JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 66, NO. 6 JUNE 1961

The Spectrum and Propagation of Relativistic Solar Flare Particles during July 17–18, 1959

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Abstract. In the interval July 17–18, 1959, one solar charged particle intensity increase was definitely observed before a sharp Forbush type decrease, and a second appeared likely following the decrease. These events were detected at sea level and at mountain altitudes. The first event followed the giant solar flare of July 16, and the solar particles appeared to arrive isotropically at the earth. The intensity time dependence of this event showed a slow rise-time comparable with its exponential decay. The integral rigidity spectrum for these particles was approximately $(cp/ze)^{-9}$. The second event, although not uniquely determined as a solar flare event, followed some minor solar flare activity and might be explained by assuming an anisotropy (impact zones for the source in the solar direction) for several hours. The integral rigidity spectrum for this second event was $(cp/ze)^{-4.5}$.

This sequence of intensity increases could be explained by the diffusion of solar particles from the July 16 flare through disordered magnetic fields to reach the earth isotropically. The effect of the mechanism for the subsequent Forbush intensity decrease is to smooth the interplanetary fields so as to leave behind only weak, regular fields through which the fast moving solar particles of July 18 arrive anisotropically at the earth.

1. THE SOLAR EVENTS

Solar flares frequently accelerate charged particles to the order of 100 Mev and, occasionally, to relativistic energies. A few of the latter events were of large enough magnitude to be recorded through their secondary radiation on the surface of the earth by continuously operating detectors such as ion chambers, neutron intensity monitors, etc. In recent years it has been possible to study in detail the time dependent behavior of the solar particle intensity arriving at the earth. Among the major events are examples in which the intensity increase to maximum occurred in a very short time, such as the events for February 23, 1956, and May 4, 1960, whereas the rise time was 2 to 3 hours for the flare of July 25, 1946. The decline of intensity following the intensity maximum was not the same for all events: many of the events are described by power-law time dependence. From the detailed study of the February 23, 1956, solar-proton event it has been shown [*Meyer, Parker, and Simpson,* 1956] that the rise-time to intensity maximum and the subsequent decline of intensity are the result of solar particle propagation through magnetic fields in the interplanetary medium extending beyond the orbit of earth. Since each of the large-scale events has taken place at widely spaced intervals in time and at different phases of the solar cycle, it has been relatively easy to describe different interplanetary magnetic field conditions that satisfy the time dependence of each solar particle intensity increase at the earth. These large-scale events distributed over long time intervals, however, have made it difficult to develop a unique theory to describe all events without excessive adjustment of parameters for any given period. Therefore, it is of great interest to find two solar proton intensity increases, separated by only a short interval of time, in which the time dependent nature of the increases differs. The purpose of this paper is to describe two events, one which is certainly proton production and the other which, on the basis of our analysis, appears to be solar production, but whose requirements for propagation in the interplanetary medium are greatly different.

The first event followed the giant solar flare of July 16, 1959. The second event followed a solar

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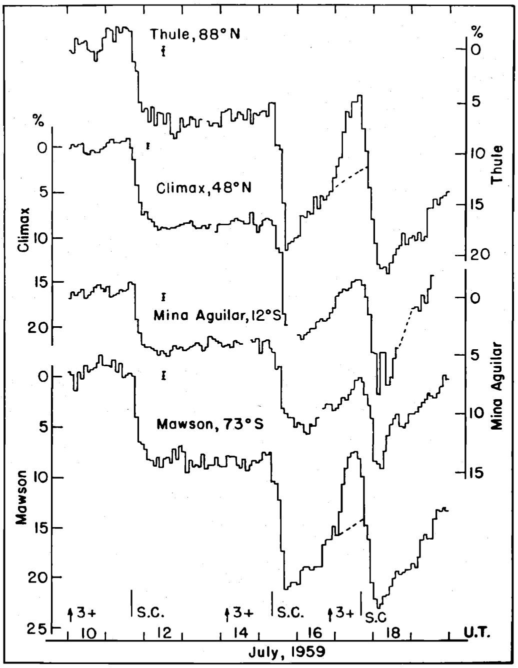

Fig. 1. Neutron intensity monitor data. Deviations, in per cent, from the average intensity recorded during July 6 to 10, 1959.

flare most readily identified by its polar-cap absorption on July 18. For the first event the solar particles appeared to come isotropically to the earth, whereas for the second event, we explain the available data on the basis of a solar particle increase assuming extreme anisotropy persisting for many hours. Such a combination of events places additional constraints upon any model for interplanetary or solar fields proposed to account for the propagation and storage of solar particles. The events we report here were part of a sequence of large-scale events following the greatest solar activity of the present cycle. This period began on July 10, 1959, with the 3+ flare indicated in Figure 1. This flare was followed by low-energy protons arriving at the earth to produce polar-cap absorption [*Reid and Leinbach*, 1959] and has been measured directly by balloon observations at polar latitudes [*Brown and D'Arcy*, 1959]. The slowly moving, highly charged gas from the flare arrived at the earth to produce a sudden commencement on July 11, and it provided the mechanism for the sharp Forbush-type decrease of cosmic-ray intensity as shown in Figure 1. The next great event was on July 14 and led to a sudden-commencement magnetic storm at the earth on July 15 that was one of the greatest in the present solar cycle. Again a sharp Forbush decrease of intensity occurred. Thereupon the cosmic-ray intensity slowly began to increase in the vicinity of the earth. The third 3+ flare occurred late on July 16, and led almost immediately to the beginning arrival of particles in the vicinity of the earth, increasing slowly in intensity to a maximum on early July 17, after which followed a slow decline of intensity. This was terminated by an additional sharp Forbush-type intensity decrease bringing the total cosmic-ray and solar particle intensity to its lowest value of the present solar cycle (J. A. Simpson, unpublished). The arrival of relativistic solar particles after the 3+ flare of July 16 and their observation at ground and mountain stations, is the event described in section 2 of this paper. A smaller solar event on July 18 apparently also produced relativistic particles reaching the earth. The analysis of this event is given in section 3. Thus the first event on July 17 and the second event on July 18 are separated by a different type of solar phenomenon producing a sharp decrease of galactic cosmic radiation. We suggest that the propagation of particles from the sun

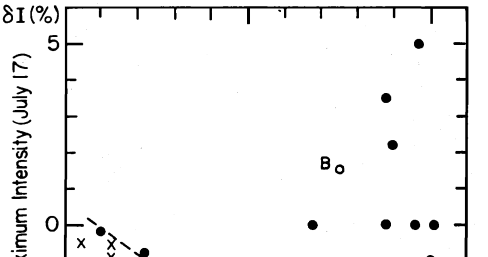

Fig. 2. Deviations, in per cent, at the time of maximum solar particle intensity on July 17 vs. deviation at minimum intensity during the Forbush decrease of July 15. (B: Bergen station.)

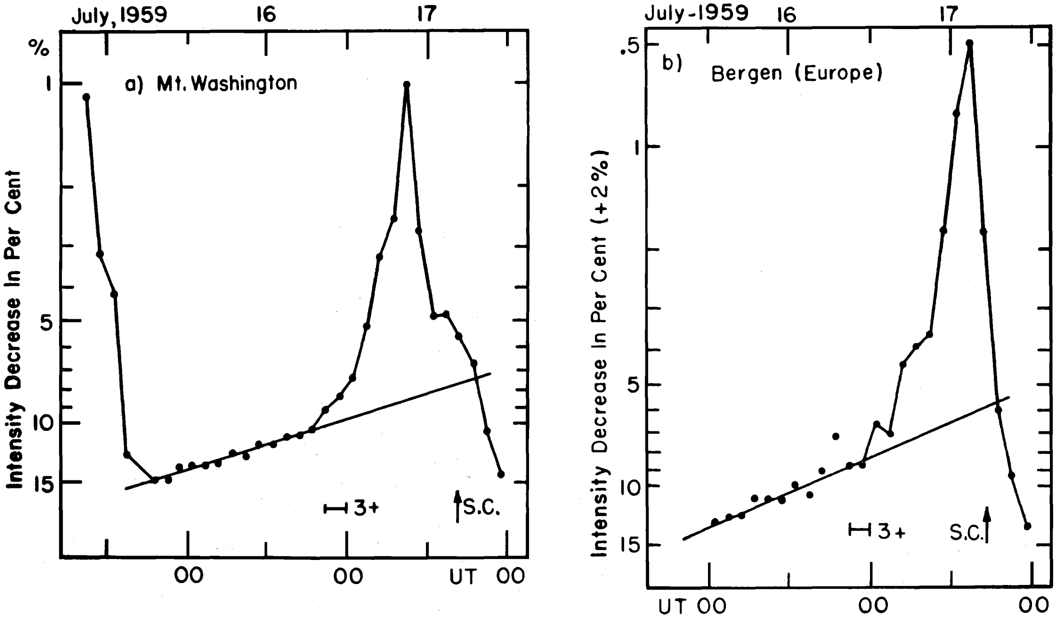

Fig. 3. Neutron intensity monitor data. Semilogarithmic plot of relative deviations after the Forbush decrease of July 15, for Mt. Washington (56°N, 357°E geom.; cutoff: 1.03 bv) and Bergen (62°N, 95°E geom.; cutoff: 0.94 bv). (Reference level: average intensity through July 12 to 14, 1959.)

and the interplanetary medium before the sharp decrease in intensity is entirely different from the propagation after the sharp decrease of intensity.

Since not only the large flares but several of the smaller flares produced nonrelativistic particles that could reach balloon altitudes at high latitudes, many of the events studied at low energies during this period are difficult to analyze because of the superposition of particle fluxes from different events. Therefore we restrict our analysis to the relativistic particles whose effect is observed deep in the atmosphere by neutron intensity monitors and by meson telescopes. The work we report here is based upon data from the records of the University of Chicago Cosmic Ray Network and was extended in the final stages of analysis by the sets of data collected and distributed by H. Carmichael and J. Steljes of Chalk River, and by independent investigators throughout the world. The instruments used for analysis cover a network of more than 30 stations in both hemispheres and a wide range of longitudes.

Descriptions and interpretations of the cosmic-ray events of July 17 and 18 have been presented: for example, those of *Carmichael and Steljes* [1959]; *Wilson, Rose, and Pomerantz* [1959]; *Steljes and Carmichael* [1960]; and *McCracken and Palmeira* [1960].[2]

2. SOLAR PROTONS FROM THE FLARE OF JULY 16, 1959 AND THEIR ISOTROPIC ARRIVAL AT THE EARTH

A. Geomagnetic distribution of arriving particles. The increase of intensity was readily observed to the highest geomagnetic latitudes in both hemispheres. For example, in the northern hemisphere at Thule (88°N), Figure 1, at Resolute (83°N), and at lower latitude stations there

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[2] Note added in proof. In more recent work Rose and Lapointe (private communication) support as the explanation for the intensity peaks on July 18 an entirely different point of view from that suggested in this paper. They favor a temporary failure in the Forbush type decrease mechanism giving apparent sources roughly in solar and anti-solar direction and allowing the anisotropic arrival of galactic cosmic ray particles. It is the further purpose of this paper to present arguments which instead favor solar particle production for this event.

is observed an excess of radiation after the 3+ flare, but this was not detected at very low latitudes. Since the largest effect for the relativistic particles occurs in the polar regions, it is not possible that this is due to any temporary change in the geomagnetic field cutoff. Consequently, it must be assumed that these are primary particles approaching the earth and that they are particles accelerated by the 3+ flare that began only an hour or so earlier. The same increase is observed in the southern hemisphere, at Mawson (73°S), and at Ellsworth (67°S), as shown in Figure 1. It is difficult to set a limiting geomagnetic latitude for the point where no increase was observed; however, it was negligibly small at Climax (48°N). Thus the solar particles must extend in energy to a few bev only. At high latitudes, the increase of intensity was observed over a wide range of longitudes—for example, in the northern hemisphere, in Europe (Bergen), and Asia (Yakutsk), and in the southern hemisphere, Ellsworth and Mawson, which differ by about 7 hours in longitude but show almost identical intensity records. From these and other data we conclude that the full increase was observed over all longitudes at the earth. It then follows that the particles incident at the earth must have been essentially isotropic in nature and extended in energies up to approximately 2 bev for protons.

B. Magnitude of the intensity increase. If we assume that these primary particles are solar protons, then to obtain the total intensity at any given time the galactic background intensity must be removed. This is complicated by the fact that cosmic-ray intensity of nonsolar origin was recovering from two superimposed sharp decreases of intensity. In addition, there persisted a daily solar variation of relatively large amplitude and irregular behavior during these periods of high solar activity. This is likely to increase the errors for measuring total intensity at different longitudes at a given absolute time.

For the purpose of the analysis reported here we use the results of Simpson (Midwest Cosmic-Ray Conference, Iowa, 1959, unpublished) and of *Roederer, Santochi, Anderson, Cardoso, and Manzano* [1960], who show that one of the main properties of the three successive sharp decreases of intensity on July 11, 15, and 17 is their linear superposition. We shall assume that the relaxation time for short periods is roughly independent of energy and that the deviations of intensity from the reference level are proportional to the maximum deviation at the time of minimum intensity on the Forbush decrease. To show the separation of the high-latitude intensity increases from the recovery of the galactic cosmic radiation, we have plotted in Figure 2 the relative deviations δI at the time of maximum solar particle intensity on July 17 as a function of the deviations δI_0 during the Forbush decrease of July 15 at the time of minimum intensity for galactic particles. (For a reference level we use the average intensity during July 12 to 14.) It is noted that those stations that deviate greatly from the 'normal' curve are at high latitudes with geomagnetic cutoff rigidities below approximately 1.5 bv. The group of European stations, which were near local noon at the time of maximum intensity, with cutoff rigidities over 1.5 bv shows the contribution of daily variation, but Bergen (cutoff = 0.94 bv) is well over the expected level for recovery plus daily variation. In this type of analysis the difference between the observed and the expected deviation for the recovery from the sharp cosmic-ray intensity decrease represents the contribution of solar particles. The counter telescopes, which measure the effect of primary particles of much greater energy, show only the expected changes from the galactic cosmic radiation.

The magnitude of the intensity increase may also be measured by extrapolation of the background cosmic-ray intensity on a semilogarithmic plot. Figure 3, *a* and *b* represent two examples showing that the deviations δI follow an exponential recovery up to the point when the first solar protons appear to arrive. The magnitude of the solar particle contribution above the extrapolated intensity has been estimated in this manner and the data obtained from this technique were used in the following section to deduce the time dependence and spectrum of the solar particles.

Although the contribution of the daily intensity variation is not eliminated by this technique, stations grouped in small intervals of longitude were used to determine a spectrum so as to reduce the effect of the daily variation.

C. Spectrum of the solar particles. The restriction of the intensity increase to detectors with cutoff rigidities less than approximately 1.5 bv (Chicago) and extending to near zero bv (Thule, Resolute) show that the observations are a combination of the energy distribution of solar particles and their absorption effect in the atmosphere. We estimate the relative dependence of the primary spectrum on magnetic rigidity by defining the relative increases of the total counting rate N at sea level and at mountain altitudes $\delta I = \delta N/N$, and by taking the nucleonic component yield functions relating the variation of the primary particle flux to the nucleonic component intensity deep in the atmosphere. Thus,

$$\frac{\delta N}{N}\ (\text{per cent}) = \int_{R_0}^{\infty} \frac{\delta j}{j}\, S_{R_0}(R, x)\, dR$$

where $j(R)$ is the differential rigidity spectrum of the galactic cosmic ray background, and S_{R_0} (R, x), in per cent/bv, is the specific yield function.

Nucleonic yield functions have been improved over the past several years by increasing knowledge of the intensity variations and changes of primary spectrum with time, and by more refined knowledge of geomagnetic cutoffs [*Simpson, Fonger, and Treiman*, 1953; *Dorman*, 1957; *Brown*, 1957; *Webber and Quenby*, 1959]. They all have, however, a low rigidity cutoff between 1 to 2 bv produced by atmospheric absorption of the normal cosmic-ray spectrum. With an additional flux of particles of solar origin, several orders of magnitude greater than the cosmic-ray flux at the top of the atmosphere, we expect to observe particles of energies normally assigned below the atmospheric cutoff. For the analysis here a straight extrapolation of the nucleonic yield functions as given by Webber and Quenby has been used, and we have assumed a relative variation of the primary particle spectrum of the form $\delta j/j = K(t)R^{-\gamma}$, where $R = cp/Ze$ is the magnetic rigidity. Using this function combined with the extrapolated yield function, the value for γ that provides the best fit is $\gamma = 7.5$, shown in Figure 4 for both mountain and sea-level stations. These points are drawn mainly from data in a small range of longitude in North America, but data from Bergen and Yakutsk are also included. A rough correction for the daily intensity variation contribution was applied to the Bergen data. Mountain station increases were reduced to sea level using an absorption length of 92 g/cm² deduced from Mt. Washington and Sulphur Mountain. Thus the *integral* rigidity spectrum of the solar radiation is R^{-9}, although some higher values for the exponent are also possible. (*McCracken and Palmeira* [1960] have also estimated approximately the same value as shown above for the exponent γ.) This steep spectrum is very similar to that found for other large solar relativistic proton events [*Meyer, Parker, and Simpson*, 1956]. Interestingly, for the low-energy solar protons observed on other days in July 1959, *Brown and D'Arcy* [1959], Winckler, Ney, and Fenton and Simpson, all observed a differential energy spectrum varying from approximately $E^{-4.2}$ to $E^{-4.5}$ (E = kinetic energy) that yields an integral rigidity spectrum similar to R^{-6}.

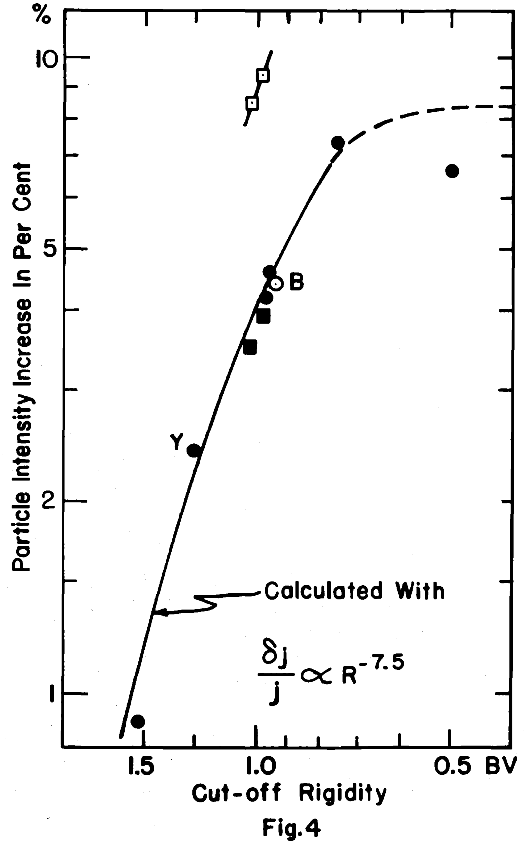

Fig. 4. Solar particle increases for mountain and sea level stations as a function of geomagnetic cutoff rigidity. Mountain stations (□) are also plotted reduced to sea level intensity (■). (B: Bergen; Y: Yakutsk.)

D. Time dependence of the solar particle flux and its implications for the propagation of solar particles on July 17. The solar flare of July 16 began at about 2115 UT and was observed until after 0100 UT July 17 [*Howard and Babcock*, 1960]. Polar-cap absorption began about 2 hours later and the maximum absorption was reached about 16 hours after its onset [*Leinbach and Reid*, 1960]. Solar protons were observed at balloon altitudes by Brown and D'Arcy and others, the enhanced intensity being approximately 3.5 times the normal background near 0000 UT, July 17. Intensity increases at low altitudes and high latitudes are expected, however, only when the extra flux at the top of the atmosphere reaches a considerable value over the normal background and sufficiently high energy. Neutron monitor increases were delayed by the order of 2 to 4 hours and the full intensity was not reached for approximately 10 to 12 hours after the beginning of the solar flare. Two outstanding examples giving the time dependence of the intensity increase for particles above approximately 1 bv magnetic rigidity appear in Figure 5. The intensity decline appears to be exponential until obscured by the onset of the Forbush decrease after approximately 1700 UT. Thus, in first approximation, the rise to full intensity and the subsequent decline have time constants that are of the same order of magnitude.

This suggests that the arrival of solar protons is controlled by storage and scattering magnetic fields near the sun and in the interplanetary space. For example, it is possible to develop a diffusion model for this flare event based upon the analysis of the cosmic-ray intensity increase of February 23, 1956, by *Meyer, Parker, and Simpson* [1956]. Several approximations depending mainly on the time t elapsed following the injection of particles by the sun have been developed by Meyer, Parker, and Simpson in the appendix of their paper. For conditions such that the diffusing particles are approximately midway inside the borders of a magnetic barrier concentric with the sun, the distribution of particle density at a

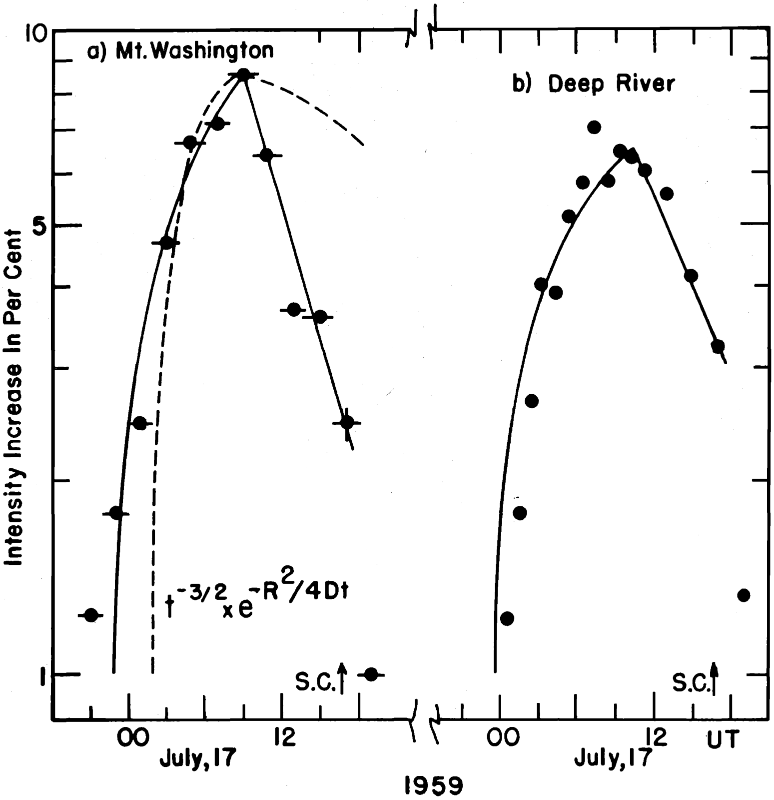

Fig. 5. Neutron intensity increases due to solar radiation on July 17 as a function of time. For Mt. Washington the dashed line is calculated with expression $t^{-3/2} \cdot \exp(-R^2/4Dt)$.

distance r from the origin $J(E, r, t)$ is given by the solution

$$J(E, r, t) = Kt^{-3/2} \exp(-r^2/4Dt) \qquad (1)$$

where D is the diffusion coefficient, multiplied by the factor

$$1 + O(a^2r^2/D^2t^2) \qquad (2)$$

where a is the inner border radius of the barrier. When the particles reach the external border $r = b$ of the magnetic barrier, however, the series expansion reduces the first approximation to an exponential function of time, given by

$$J(E, r, t) = K' \exp(-\pi^2 Dt/b^2) \qquad (3)$$

Thus the main parameters of the magnetic barrier suitable for diffusion may be crudely approximated as follows: The intensity maximum for (1) occurs at $t = r^2/6D$. Using $t_{\max} = 10$ hours and $r = 1$ astronomical unit, we obtain for the diffusion coefficient $D = 10^{21}$ cm² per second, which corresponds to a mean free path $\lambda = 10^{11}$ cm. The solution (1) becomes approximately exponential for t such that $\pi^2Dt \gtrsim b^2$, and this occurs in our case shortly after the maximum (roughly at $t = t_{\max}$). This leads to determination of $b = 1.9 \times 10^{13}$ cm. Independently b may be estimated from the slope of the exponential decay in Figure 5*a*. This value is $b = 1.5 \times 10^{13}$ cm. In addition, the order of magnitude of a may be estimated from factor (2). This yields a value $a = 5 \times 10^{11}$ cm. These calculations suggest that a region of magnetic irregularities with a mean free path 10^{11} cm extending from the vicinity of the sun to at least the orbit of earth, but not much farther beyond, could explain reasonably well the time dependence of this event for the relativistic particles.

In summary, the experimental evidence indicates that the particles arriving at the earth from the hour 0000 UT to approximately 1700 UT were isotropically distributed in space, but they followed the giant solar flare by 2 to 4 hours; that they have a very steep rigidity dependence corresponding to flare particles already measured in earlier events, and that if they originated in a source at the sun, they propagated to earth by diffusion or other scattering effects arising from solar and interplanetary magnetic fields possessing some disordering. The disordering of weak fields in the space between the sun and the earth seems likely at this time, since over 50 to 60 hours had elapsed from the time of the last sharp decrease of intensity, and in this intervening period much solar plasma was injected into the space between the sun and the earth capable of manipulating any weak fields in the region.[3]

3. Anisotropic Arrival of Solar Particles on July 18

A. Geomagnetic distribution of the arriving particles. Unlike the solar particle event described in a previous section, the arrival of solar particles as early as 0230 UT on July 18 (Ottawa, Deep River, Chicago) followed the sharp decrease of galactic intensity on July 17 and was entirely different. Whereas the July 17 event indicated particles arriving isotropically over a period of many hours, the event of July 18 has to be interpreted either as solar protons arriving from a point source to produce extremely sharp impact zones at the earth or, as proposed by Rose and Lapointe, as an opening up of the mechanism of the Forbush type decrease temporarily to produce an anisotropy. We believe that the arguments to be presented below open up the distinct possibility, and may, in fact, favor the idea, that this anisotropy is due to solar protons. It will be shown that this anisotropy is in favor of a source that includes the sun, and that the anisotropy persisted for the order of 9 hours. The data for several locations are shown in Figure 6. For example, in the southern hemisphere the flux of solar particles appears near Australia several hours later and disappears sharply shortly thereafter, about 1200 UT. During this period the cosmic-ray intensity over Europe recovered normally from the world-wide Forbush decrease without any significant trace of a superposed flux of solar particles, as shown by a comparison of the increase at Climax with the lack of an increase at Zugspitze (see Fig. 7). In North America the increase was not detected in the polar regions (Thule and Resolute, Fig. 7) nor at latitudes lower than approximately 44° geomagnetic. It is obvious that during the hours of approximately 0200 to 1200 UT, or later, there was a limited area in each hemisphere at the earth at intermediate latitudes extending only a few hours in longitude that received the flux of solar particles capable of penetrating deep into

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[3] For a description of over-all solar activity during July 1959 see, for example, Report no. HAO-49, High Altitude Observatory, Boulder, Colorado.

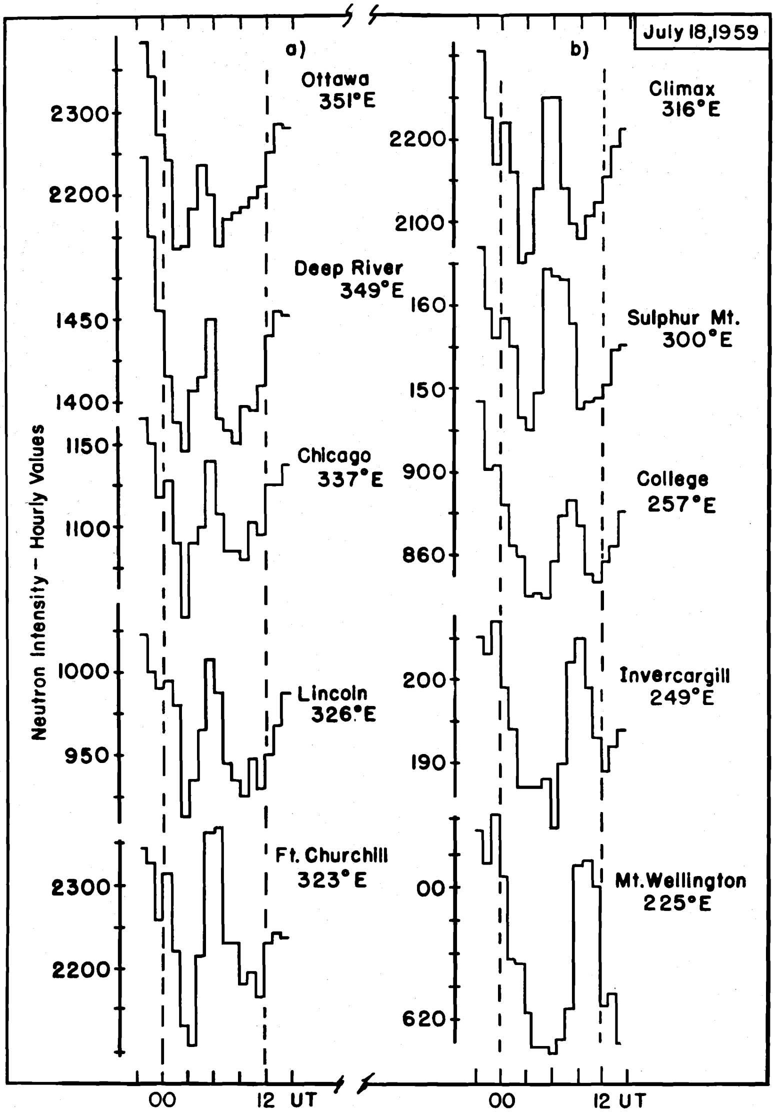

Fig. 6. Hourly neutron intensity monitor counting rates (÷ scaling factor) for stations that observed the intensity increase on July 18.

the atmosphere so that their secondary radiation could be detected by neutron intensity monitors.

The impact zones expected at the earth for the position of the sun at this time showed that the stations detecting increases were moving through the 2000-hour impact zone corresponding to particles with asymptotic direction near the sun. For the first hours of the increase the longitude extent of the impact zone over North America is compatible with a source of 10°-solid angle in the sky. At later times it appears that the source gradually increases its apparent diameter, ultimately reaching approximately 40° solid angle. The change in geomagnetic latitude of the sun between 0300 and 0600 UT was negligible. Hence, the impact zones remained fixed with respect to the sun-earth line, and variations in intensity may be assumed to represent, in part, the transit of the detectors on the earth in and out of these impact zones. Between 0600 and 1200 UT the geomagnetic latitude of the sun increases rapidly up to 25°N, and this effect

TABLE 1. Stations with Data Considered in the Present Analysis of the Distribution of the Increases

Station	Type of Detection	Geomagnetic Latitude, degrees	Geomagnetic Longitude, degrees
Thule	N	88	1
Resolute	NT	83	289
Ft. Churchill	NT	69	323
College	N	65	257
Sulphur Mt.*	NT	58	300
Ottawa	NT	57	351
Deep River	N	57	349
Mt. Washington*	N	56	357
Chicago	NT	53	337
Lincoln	N	51	326
Climax*	N	48	316
Berkeley	N	44	298
Sacramento Peak*	N	42	318
Mexico City	N	29	327
Hawaii	N	21	267
Huancayo*	N	−01	354
Mina Aguilar*	N	−12	3
Rio de Janeiro	N	−13	24
Buenos Aires	NT	−23	9
Ellsworth	NT	−67	15
Bergen	NT	62	95
Uppsala	N	59	106
Leeds	N	56	83
Herstmonceaux	NT	54	84
Munich	N	49	92
Zugspitze*	N	48	92
Jungfraujoch*	N	48	89
Yakutsk	N	51	194
Mt. Norikura*	N	26	204
Itabashi	I	26	206
Kodaikanal*	N	01	147
Kampala	N	−02	101
Lae	NT	−16	217
Sydney	N	−42	226
Hobart	NT	−52	225
Invercargill	N	−52	249
Mawson	N	−73	103

* Mountain stations; N, neutron monitor; T, counter telescope; I, ionization chamber.

combined with the increasing apparent diameter of the source changes the position and extent of the impact zone at later times. No increase in the northern hemisphere 0900 impact zone is expected, since for the relatively high latitude of the sun, solar particles with a steep spectrum, and detectors near 50° on the same hemisphere as the source, the relative increase between the merged 0300–2000 impact zone and the 0900 hour impact zone is over 100 to 1 [*Lüst and Simpson*, 1957]. This would explain why the European stations (Zugspitze, Jungfraujoch, Munich, Leeds, etc.) travel through the 0900 impact zone without observing appreciable increase in solar particle intensity.

Table 1 lists all the stations that were analyzed for increases of intensity, but only those shown in Table 2 had increases that were measurable. In this table the stations are ordered according to decreasing geomagnetic longitude, which is the same order in which the beginning of the increases was observed.

B. Time distribution for the beginning of intensity increases at the earth. Examination of the intensity increases at stations over a wide range of local times or longitudes shows that there is a systematic displacement for the times at which the intensity begins to increase. This is illustrated in Figure 8 for hourly values of neutron intensity. From a more detailed analysis using 15-minute (or shorter interval) data, we see an increase begin at about 0230 UT at Ottawa and Deep River (Canada), and at Chicago, whereas at Climax it begins at about 0345 UT, and at Sulphur Mountain at about 0430 UT. On the other hand, Figure 8 shows that within a 1-hour local time interval all stations first detecting an increase of intensity display a simultaneous onset for the increase. The duration of the increase at all stations is approximately 3 to 4 hours.

To estimate the total time over which the solar particles are arriving at the earth we note that the increase persists until 1200 UT at Mt. Wellington (Hobart) and at least between 10 to 12 UT at Yakutsk (194°E), as Yakutsk was moving into the 18–24 hour local time interval. It thus appears that if impact zones are to account for this phenomenon they must persist for about 9 hours after the onset of the event, or there must have been a succession of solar flare events producing almost identical bursts of particles.

C. Intensity and spectrum of the solar radiation. Table 2 lists the magnitudes of the intensity increases for different geomagnetic cutoff rigidities at the top of the atmosphere. Maximum intensity at Ottawa, Deep River, and College was approximately from 5 to 6 per cent above the recovering cosmic-ray intensity. At Yakutsk, using bihourly data, it was approximately 3 per cent. All these detectors were moving out of the impact zone or had recorded the intensity increase

TABLE 2. Stations Recording the Increase on July 18
Increases are expressed as percentage with respect to the intensity at minimum of the Forbush decrease.

No.	Station	Geomagnetic Longitude, °E	Cutoff, bv*	Neutron Monitor, %	Counter Telescope, %	Ratio *N/T*
1	Ottawa	351	0.96	4.7	2.8	1.7
2	Deep River	349	0.97	5.5	...	...
3	Chicago	337	1.54	9.1	4.7	1.9
4	Lincoln	326	2.5	10.5	...	...
5	Fort Churchill	323	0.11	12.5	2.8	4.5
6	Climax†	316	2.71	9.8	...	...
7	Sulphur Mountain†	300	0.98	13.4	5.6	2.4
8	Berkeley‡	298	4.4	∼5.1	...	...
9	College	257	0.5	5.7	...	...
10	Invercargill	249	1.9	9.6	...	...
11	Sydney‡	226	4.1	∼7.0	...	...
12	Mt. Wellington	225	1.7	9.5	4.5	2.1
13	Yakutsk‡	194	1.25	∼3.0	...	...

* Quenby and Webber, 1959.
† Mountain station.
‡ Bihourly data.

at late times. Their maximum values must be less than the total intensity attained at early times during the event. For three southern hemisphere stations separated by about an hour the increase was approximately 10 per cent, and most of the neutron detectors centered in the impact zone at early times reached a peak intensity of the order of 10 per cent. In several instances both neutron intensity monitors and counter telescopes simultaneously recorded intensity increases (for example, Fig. 9). The ratio was approximately 2:1 except at Fort Churchill, where it reached 9:2 for the relative increase between the neutron intensity monitor and counter telescope. This ratio is very small for steep energy spectrum particles where the ratio may attain values as high as 10:1. This result would lead to a relatively flat spectrum for the additional particles.

We may independently estimate the spectrum by assuming that (1) the particles arrive in the 2000-hour impact zone, and for this zone particles will have rigidities near the geomagnetic cutoff, and (2) for each measurement the detected additional radiation possessed a magnetic rigidity whose value was near the geomagnetic cutoff rigidity for the station. We then may estimate relative change in the primary flux $\delta j/j = K(t)\cdot R^{-\gamma}$ as a function of magnetic rigidity by comparing pairs of stations showing either increases of intensity beginning at the same time intervals or simultaneous intensity maximum. Thus we may write

$$\frac{(\delta N/N)_1}{(\delta N/N)_2} = \left(\frac{R_1}{R_2}\right)^{-\gamma}\cdot\frac{S_1(R_1)}{S_2(R_2)}\cdot\frac{\delta R_1}{\delta R_2}$$

where 1, 2 refers to stations 1 and 2, $S_{1,2}$ are the nucleonic component yield functions, $R_{1,2}$ the cutoff rigidities, and $\delta R_1 \simeq \delta R_2$ the ranges in magnetic rigidities.

The results for one pair of mountain stations and several pairs of sea-level stations are given in Table 3. The mean value for the exponent γ of the relative differential spectrum is 3.0 ± 0.4, which leads to an *integral* rigidity spectrum for the solar radiation of the form $R^{-4.5\pm1}$, where the limits in the exponent of the power law had been extended to include the uncertainty in the differential spectrum of the background cosmic radiation arising from the Forbush decrease. Thus the spectrum of the additional radiation appears to possess greater energy dependence than the cosmic ray spectrum.

We have previously noted that the small ratio between the relative increases for neutron intensity monitors and counter telescopes suggests a relatively flat spectrum for the additional particles, and this would apparently contradict the steep spectrum we found from neutron monitor data. Orbit calculations show [*Jory*, 1956; *Lüst*, 1957] that solar particles will arrive within

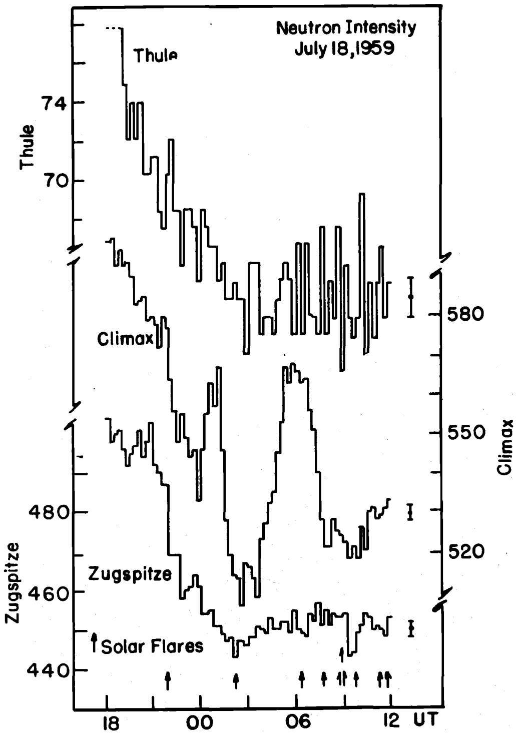

Fig. 7. Neutron monitor counting rates at Thule, Climax, and Zugspitze on July 18 as a function of universal time. Arrows indicate the beginnings of observed solar flares.

the 20-hour impact zone, preferably at relatively large angles from the vertical (16°–32°), and in this event the difference between yield functions for neutron and meson detectors has to be smaller owing to the larger absorption effect for the nucleonic component. Although no yield functions are available for directions other than the vertical, the effect observed agrees qualitatively with the expected behavior for both types of detectors.

D. Problem of the solar source of particles. These observations might be explained either by production of fresh solar particles or by a temporary asymmetry in the recovery of the Forbush type decrease giving an apparent source pointing to the sun. Considering the first point of view, we are led to search for the solar region responsible for the production of particles leading to this effect.

The solar region designated as Q 65 (Preliminary Report of Solar Activity, TR No. 411, High Altitude Observatory, Boulder, Colorado) was the source of the outstanding solar flares, radio noise emission, and phenomena leading to cosmic-ray intensity changes during the period July 10 through 16, and ending with the flare of importance 3+ on July 16 at 2115 UT. After this time only minor solar flares were reported on the visible hemisphere of the sun, including the period of July 18. Following the flare of July 16, polar-cap absorption increased approximately $1\frac{1}{2}$ hours after the flare and continued until after July 20 [*Leinbach and Reid,* 1960]. The magnetic storm that was a consequence of the July 16 flare was well under way on July 18 during the period of the analysis we report here. In addition, during the early hours of July 18, low-energy protons apparently arrived at forbidden southerly latitudes, namely cosmic noise absorption up to 12 db was observed at King Salmon, Canada [*Leinbach and Reid,* 1960].

Thus if the particles come from the sun we

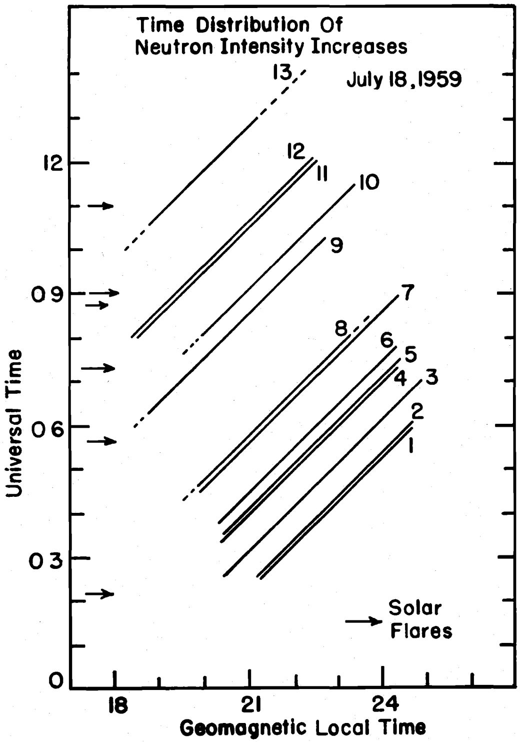

Fig. 8. Universal time distribution of the increases observed on July 18 vs. station local geomagnetic time. Horizontal arrows indicate the beginning of the observed solar flares. Numbers that identify the stations are in the same order in which these appear in Table 2.

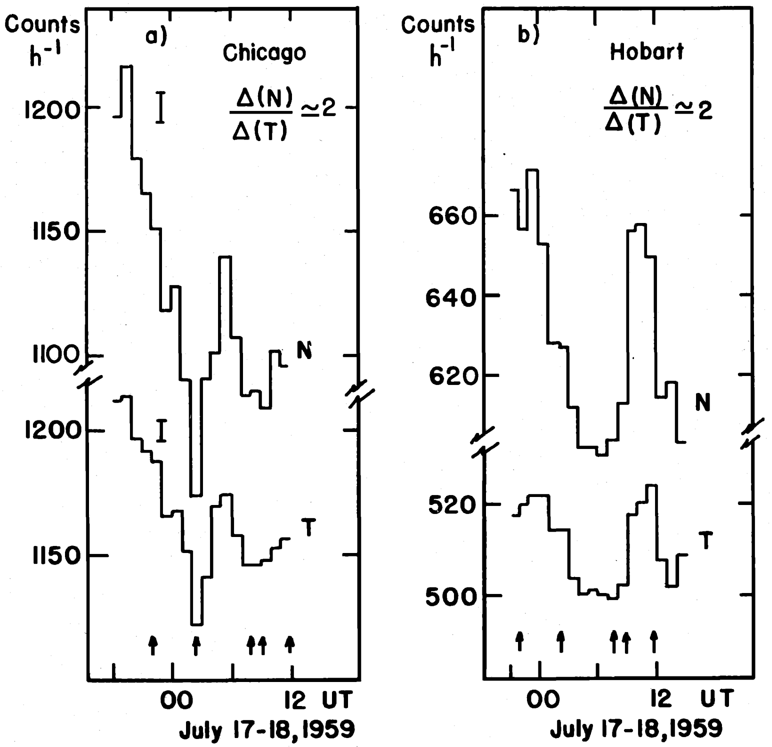

Fig. 9. Comparison of simultaneous neutron intensity monitor (*N*) and counter telescope (*T*) records on July 18 for Chicago and Mt. Wellington (Hobart).

must choose between their production in the July 16 event, with their subsequent holdup in the vicinity of the sun until July 18, when they arrive from the direction of the sun, or we must assume that a subsequent flare, or flares, during the early hours of July 18 accounts for the high-energy particles which arrived at the earth. The former event appears extremely unlikely since the particles arrive anisotropically. An investigation of the optical, solar radio emission and ionospheric effects of solar flares during July 18 makes it improbable, however, that any major flare escaped detection in the visible face of the sun. For example, Table 4 lists all the flares reported until 1200 UT for July 18 with no evidence for large flares.

Since the impact zone effect persists for so many hours it is not likely that any flare production on the back side of the sun could account for this effect.

Thus we are left with the possibility that the observed small solar flares are the origin of the particles on the basis of the present analysis. For example, the early intensity increase that began at about 0230 UT (Ottawa, Deep River, and Chicago) follows a subflare observed in the *Q* 65 region at about 0211 UT, and the increases beginning later at College and at the Australian stations follow closely some flares of importance 1 and 1+.

We wish to point out two other possibilities that appear less attractive. (1) An electromagnetic mechanism producing the sharp Forbush decrease in interplanetary space was fully effective during the hours of these observations. If, therefore, in a particular direction of space, namely, the direction of the sun, this mechanism were not effective for the removal of galactic cosmic-ray particles over a period of 9 to 10 hours, then the increase of intensity analyzed here would be attributed to the particles leaking through this particular region of the sky. This hypothesis would require that the Forbush mechanism be fully restored for the remainder of the days during which the cosmic-ray intensity gradually returns to its former level. This possibility does

TABLE 3. Exponent for the Power-Law Rigidity Spectrum of the Relative Variation in Primary Intensity $\delta j/j = K(t)\cdot R^{-\gamma}$ as Determined from Five Pairs of Stations with Simultaneous Maximum Intensity Increases

Stations	Cutoff Rigidities (bv)	Exponent γ
Climax/Sulphur Mt.	2.71–0.98	3.0 ± 0.1
Chicago/Lincoln	1.54–2.5	2.8 ± 0.8
Mt. Wellington/ Invercargill	1.7 –1.95	3.6 ± 2.2
Mt. Wellington/ Sidney	1.7 –4.1	2.6 ± 0.4
Lincoln/Berkeley	2.5 –4.4	2.9 ± 0.9
Weighted Mean		3.0 ± 0.4

not seem very likely, and it is inconsistent with the observations of the steep spectrum of the additional radiation described earlier in section 3, *D*, which is considerably different from the cosmic radiation spectrum or the Forbush decrease spectrum.

(2) Since this is a local time phenomenon, and since the effect is locally near the antisolar direction, we might imagine the consequences of a strong solar wind interacting with the geomagnetic field to produce the stretched-out and distorted dipole field on the night side of the earth as the earth rotates. Such an effect should result in magnetometer observations indicating this effect. Although the severe geomagnetic storm that began on July 17 was still in progress early on July 18, mainly in high latitude regions, there is no close correlation between the geomagnetic field variations and the time distribution of the observed cosmic ray intensity increases. In particular, the magnetic records of Toolangi Observatory, Victoria (K. B. Fenton, private communication), near the detectors that observed the increases in the southern hemisphere impact zone, show that between 09 and 12 UT, when the cosmic-ray intensity reached its maximum, the geomagnetic field was quiet enough in that region so as to discard any possible correlation between both phenomena.

This last evidence also eliminates here the explanation given by *Kondo, Nagashima, Yoshida, and Wada* [1959] to account for other cosmic-ray intensity increases observed during some Forbush type decreases; namely, the decrease in the geomagnetic cutoff rigidity due to large decreases in the intensity of the geomagnetic field.

Thus although we have not completely proved that the particles are of solar origin, owing to the small magnitude of the associated solar events, it appears to be the most likely explanation for the effect observed here. We wish to point out, in addition, that a few hours earlier there was a shorter increase of intensity that we have not analyzed in this paper because of its smaller size and short duration (about 1 hour).

4. SUMMARY AND CONCLUSION

The analysis made in the preceding sections of the increases occurring July 17 to 18, 1959, supports a solar origin for the additional radiation detected in both events. In the first event particles from a giant solar flare propagate through disordered magnetic fields, extending throughout the space between the sun and the earth, to arrive isotropically at the earth. On the other hand, the first increase on July 18 follows a small solar flare by about 20 minutes, and strong anisotropy for relativistic particles coming from the direction of the sun is maintained during about 9 to 10 hours. So the interpretation of both events as a whole leads us to a further problem; namely, conditions in the inner solar system require changes of the interplanetary fields from disordered to more regular or weak fields to account for the impact zone effect observed on July 18.

Since both increases are separated by a sharp Forbush intensity decrease beginning shortly after 1700 UT July 17, one may consider the intervention in the increases of the dense solar plasma ejected on July 16 and advancing toward the earth as producing the observed geomagnetic storm effect and the removal of galactic cosmic-ray particles beginning July 17. This moving conducting plasma is able to change the magnetic field distribution of the medium through which it progresses, so it is possible that a distorted interplanetary field might be swept by an advancing front so as to leave behind smoother and weaker fields through which the later solar particles travel to reach the earth at the characteristic impact zones. *Fan, Meyer, and Simpson* [1960] reported and explained in this way a very similar effect observed with Pioneer V during the interval March 31 to April 1, 1960.

TABLE 4. Flares and Subflares between 2155 UT (7/17) and 1200 UT (7/18) Reported by National Bureau of Standards, 1959.

Date, UT	Start, UT	End, UT	Maximum, UT	Location	Reg.	Importance	Observatory
7/17	2155	....	....	21N 57W	5265	Sub	Lockheed
7/18	0211	....	....	19N 60W	"	Sub	Lockheed
	0539	0750	0624	15N 55W	5265	1+	Abastumani
	0620	0630	0624	10N 63W	"	1+	Simeiz
	0623	0630D	....	20N 60W	"	1	Capri S
	0718	....	....	22N 61W	5265	Sub	Simeiz
	0718	0736	....	23N 63W	"	1	Good Hope
	0721	0730	....	24N 60W	"	1	Krasnya
	0721E	0728	....	24N 61W	"	1	Zurich
	0739	0812	0743	20N 62W	"	1+	Simeiz
	0742	0757	0746	21N 62W	"	1	Good Hope
	0754	0800	....	24N 60W	"	1	Krasnya
	0724	0728	....	16N 24E	5280	1	Zurich
	0843	0849	0846	14N 65W	5265	1	Simeiz
	0846	....	....	13N 55W	"	Sub	Simeiz
	0854	0906	....	15N 28W	5265	1	Meudon
	0854	0909	0856	15N 25E	5280	1+	Krasnya
	0855	0913	0900	16N 22E	"	1	Good Hope
	0858	0903	0900	21N 27E	"	1	Krasnya
	0852	0908	....	15N 24E	"	1	Arcetri
	0856E	0905	....	13N 23E	"	1	Capri G
	0858E	0913	....	13N 28E	"	2	Schanins
	0859	0912	0855	15N 25E	"	1	Dunsink
	0901	....	....	10N 21E	"	Sub	Arcetri
	0932	0956	....	15N 08E	5277	1	Zurich
	1102E	1120	....	21N 52W	5265	1	Good Hope
	1103	....	....	21N 53W	"	Sub	Stockholm
	1105E	1120	....	20N 51W	"	1	Zurich
	1138	....	....	20N 65W	5265	Sub	Stockholm
	1139	1231	1147	28N 88W	5265	1	Good Hope
	1144	1205	....	32N 85W	"	2	Stockholm

Acknowledgments. I wish to thank Professor J. A. Simpson, under whose guidance this work was done, for his aid, encouragement, and constant advice. I also wish to thank Dr. P. Meyer for stimulating discussions. Cosmic-ray data provided by the following investigators all over the world were fundamental for the completion of this work and are gratefully acknowledged:

Dr. M. A. Pomerantz, Dr. D. C. Rose, Prof. S. A. Korff, Dr. H. Carmichael, Dr. J. A. Lockwood, Prof. R. L. Chasson, Dr. R. B. Brode, Dr. J. G. Roederer, Dr. G. Schwachheim, Prof. B. Trumpy, Dr. A. E. Sandstrom, Dr. P. L. Marsden, Dr. D. R. Palmer, Dr. B. Meyer, Dr. H. Debrunner, Dr. G. V. Shafer, Dr. Y. Miyazaki, Prof. V. Sarabhai, Dr. D. M. Thomson, Dr. A. G. Fenton, Dr. K. W. Ogilvie, Dr. C. T. Lewis, and the University of Amsterdam Physics Laboratory.

I also want to thank the Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina) for fellowship support. Work for this paper was supported in part by the U.S.A.F., Air Research and Development Command, Geophysics Research Directorate, contract no. 19 (604)-4554, and in part by a grant from the National Academy of Sciences–National Research Council, IGY Project 50.1.

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(Manuscript received December 9, 1960.)