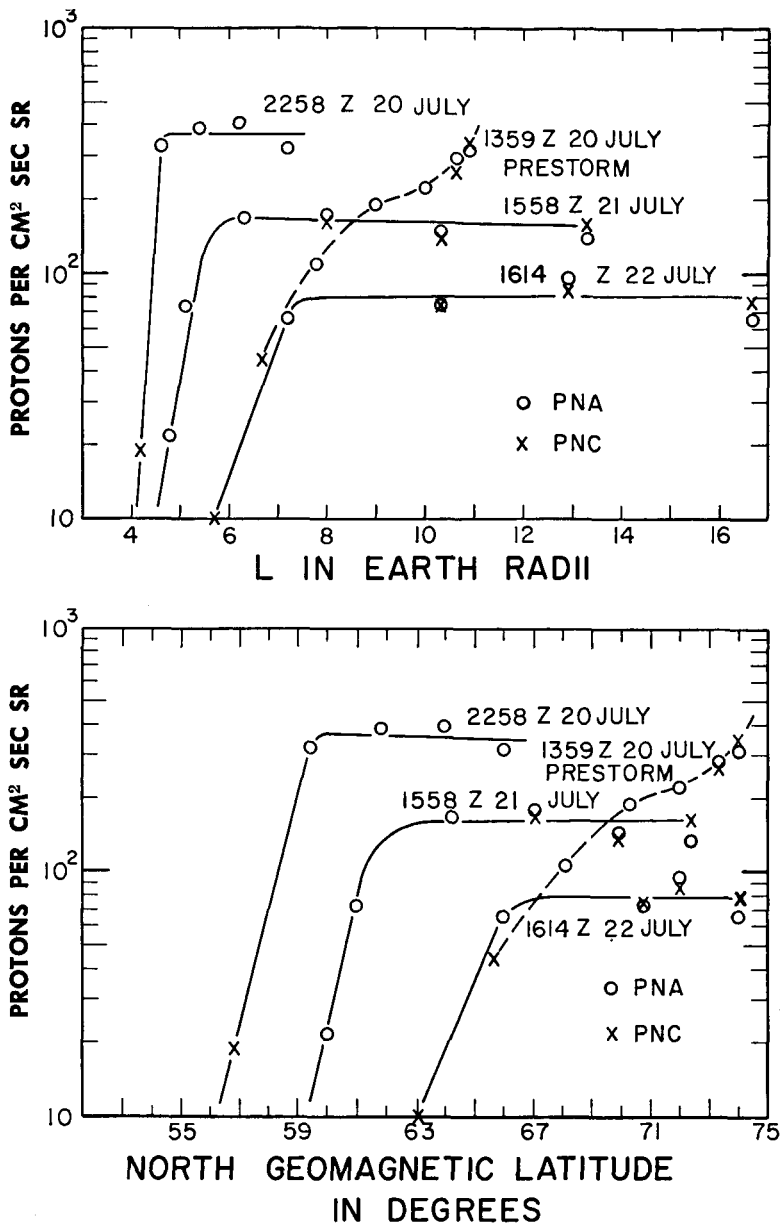


Fig. 10. Latitude and L dependence of 1- to 15-Mev solar protons observed by Injun 1 in relation to the storm of July 20.

cutoffs at L_c between 5.0 and 6.0 and $L_c = 5.3$, respectively (similar to the prestorm cutoffs on July 13), and with the associated maximum PN fluxes being 300 and 520 protons/cm² sec ster. After the storm began, a high-latitude pass at 1921 UT July 20 showed a plateau flux of 570 protons/cm² sec ster extending throughout the range $14.4 < L < 24.8$; no data exist at lower

L values, and so the cutoff here is not determinable.

In Figure 10 the data for the pass of 2258 UT July 20, occurring about an hour after the main phase of the storm began, demonstrate the main-phase cutoff shift to $L_c = 3.8$. This cutoff shift, though large, is a little less than that for the storm of July 13, and is probably related to

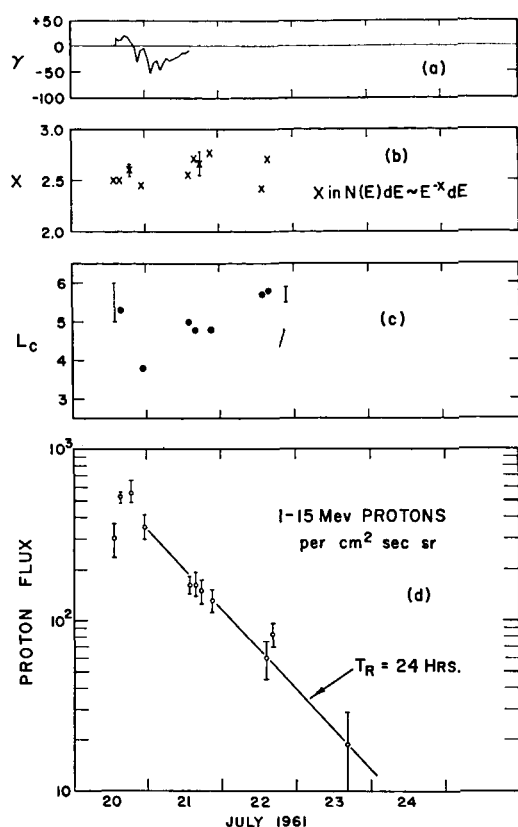


Fig. 11. Analysis of storm of July 20 for 1- to 15-Mev protons. (a) Variations in the horizontal component of magnetic intensity derived from observations at four low-latitude stations, measured in gammas (10^{-5} gauss). (b) Time variation in the exponent in a power-law description of the solar proton spectrum. (c) Time variation in the geomagnetic cutoff L_c in earth radii. (d) Time dependence of plateau flux.

the fact that the storm of July 20 produced a smaller magnetic disturbance than the storm of July 13. For the pass of 2258 UT July 20, a plateau flux of 360 protons/cm² sec ster began at $L = 4.6$; consideration of this plateau value in conjunction with that of 1921 UT July 20 shows that rapid decrease of proton intensity occurred in the period of transition from the initial to the main phase of the storm, a behavior similar to that found in the storm of July 13.

In the poststorm period, 15 data passes extending to 1306 UT on July 24 contribute in different degrees to establishing the spatial and temporal variations exemplified in parts of Fig-

ures 10 and 11, variations which are, in general, similar to those found after the storm of July 13. The cutoff and knee move toward and ultimately reach the prestorm positions, as shown in Figure 10 in the passes of 1558 UT July 21 and 1614 UT July 22. The amplitude of the plateau values decays exponentially with a relaxation time of 24 hours as shown in Figure 11d, a time which may also be that occurring in the latter part of the main phase of the storm and which is four hours longer than that found after the storm of July 13. Protons were found at positions with L as large as 23 earth radii.

With regard to the protons of energy greater than 40 Mev, they appear at L values smaller than those found with the 1- to 15-Mev protons and have an omnidirectional flux less than 20 protons/cm² sec.

In a power-law spectrum (Figure 11b), the flux of all protons would be described by an exponent varying between 2.4 and 2.8, no characteristic trend being discernible.

In Figure 11c, showing the temporal variation in the cutoff, vertical lines designate the range for cutoffs not clearly marked in the data.

Storm of July 26. The sudden commencement magnetic storm of 1950 UT July 26, which was practically coincident with a Forbush decrease, followed the appearance on July 24 of two large flares in the McMath plage region 6178: a class 3 flare existed from 0500 to 0640 UT and a class 2⁺ flare from 1722 to 2214 UT. The storm lasted until about 1200 UT July 28 and was the largest in duration and magnitude of the storms occurring in July (see Figure 4).

The first Injun observation of 1- to 15-Mev protons took place during the prestorm pass of 1336 UT July 26. As is shown in Figures 12 and 13, and in accord with the behavior before the storms of July 13 and 20, the protons had a cutoff at $L_c = 5.4$, and beyond this point the intensity rose sharply to a maximum of 520 protons/cm² sec ster. The pass of 1524 UT July 26 also prestorm, showed the cutoff relatively unchanged at $L_c = 5.6$, but the plateau intensity raised to 630.

One hour after the storm began, the pass of 2052 UT July 26 showed a relatively slight initial-phase shift of the proton regions to lower values of L , to $L_c = 4.7$. Here, however, in contrast to the corresponding flux changes in the storm of July 13, the plateau intensity is less

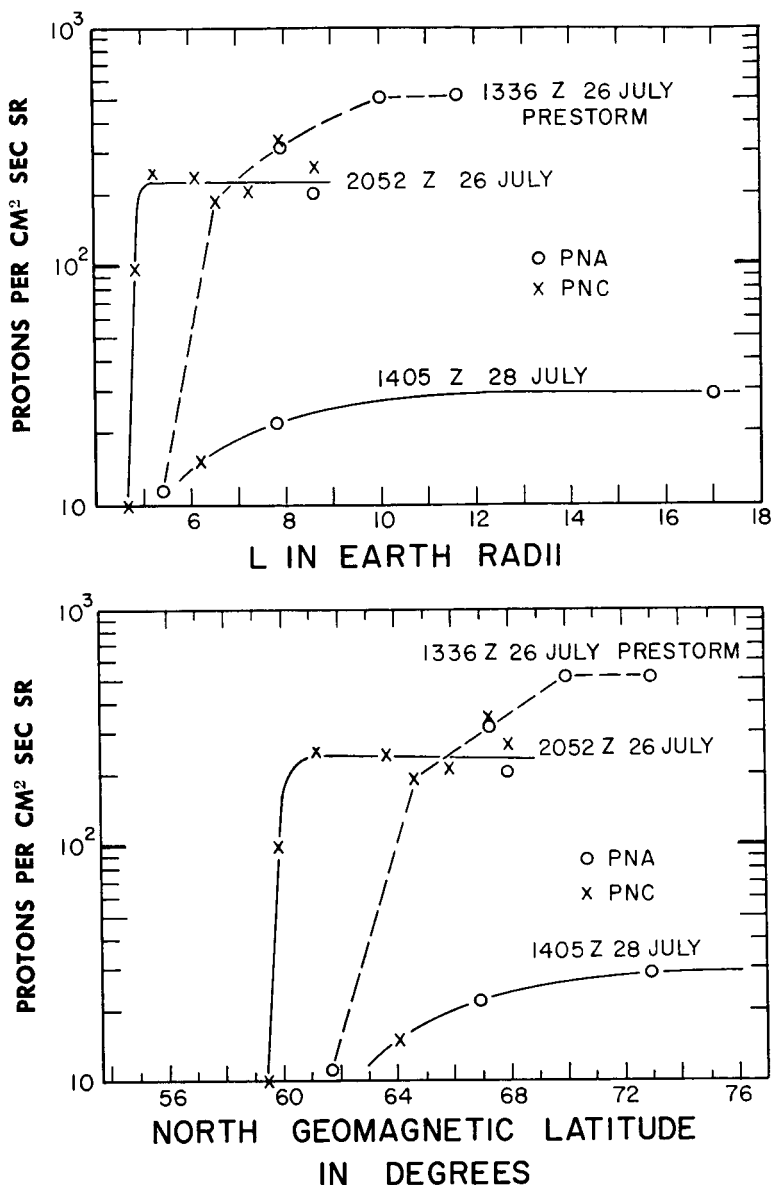


Fig. 12. Latitude and L dependence of 1- to 15-Mev solar protons observed in Injun 1 in relation to the storm of July 26.

than the prestorm value, perhaps indicating that most of the 1- to 15-Mev protons leaked out of the storm-producing plasma before the plasma reached the earth. After the initial-phase pass of 2052 UT July 26, and except for the plotted poststorm pass of 1405 UT July 28, the data are relatively meager but not inconsistent with much of the general solar proton behavior found during the other storms: an initial phase

pass at 2238 UT July 26 showed that there were no protons in regions with L less than 4.5. During the main phase of the storm, a pass at 2253 UT July 27 showed that the proton cutoff was shifted to $L_c = 3.4$. In the recovery and post-storm period, passes at 1220 UT July 28, and 1405 UT July 28 showed respective L cutoffs of 3.2 and 6.0, whereas the pass at 2125 UT July 28 showed that there were no protons below

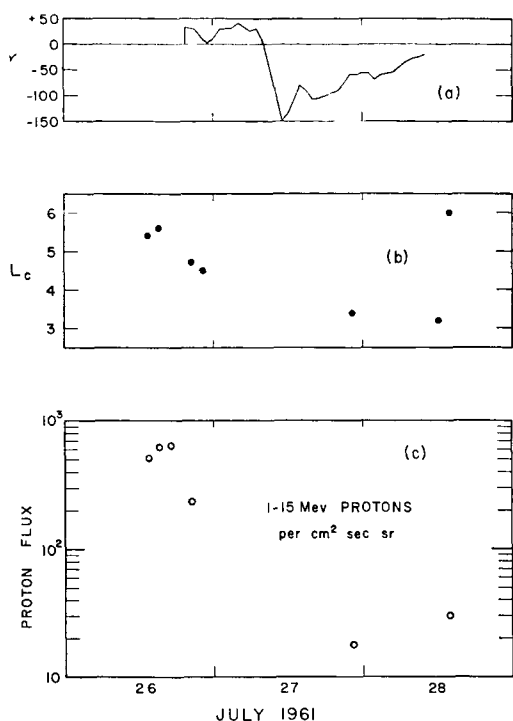


Fig. 13. Analysis of storm of July 26 for 1- to 15-Mev protons. (a) Variations in the horizontal component of magnetic intensity derived from observations at four low-latitude stations, measured in gammas (10^{-6} gauss). (b) Time variations in geomagnetic cutoff L_c in earth radii. (c) Time dependence of plateau flux.

$L = 4.2$. If the proton decay is exponential during and after the main phase, the relaxation time is about one day.

With regard to the protons with energy above 40 Mev, their omnidirectional intensity did not significantly exceed cosmic-ray background at $L > 5$ during the entire storm.

4. DISCUSSION

Although the period July 11–28 was one of great solar and geomagnetic activity, both the first and last storms of the interval, those designated July 13 and 26, were preceded by sufficiently long periods of inactivity to permit reasonably straightforward correlations between various solar and terrestrial events. The storm of July 18 and, with the exception of its recovery and poststorm period, the storm of July 20 involve sufficient overlapping of events to cloud the scene somewhat. Nonetheless, the over-all

picture we infer from our more straightforward observations appears to fit these other storms quite well also. A typical sequence of events is as follows:

1. A solar flare takes place; its occurrence may be observed essentially immediately on and/or near the earth in electromagnetic radiations and in related ionospheric disturbances. The flare ejects a plasma containing a broad spectrum of energetic particles.

2. If the plasma contains an appreciable number of high-energy particles ($E > 40$ Mev), they may reach the earth within a few hours after the beginning of the flare, and in addition to being detected themselves at high latitude and altitude, may give rise to several secondary effects: increased counts in sea-level neutron monitors, riometer absorption, small magnetic disturbances, increased ionization, etc.

3. Lower-energy (1- to 15-Mev) protons ejected by the flare are largely contained in the main body of the plasma. Those beginning to be detectable at high latitude and altitude some 20–40 hours after the flare represent a leakage from the containment of the main body of the plasma and are a forerunner of its arrival. They are found above 'normal' (i.e., prestorm) geomagnetic cutoffs, about $\theta = 61^\circ$ and $L_c = 5.5$ earth radii. Recently, Reid [1962] has suggested that these 'forerunner' protons may have been interplanetary matter pushed ahead and raised to our detectable energy range by the expanding solar magnetic field.

4. The sudden commencement of a geomagnetic storm indicates the arrival of the main body of the plasma to the immediate vicinity of the earth. The intensity of protons in the 1- to 15-Mev region increases greatly during the initial phase of the storm, especially toward the end, but there are, in the main, only minor decreases in the geomagnetic cutoffs compared to the prestorm values.

5. The flux of 1- to 15-Mev protons is also high at the time of the beginning of the main phase of the storm; however, there may be a rapid dissipation of particles during that part of the main phase when the horizontal force is approaching its maximum negative value. During this period, for the first time, considerable and consistent equatorial shifts of the geomagnetic cutoffs are clearly evident: low-energy protons are detectable at latitudes down to θ

TABLE 2. Summary Values of L Cutoff in Earth Radii of 1- to 15-Mev Protons in Relation to Storm Periods in July 1961

Prestorm	Initial Phase	Within One Day after Beginning of Main Phase
6.1	4.4	3.4
4.6-5.0	4.8	3.5
5.0-6.0	4.7	3.0-3.2
5.3	4.5	3.3
5.4		3.4-3.9
5.6		3.5
		3.8
		3.4

= 53° - 55° and L_c = 3.0-3.9 earth radii. The cutoff depression is apparently directly related to the magnitude of the main phase of the storm, and in addition depends on the energy of the protons.

6. In the latter part of the main phase of the magnetic storm and during the recovery period, the cutoffs gradually return to their prestorm values, whereas the plateau flux of 1- to 15-Mev protons decays exponentially with a relaxation time of about one day.

All these characteristics and their relation to results of other observers are further discussed below. The relation between the observed cutoffs for the 1- to 15-Mev protons and the storm periods is summarized in Table 2.

The characteristics of solar protons from Injun data for the energy range 1 to 15 Mev and above 40 Mev show some general similarities with results obtained by balloons for protons in the general range 88-300 Mev:

1. Some protons precede the main plasma stream and enter the geomagnetic field before the storm begins [Winckler, Bhavsar, and Peterson, 1961; Charakhchian *et al.*, 1960; Brown and D'Arcy, 1959]; this property was correctly inferred earlier through studies of ionospheric absorption of cosmic radio noise [Bailey, 1959; Little and Leinbach, 1958; Reid and Leinbach, 1959].

2. There is a storm-time cutoff shift to lower latitudes [Anderson, Arnoldy, Hoffman, Peterson, and Winckler, 1959; Freier, Ney, and Winckler, 1959; Winckler, Bhavsar, and Peterson, 1961].

3. The major depression of the cutoff occurs

at the beginning of the main phase of the storm [Winckler, Bhavsar, and Peterson, 1961].

With regard to some dissimilarities, Injun data indicate:

1. There is conclusive evidence for the containment of solar cosmic rays in the storm stream.

2. There is no increase, but rather a slight decrease, in the cutoff during the initial phase of the storm.

3. Large fluxes are present in the latter part of the initial phase of the storm as well as in the beginning of the main phase.

4. There is an exponential decay whose relaxation time is about one day for the 1- to 15-Mev protons in the period beyond the peak of the main phase of the storm.

With particular reference to the decay starting in the latter part of the main phase, but with general applicability to all the temporal variations, we cannot fit the time changes of the plateau values with a power law in time. We thus are at variance with other workers: a T^{-2} decay was observed with the space probe Pioneer 5 [Arnoldy, Hoffman, and Winckler, 1960] and with balloons [Winckler, Bhavsar, and Peterson, 1961; Biswas and Freier, 1961]. Also with balloons, Anderson and Enemark [1960] observed a T^{-2} decay, while Earl [1961] could not fit data with either an exponential or power law. We emphasize that the relaxation times we treat refer only to the interval beginning with the peak of the main phase and extending through the poststorm period. They are probably best suited to describe the decay at latitudes above those where the prestorm plateau begins.

Observations very similar in many respects to those reported here for the July storms have been made of a solar flare and geomagnetic storm at the end of September 1961 by Injun and simultaneously by Explorer 12. These have been described by Van Allen and Whelpley [1961] and by Van Allen *et al.*, [1962]. Solar protons of energy greater than 40 Mev were first observed by the SpB detector on Injun on the first high-latitude pass after the flare of 2202 UT September 28. At the same time considerable fluxes of protons above 23 and 40 Mev were observed by SUI detectors on Explorer 12 at a distance near its apogee of about 80,000 km. These high-energy fluxes died away over

the next day, as observed by both satellites, whereas the 1- to 15-Mev flux seen by the p-n junction detectors on Injun gradually increased. On the pass following the sudden commencement of a geomagnetic storm at 2108 UT September 30, the flux of 1- to 15-Mev particles seen by Injun increased markedly by a factor of more than 10 to 7700 protons/cm² sec ster. At the same time, a sharp increase of particles over 23 Mev was also observed by Explorer 12. However, neither satellite observed any substantial simultaneous increase in the flux of particles over 40 Mev. The low-energy flux observed by Injun decreased rapidly in a few hours and then exponentially over the next several days with a relaxation time of about 1 day. Insofar as data are available, the flux of particles over 23 Mev seen by Explorer 12 showed comparable behavior.

The latitude dependence of the 1- to 15-Mev protons during the September event was like that of the July events. At 2330 UT September 29, 22 hours before the sudden commencement, the cutoff occurred at $L_c = 5.5$ and the plateau ran from about $L = 7$ out to 17.5 earth radii. At 2340 UT September 30, after the sudden commencement at the time of the transition to the main phase of the storm, the cutoff occurred at $L_c = 3.0$ and the plateau ran from $L = 4.5$ to > 19 . It is clear that the temporal and spatial behavior of the solar protons in the September event is in agreement with the over-all picture drawn from the July events discussed in this paper.

The containment of solar protons in the storm stream agrees both with the magnetic bottle concept of Gold [1959] and with the 'blast' model of Parker [1961] (see also McCracken [1962]). It seems reasonable that the large fluxes we observe around the time of transition between the initial and main phases of the storm result from a concentration of particles against the leading edge of the magnetic container. Such a concentration in space (also indicated by the Explorer 12 data) would be accentuated by the collision between the solar stream and the geomagnetic field. As the magnetic front arrives at and sweeps past the earth, it reaches in as close as seven to eight earth radii according to our data. Low-energy particles in the distorted, turbulent field region near the interface between the plasma stream and the magnetosphere may become at-

tached to geomagnetic field lines and spiral into the 1000-km altitude where they are detectable by Injun's p-n detectors. After the leading edge of the plasma-containing stream sweeps past, the flux decreases sharply. Later, in the period beyond the peak of the main phase, the decay rate of the plateau flux fits an exponential with a relaxation time of 20-24 hours for 1- to 15-Mev protons. The particles present in the geomagnetic field after the main disturbance has passed probably represent the residue diffusing from interplanetary space where they have been contained. We note, however, that the relaxation times are consonant with those of storms, suggesting that these particles may have become geomagnetically trapped and thus represent the high-energy end of the protons forming the diamagnetic ring current which, in the theory advanced by Singer [1957], Dessler and Parker [1959], and Akasofu and Chapman [1961], produces the main phase of the storm.

However, strong evidence against geomagnetic trapping of the solar cosmic rays is the fact that particles are consistently observed in regions with large L and θ ; that is, on field lines whose equatorial crossings occur at 13 to more than 20 earth radii, where the field is weak and distorted. Particles on these field lines could be easily removed from a trapped condition and, in the first instance, would be difficult to trap because of the breakdown of the adiabatic invariant at large L . However, these arguments do not exclude the possibility of temporary trapping for solar protons on field lines with small L values. In addition, main-phase trapping of the 1- to 15-Mev solar protons would be inconsistent with the recent proposal by Dessler, Hanson, and Parker [1961], that the particles producing the main phase are ambient protons raised to kilovolt energies by hydromagnetic heating through contact with a solar plasma. It is not unreasonable that the exponential decay of the residual particle flux may be due to the conditions of the plasma's travel through interplanetary space or even to the circumstances of its production at the sun.

The extensive measuring period and geographical coverage of the satellite data establish the characteristics of the temporal and spatial variations of the geomagnetic cutoffs in detail for the 1- to 15-Mev protons and to some extent for those above 40 Mev; the general behavior is

probably applicable to protons over a wide energy range: the magnitude of the main-phase shift to lower latitudes and the period and rate of recovery to normal depend on the particle energy, the magnitude of the storm-time field depression, and the location of the observation site. (Yoshida and Wada [1959] also noted that the reduction in the cutoff is a function of the storm field.)

The time dependence of the cutoff recovery is a function of position, as is evident in all the satellite data showing the variation of proton intensity with L and θ . This characteristic is also clear from balloon data where on July 16, 1959, for example, solar protons were still arriving at Murmansk at $\theta = 64^\circ$ [Charakhchian et al., 1960] though their influx had ceased at Minneapolis at $\theta = 56^\circ$ [Kellogg and Winckler, 1961] where in general the recovery was completed before the storm ended [Winckler, Bhavsar, and Peterson, 1961]. The longer duration of proton intensity at high latitudes was also observed by Anderson and Enemark [1960] and Brown and D'Arcy [1959]. With regard to the speed of recovery, we observe that the return to normal is fastest at the lower edge of the proton region and lengthens with increasing latitude.

In general, the temporal changes should be related both to the position of the observation site and to the details of the storm period. The totality of change in the over-all situation is complex because it is undoubtedly affected by different physical processes including: in the prestorm period, the leakage from the main stream of the plasma into the geomagnetic field; in the initial phase and part of the main phase of the storm, the collision of the plasma with the geomagnetic field and entry of the particles into the field; in the diminishing part of the main phase and recovery phase, the interaction between the particles and the changing fields they produce. For a discussion of the propagation of solar cosmic rays and interplanetary magnetic fields, see Meyer, Parker, and Simpson [1956]; Gold [1959]; Parker [1961]; and McCracken [1962]. For treatments of various aspects of magnetic storms, see Chapman and Ferraro [1933]; Singer [1957]; Dessler and Parker [1959]; Akasofu and Chapman [1961]; Dessler, Hanson, and Parker [1961]; and Vestine [1961].

There is excellent correlation in the general

temporal behavior of the flux of protons detected by Injun at high latitudes and the results (Leinbach, private communication) of the absorption of cosmic radio noise detected by the oblique riometer at College, Alaska: starting times and periods of increase, decrease, and maximum are practically coincident. The agreement is perhaps not surprising since Injun's orbit intersects lines of force that penetrate the absorption region. There appears to be no doubt that many of the Injun protons at 1000 km penetrate into the lower ionosphere to produce the cosmic radio noise absorption.

In addition, the spatial variation of the flux at 1000 km marks a region very similar to that of the polar-cap absorption in the lower ionosphere. Consider, for example, the prestorm pass of 1717 UT July 12, recalling that all data reported here refer mainly to passes over North America and that polar-cap absorption occurs generally before the storm. The flux of 1- to 15-Mev protons has a sharp cutoff at $\theta = 63^\circ$ and rises sharply to about $\theta = 65^\circ$, where the rate of increase slackens to a plateau flux beginning about 71° and extending to about 75° , the highest latitude for which telemetry is here available. This variation of the 1- to 15-Mev flux is practically identical with that of the polar-cap absorption reported by Reid and Leinbach [1959] for 24 events during the IGY riometer program: the duration and intensity of polar-cap absorption at College, $\theta = 64.7^\circ$, is less than that at more northern stations; and at Farewell, $\theta = 61.4^\circ$, the absorption is with few exceptions either weak or absent. On the other hand, riometer records at Barrow, $\theta = 68.6^\circ$, and Thule, $\theta = 88^\circ$, show a striking similarity, apparently placing at the auroral zone the low-latitude limit of the zone of uniform polar-cap absorption.

The excellent agreement between the spatial variation of the polar-cap absorption and the 1- to 15-Mev proton flux is abundantly clear: Farewell is at the proton cutoff; College is in the region where the flux is rising sharply; Barrow is in the plateau region which in our data extends to about 75° , but which no doubt reaches to the pole. The latitude variation of the protons (as well as the general trend of the energy spectrum) is also similar to that deduced by Bailey [1959] to fit his ionospheric absorption measurements at very high frequencies for the event of February 23, 1956. It is significant that

the omnidirectional flux of Injun protons with energy above 40 Mev was 20 protons/cm² sec or less during the storm of July 13. It consequently appears that the polar-cap events studied by *Reid and Leinbach* [1959] are due primarily to protons of energy 1–15 Mev. In addition, when these protons are contained in the storm stream, as in the storm of July 13, the region of polar-cap absorption should show the storm-time depression to lower latitudes and the gradual return to prestorm conditions. At times when the dominant solar proton energy is not 1–15 Mev, the absorption region should move, for example, toward the equator for more energetic protons. Consequently, if the coincident storm is not overpowering, the polar-cap absorption at about 1100 UT July 18 should show a spatial variation similar to that shown in Figure 9 for the protons above 40 Mev in the pass of 1140 UT July 18.

A further result of interest from the July solar proton data concerns the temporal variation in the energy spectrum of the particles. Our results lead to two conclusions: the energy spectrum varies (1) within a single event, and (2) from one event to another. These conclusions are in agreement with those of other workers about higher-energy particles [*Winckler, Bhavsar, and Peterson*, 1961; *Winckler and Bhavsar*, 1960]. Variation within a single event is exemplified in all four July storms to some degree. It is especially marked in the events of July 18, in which more high-energy than low-energy particles were observed early in the day, and vice versa later. The regularity shown in the behavior of the exponent with time in the storm of July 13 may have some significance; however, it does not occur again in the storm of July 20. A similar change in the exponent in a power-law spectrum was observed by *Winckler and Bhavsar* [1960] for balloon-measured protons of $E > 105$ Mev at Minneapolis during the geomagnetic storm of May 12, 1959. They attribute the change to the action of the geomagnetic field on the proton beam from space, whereas our changes in the exponent occur at sufficiently high latitudes and altitude to be attributed to the proton stream itself.

Recently, *Bailey* [1962] has summarized observations of the time variations of the energy spectrum of solar cosmic rays. Bailey's own data on ionospheric absorption of VHF, and rocket-

borne Geiger counter, scintillation counter, and emulsion results of *Davis, Fichtel, Guss, and Ogilvie* [1961] and *Ogilvie, Bryant, and Davis* [1962] indicate that a power-law spectrum with constant exponent is not adequate to describe solar protons. As was noted earlier, the fact that our results cover only two energy ranges prohibits any direct comment on this matter; however, the fact that we observe quite wide variations in the exponent (using a constant exponent spectrum) leads us to believe that the conclusion of Bailey and of Davis and others is indeed correct.

The maximum flux of 1- to 15-Mev protons that we observed in July 1961, 33,000 particles/cm² sec ster, is one of the largest in this energy range yet reported. It is only slightly less than the value reported by *Ogilvie, Bryant, and Davis* [1962] for the event of November 12, 1960, and lends further strength to *Bailey's* [1962] conclusions concerning the radiation hazard of solar protons.

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