question was closer to that of a π than a μ, but not conclusively so.

(b) Energy of the Secondary

The measured secondary range is 4.81 ± 0.04 cm which is 60 ± 1 Mev for a pion when straggling is taken into account. The K ending has all the appearances of a true ending rather than that of a decay in flight. However, we have attempted to make quantitative estimates of the possibility that this event is a τ' decaying in flight. Pushing the measurement of the angle between K ending and secondary to its lowest possible limit gives 49°. Such an angle would require a τ' with greater than 60-micron residual range at the time of decay. From gap and scattering measurements, and the lifetime, abundance, and decay spectrum of the τ', one can estimate the probability of a τ' decay in flight which appears like this K ending relative to the probability of a similarly appearing K ending which is not a decay in flight. For this case our estimated relative probability is $\sim 10^{-13}$. One should also consider the remote possibility that in the last grain the K^+ scatters $\sim 60°$ and then decays in the forward direction as a τ' before reaching the next grain. This has a relative probability $\sim 10^{-15}$.

At the K ending the secondary grain counts are more than 30% above minimum. However, another remote possibility would be a $K_{\pi 2}$ where the π^+ interacts very close to the K ending and gives a zero-pronged star except for an outgoing pion of lower energy. We estimate a relative probability of $\sim 10^{-9}$ for this possibility.

Because of these extremely low probabilities and of the appearance of the K ending, we rule out τ' and $K_{\pi 2}$ as reasonable explanations for this event.

ACKNOWLEDGMENTS

We thank Professor R. Dalitz and Professor W. F. Fry for helpful discussions. We are indebted to Mrs. Enid Bierman for valuable suggestions and for helping with the measurements.

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Initial Stages in the Propagation of Cosmic Rays Produced by Solar Flares*

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The propagation of solar cosmic rays produced in the February 23, 1956 flare has been studied from the time they leave the flare region to the time when the terrestrial cosmic-ray intensity reaches a maximum value. Within this interval there are observed not only strong anisotropies in the incident radiation, but also relatively large differences in time (≤ 9 minutes) between the commencements of the intensity increases in different parts of the world. This distribution of time delays is superposed upon the transit-time delay which all particles experience between production and detection.

From these experimental results, and the calculations of orbits connecting the sun and earth at the time of the flare, it is shown that there are broad impact zones on the earth within the first ten minutes of the cosmic-ray intensity increases. Using the recently deduced flare-particle spectrum, cosmic-ray intensities at the top of the atmosphere have been determined for the different impact zones. For this flare event the "2000 hour" impact zone becomes as important as the "0900" and "0300" hour impact zones.

These results demonstrate that the first flare particles arriving at the earth were not of low energy, and that the low-energy particles arrived later—the delay being an inverse function of energy. This energy-dependent spread of first arriving particles is called the dispersion effect arising from the mode of particle propagation from the flare source to the earth. These conclusions show that back scattering from disordered magnetic fields beyond the orbit of the earth does not account for the time delays.

Various alternatives are considered for production of this distribution of onset times. The most likely process appears to be propagation through magnetic fields by diffusion. Since the impact-zone data for all geomagnetic latitudes, including both polar regions, predict a distant source in the direction of the sun but of order one radian solid angle in the sky, and since sufficient diffusion around the earth to produce the required time delays would destroy the observed impact-zone effects, it is suggested that there may exist a diffusing envelope around the sun which accounts for both the apparent source size and the dispersion effect. Small irregularities in the general solar dipole field are invoked to produce the diffusion. Calculations show that the predicted dispersion effect agrees with the observations, and that other details following from diffusion are satisfied. There is evidence of a dispersion effect for the flare particles of November 19, 1949.

The implications of these results for possible uniform magnetic-field distributions between the sun and earth are reviewed, and it is shown from the orbit calculations and the dispersion effect that the predictions are not in agreement with observations.

There is a transition period between the time when impact zones are dominant and the time when isotropy sets in. The subsequent storage of the solar cosmic-ray particles is not further considered in this paper, except for the bearing of these observations at early times upon the character of the interplanetary storage magnetic fields.

I. INTRODUCTION

THE energy spectrum and time dependence of cosmic-ray particles produced in the solar flare of February 23, 1956, have been investigated for late times in the development of the increase of cosmic-ray intensity.[1] At these late times there was convincing

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[1] Meyer, Parker, and Simpson, Phys. Rev. **104**, 768 (1956).

evidence that the radiation approached the earth isotropically over a wide range of particle energies. From the slow decline of intensity with time it was also clear that particles could be stored within the solar system for approximately 15 hours or more after the termination of the solar event. Since there were pronounced anisotropies in the radiation which first arrived at the earth, the isotropy which developed later must be produced by the storage magnetic fields. Interplanetary magnetic fields provide the only mechanism known at present for producing both storage and isotropy. Disordered magnetic fields were invoked for the storage and diffusion of charged particles out of the solar system. Recently, alternate suggestions have been made that the magnetic fields should be uniform, or ordered, rather than disordered.[2,3]

To understand the physical processes by which cosmic-ray particles are propagated from the region of production at the sun, we shall investigate in this paper charged-particle propagation from the time of production at the source to the time when the directions of the particle trajectories arriving at the earth become almost random. Though the influence of the external geomagnetic field and scattering in the interplanetary fields are poorly understood, the main effects are sufficiently outstanding to justify a quantitative study of this phenomenon.

We shall show that strong anisotropies existed in the form of impact zones only during the early period of the cosmic-ray intensity increase and that these anisotropies are satisfied by a large apparent source of cosmic rays located in the direction of the sun. We find that the first particles arriving at the earth do not include low-energy particles. The low-energy particles arrive substantially later with their delay being a smooth function of particle energy. These conclusions lead us to suggest a diffusion model for the escape of cosmic-ray particles from magnetic fields in the source region.

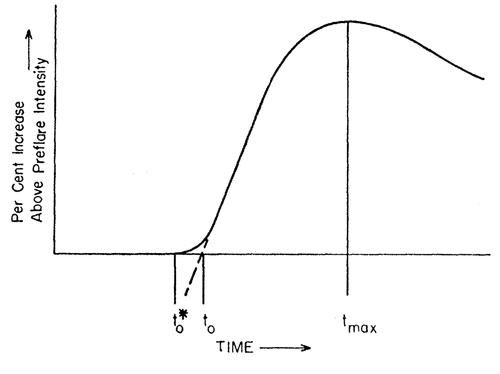

FIG. 1. This curve illustrates the definition of pre-onset time, t_0^*; onset time, t_0; and the time of maximum intensity, t_m.

We also find that these observations during the early part of the intensity increase place severe restrictions upon possible models for the storage magnetic fields and particle propagation at late times.

II. DELAYED ARRIVAL OF LOW-ENERGY PARTICLES

The times for which cosmic-ray particles begin to arrive at detectors distributed over the world may be compared by defining on onset time t_0 as shown in Fig. 1.[4] We have determined this onset time rather accurately for the 19 detectors whose positions and onset times are indicated on the map, Fig. 2. There is a range of 9–10 minutes in t_0 which cannot be accounted for by timing, or other experimental errors. The earliest onset times are spread out in longitude from Cape Schmidt[5] to Freiburg,[6] and perhaps as far west as the British Stations. This is a longitude range of over 160° in the northern hemisphere, extending from early morning to early afternoon hours local time.

The observations from the Asia-Europe areas have been compared with Chicago (U.S.A.)[1] and Ottawa (Canada)[7] in Fig. 3. We find no evidence for particles arriving before 0349 U.T. at Chicago, or before 0350 at Ottawa (the respective onset times are 0350 and 0353), whereas the detectors in Europe and Asia experienced a sharp increase of intensity at about 0344 U.T. for all types of detectors.[8] Fortunately, the

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[2] A. Ehmert, Proceedings of the Conference on Cosmical Electrodynamics, Stockholm, Sweden, September, 1956 (unpublished).

[3] S. Hayakawa (private communication). Also Cocconi, Gold, Greisen, Hayakawa, and Morrison (communication received September, 1957).

[4] Several cosmic-ray recorders display intensity as a function of time in sufficient detail to reveal a small increase leading into the sharp rise of intensity. This is identified as a "foot" on the intensity curve. We define this foot as the pre-onset increase and specify the beginning of this pre-onset as t_0^*. The steep slope of the intensity increase when extrapolated to the time axis defines the onset time t_0 as illustrated in Fig. 1. These are times observed at the earth.

[5] Dorman, Kaminer, Koivava, Shafer, and Schwarzman, Nuclear Phys. **1**, 585 (1956).

[6] Sittkus, Kahn, and Andrich, Z. Naturforsch. **11a**, 325 (1956), and to be published.

[7] D. C. Rose and J. Katzman, Can. J. Phys., **34**, 884 (1956).

[8] S. N. Vernov [Dorman, Feinberg, Giokova, Grigorov, Kopilov, Sanin, Shafer, and Vernov (private communication, June 22, 1957)] has recently provided us with a re-evaluation of all the data from the cosmic-ray intensity increases recorded in the U.S.S.R. Using our criterion for onset times, we list below the revised onset times for the Soviet stations:

Station	Geomagnetic coordinates Lat.	Geomagnetic coordinates Long.	t_0
Tbilisi	36°N	122°	0341
Sverdlovsk	48°N	141°	0341-2
Moscow	51°N	120°	0342-3
Yakutsk	51°N	193°	0343-4
Cape Schmidt	63°N	227°	0344-5

According to this report an over-all error of about 1 min is to be assigned to each of the foregoing values for t_0.

We wish to make two comments regarding these new data: First, even taking into account the assigned errors in timing, there appears to be a systematic delay in onset time with increasing geomagnetic latitude. It is well established that within any given impact zone the magnetic rigidity of particles which are permitted to arrive decreases with increasing geomagnetic latitude. Consequently, this small and systematic spread in onset times is explained if we assume that the highest energy particles arrive first,

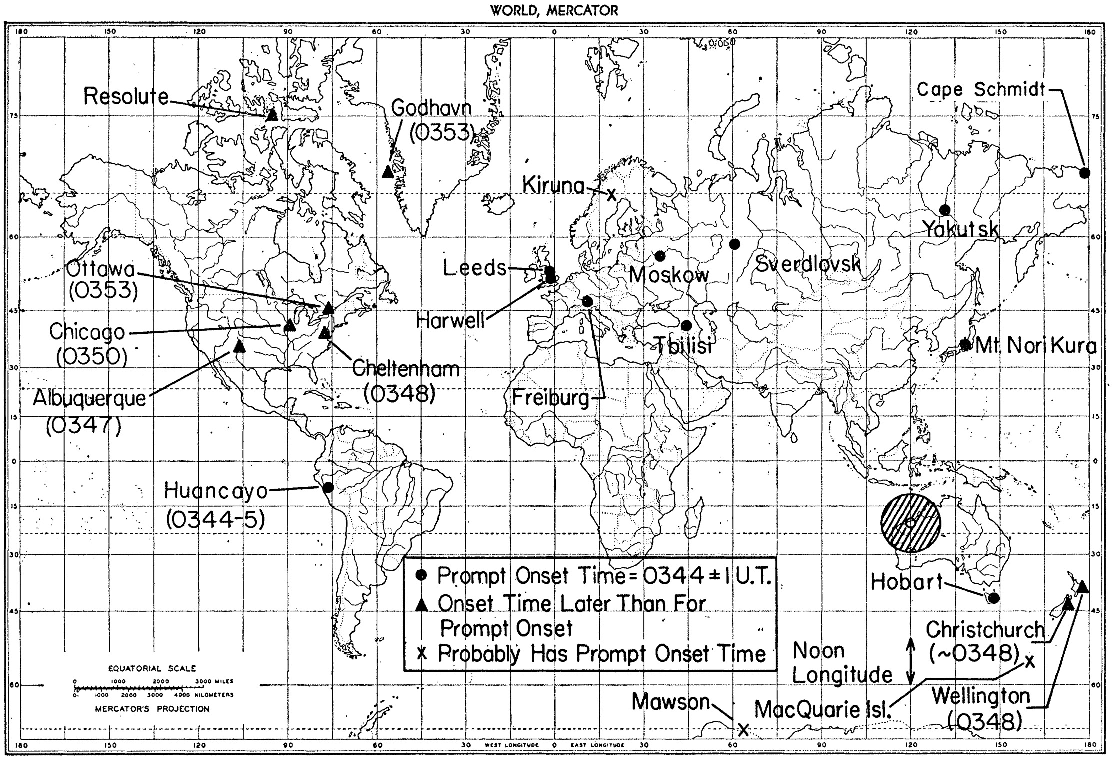

FIG. 2. World-wide distribution of cosmic-ray intensity recorders for which the onset time has been established. The symbol × indicates those stations for which a prompt onset time has been inferred from the data.

magnitude of this solar cosmic-ray effect was sufficiently large to obtain a measure of the effectiveness for excluding particles from some regions of the earth at this time. An increase as small as 15–20% beginning near 0344 would have been readily detected at Ottawa, but no effect was observed even though the primary intensity in Europe exceeded background by >5000%. We conclude that the mechanism preventing the arrival of solar-produced particles at Chicago and Ottawa must have been exceedingly effective. These arguments also apply to the observations in the southern hemisphere wherein the onset time for the neutron monitor in Wellington Harbor[1] was delayed at least 4 minutes with respect to the ion-chamber onset time at Hobart, Tasmania.

We shall investigate the implications of this range of onset times, and their distribution over the earth, for understanding the propagation of solar cosmic rays during the first half hour of the event.

The observations reported in Figs. 2 and 3 were obtained with either ion chambers, counter telescopes or neutron-intensity monitors. If a beam of particles arrives at the top of the atmosphere containing a mixture of high- and low-energy particles, then all three types of detectors would respond to the secondaries of the high energies and at least the neutron

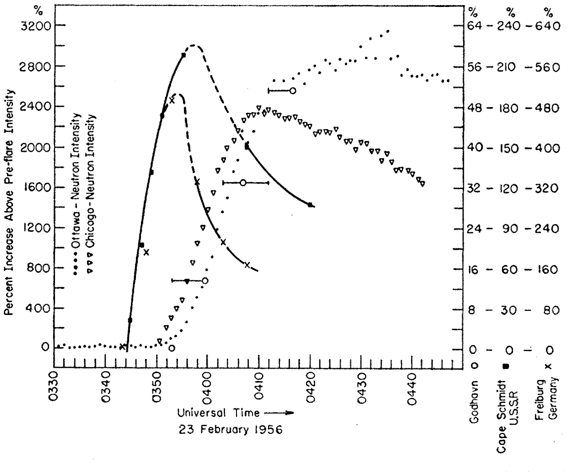

FIG. 3. The intensity increases with prompt onset are shown for Cape Schmidt (U.S.S.R.) and Freiburg (Germany). Delayed intensity increases are shown for the neutron monitors at Chicago and Ottawa. Note the absence of any increase of intensity at Ottawa before 0349 U.T.

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i.e., that there is a small dispersion effect within an impact zone similar to the large dispersion effect (Fig. 6) we find between the "0900" and the "2000" hour impact zones. Second, although this small effect may be real, it is small compared with the observed time differences of 9–10 minutes, and represents a small spread of particle energies. Therefore, the assumption we have made in this paper, namely, that the onset time in Europe and Asia is represented by a unique, prompt onset at 0344±1 U.T. is still satisfactory for studying the initial phases of propagation and does not change appreciably the results shown in Fig. 6.

monitor would respond to the secondaries from the low-energy particles (>1 Bev). Thus, a spread in the measured times of onset among a group of detectors cannot be accounted for by the response characteristics of the detectors.

We now examine the behavior of the primary beam in the geomagnetic field. If the solar cosmic radiation arrived isotropically at the earth, then, from Fig. 2, the promptly arriving particles in the geomagnetic latitude range 0°–55° would also have access to the North American stations where the geomagnetic cutoff is low, i.e., Chicago and Ottawa. Since there was no prompt onset at these latter locations, we conclude that the radiation did not arrive isotropically; hence the source as seen at the earth must be limited in size.

The problem of determining at what positions inside the terrestrial magnetic field particles arrive as a function of their energy, if the source at infinity is of finite size, has been treated extensively recently. The allowed regions of impact on the earth are called impact zones. From the above general arguments we conclude that impact zones of some kind existed during at least the first 10 minutes of solar-particle arrival at the earth.

It was shown in earlier papers from this laboratory[9–11] that, although the exclusion of high-energy particles from regions outside the main impact zones may be complete, there is a background region extending over all longitudes which arises from connecting orbits of low-energy particles—energies near the geomagnetic cutoff for the observing position in the background zone. Thus, even though we may account for the exclusion of high-energy particles for some regions of the earth, we cannot argue that low-energy particles are similarly excluded. Since the discrimination against the arrival of prompt particles is exceedingly good as shown in Fig. 3, it then follows that the promptly arriving particles were of high energy: the low-energy particles arrived later.

With the two assumptions that the impact zones existed during the first 10–15 minutes of the cosmic-ray increase, and that the low-energy particles arrive late in this time interval, we are led to the following alternative explanations for the late-arriving particles:

(a) Either the late-arriving particles come from directions other than the limited source so that they have access to regions of the earth otherwise forbidden for a source at the sun, or

(b) They arrive from the same source as the prompt particles but with lower energy so they may enter the background zone inaccessible to high-energy particles.

For alternative (a), two extreme possibilities have been proposed, both of which involve the question of how magnetic fields are distributed in the interplanetary medium. If disordered magnetic fields exist beyond the orbit of the earth as is suggested by the study of the flare event at late times,[1] then cosmic-ray particles might be backscattered from these fields to arrive late with respect to the high-energy particles. This backscattering rests upon the erroneous assumption that Chicago and Ottawa were in highly forbidden zones for particles of *all* energies; we discard backscattering to account for the delayed onsets. The opposite extreme assumes a uniform field throughout the space between the sun and the earth with its direction inclined with respect to the sun-earth line so that only high-energy particles can arrive promptly.[2] We shall show later that this suggestion does not agree with experimental evidence for early or late times in the history of the flare.

We, therfore, explore alternative (b) wherein the particles of all energies during the first 10–15 minutes come from the source direction but only the high energies arrive promptly at the earth. The time delay in transit as a function of particle energy arising from particle velocity distribution does not account for more than 10% of the time-delay effect reported in Fig. 3. Before investigating further the origin of the assumed time delays as a function of energy, we shall critically discuss the properties of the impact and background regions on the earth at the time of the giant flare.

III. SUN-EARTH ORBITS AT THE TIME OF THE FLARE, AND THE DISTRIBUTION OF COSMIC-RAY INTENSITIES OVER THE EARTH

To understand more fully the characteristics of impact and background zones for the first half hour of the solar flare, we have extended earlier orbit calculations both in numbers of orbits and their rigidity range, beyond those recently reported, using the AVIDAC computer. We are aware that idealized orbit calculations take into account neither the imperfections in the geomagnetic field nor particle scattering which may arise from disordered fields in the interplanetary volume. But since we know from our discussion in the previous section that these defects in the model are insufficient to destroy pronounced anisotropies produced by a source of finite size, we shall use the orbit calculations as a guide in drawing our conclusions on the behavior of impact zones at the time of flare onset.

We wish to know for each detector location the primary-particle rigidities and relative counting rates at the top of the atmosphere under the assumption that particles are deflected only by the geomagnetic dipole field.

Methods have been discussed by which the counting rates R at the top of the atmosphere may be determined; the counting rates for different impact zones mainly depend on the allowed opening angles Ω in which the particles arrive, on the range of allowed rigidities, and the form of the differential rigidity spectrum $j(pc/Ze)$

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[9] J. Firor, Phys. Rev. **94**, 1017 (1954).

[10] F. S. Jory, Phys. Rev. **103**, 1068 (1956).

[11] R. Lüst, Phys. Rev. **105**, 1827 (1957).

$=j(N)$ at the source. Thus

$$R(\lambda,\varphi)=\int_{N_{\min}}^{N_{\max}} j(N)\Omega(\lambda,\varphi)dN,$$

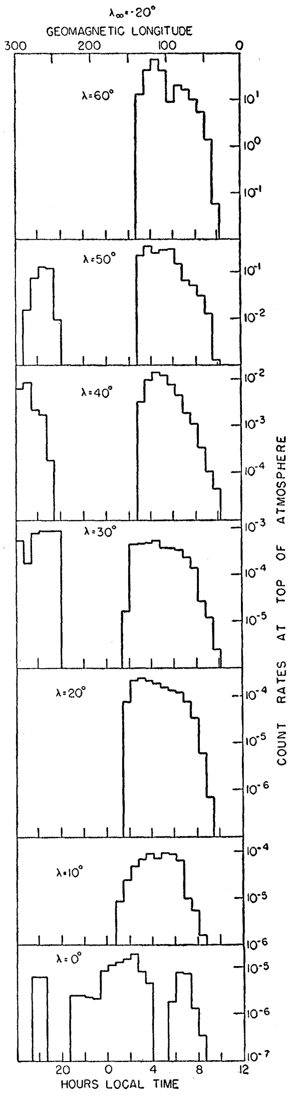
where λ and φ are the geomagnetic latitude and longitude, respectively.

For late times during the intensity increase we have already derived a differential rigidity spectrum proportional to N^{-8} near the earth.[1] The spectrum at the source during the early part of the event may not have been quite as steep; therefore, we have assumed that the differential rigidity spectrum was N^{-6} at the time of onset.

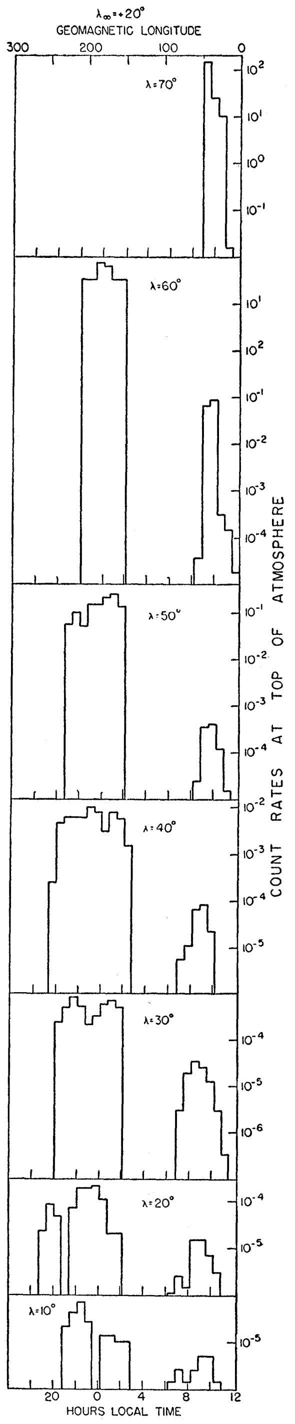
We have also assumed that the range of magnetic rigidities extends out to 30 Bev since there was an appreciable increase of intensity at the geomagnetic equator. The solid angle of the solar source was selected as $\pm 15°$ in latitude, and $\pm 10°$ in longitude. It has already been shown that even if the source area exceeds the size of the sun by a much larger amount than we have taken here, there still exist distinct impact zones.[11]

Since we are concerned primarily with observations deep within the atmosphere, the principal contributions from primary particles come from particles arriving within $\leq 30°$ from the vertical, and we limit the selection of orbits to these small angles with respect to the vertical. For this study we have used the AVIDAC computer to obtain the flare-particle orbits and used them along with the orbits recently published by Jory[10] and Lüst.[11,12]

The results are shown in Figs. 4(a) and 4(b) with a relative logarithmic scale for the counting rates at the top of the atmosphere with the source position $\lambda_\infty = -20°$. This was nearly the position of the sun with respect to the geomagnetic field coordinates at the time of flare onset. If the sun had been located in the plane of the geomagnetic equator ($\lambda_\infty = 0°$) the three most important impact zones would occur at longitudes centered at approximately "0900," "0300," and "2000" hours local solar time for particles of positive charge. But since the sun was south of the geomagnetic equator for the flare of February, 1956, we see from Fig. 4(a) that the "0900" and "0300" impact zones merge as one broad impact zone in the northern hemisphere. In the southern hemisphere, Fig. 4(b), the "0900" zone remains apart while the "0300" and "2000" hour zones have merged.



(a)



(b)

FIG. 4. The calculated counting rates expected at the top of the atmosphere at the time of the February, 1956 flare using a differential particle-rigidity spectrum $\alpha[PC/Ze]^{-6}$, (a) for the *northern* hemisphere; (b) for the *southern* hemisphere.

If the solid angle of the source is increased, the impact zones will extend over a wider range of longitudes than shown in Fig. 4. It is clear from Fig. 2 that, since the prompt onset time associated with the merged "0900" and "0300" impact zones is observed over a 160° longitude band, the effective source at the time of the flare must have had a larger solid angle than the source used for our calculations; we shall discuss this matter later.

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[12] Space limitations make it impossible to include these orbit solutions here. A table containing the orbit parameters for the study of the solar flare has been deposited as Document No. 5356 with the ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington 25, D. C. A copy may be secured by citing the Document number and by remitting $2.50 for photoprints, or $1.75 for 35-mm microfilm. Advance payment is required. Make checks or money orders payable to: Chief, Photoduplication Service, Library of Congress.

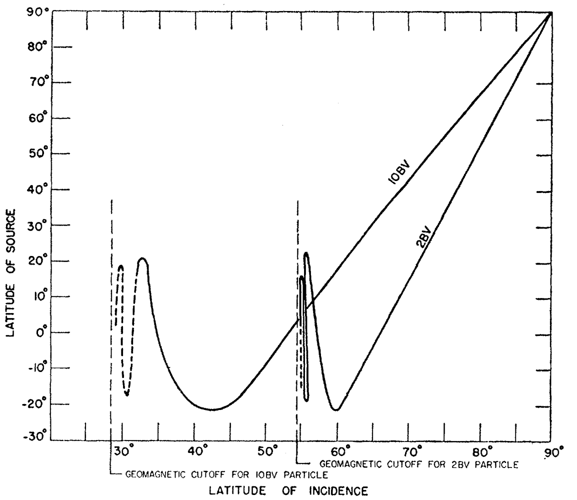

FIG. 5. For low particle magnetic rigidities the particles admitted to the "2000 hour" impact approach asymptotically the geomagnetic cutoff rigidity.

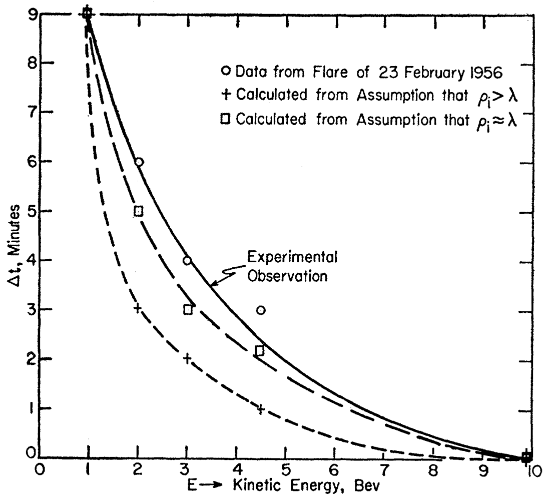

FIG. 6. The dispersion effect. The time delays for the first-arriving particles as a function of energy. The results of calculations for diffusion through a solar dipole field with irregularities of scale size λ are shown for comparison.

For a given geomagnetic latitude it has been shown that the magnetic rigidities of particles arriving close to the vertical are different in different impact zones. Particles with highest rigidity arrive in the "0900" hour zone, whereas particles of successively lower rigidity arrive in the "0300" and "2000" hour zones. Particles with magnetic rigidities very close to geomagnetic cutoff rigidity at a given latitude produce background radiation for that latitude distributed over all geomagnetic longitudes. For latitudes above about 60° this background radiation will have rigidities less than 1 Bv and, hence, will not produce any observable effect deep in the atmosphere at these high latitudes.

The relationship between source latitude and latitude for arrival is shown graphically for particles of 2 Bv and 10 Bv rigidity in Fig. 5 (derived from reference 9). We observe that for a given source latitude and particle rigidity the impact points approach asymptotically the geomagnetic cutoff latitude for that rigidity. Therefore, outside the two major impact zones the incoming particles are restricted in rigidity to a small spread of rigidities near the value of the geomagnetic cutoff prevailing at the location of the observation. In the vicinity of the 2000-hour zone this effect forbids higher energy particles from arriving at the intermediate and high geomagnetic latitudes. For example near $\lambda = 50°$ the particles arriving within $\pm 32°$ of the vertical are admitted only in the rigidity range 3.0 ± 0.2 Bv.[13] On the other hand, in the merged "0900" and "0300" hour impact zones, particles with a much wider range of rigidities, and of higher rigidity, are admitted within the same solid angle and for latitudes extending from 0° to high latitudes.

Since the differential spectrum of flare particles is approximately N^{-6}, most of the radiation is of low rigidity and contributes strongly to the spread-out "2000" hour zone. Figure 4(a) gives the important result that the intensities in the "0900–0300" zone and the "2000" hour zones for the northern hemisphere should be comparable for this spectrum. This is in agreement with the observation that maximum intensities for the nucleonic-component increases in Europe and North America are of the same order of magnitude. (See reference 1, Fig. 1.)[14] In the southern hemisphere the maximum intensity of Wellington was unusually large for a background-zone location, but the results in Fig. 4(b) show that this is to be expected if Hobart lies in or near the "0900" hour spread-out impact zone.

From the foregoing results it is clear that if a burst of particles from the source contained particles of all magnetic rigidities, then the prompt onset time observed in the "0900–0300" hour regions would also have been obtained in the spread-out "2000" hour zone, which includes Chicago and Ottawa. Since this did not occur (Fig. 3), we conclude that the radiation of high magnetic rigidity began to reach the earth first. Hence, the prompt onset time will only be observed in the merged "0900–0300" hour zone in the northern hemisphere, and the "0900" hour zone in the southern hemisphere, whereas the delayed onset times in the

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[13] A large number of orbits were integrated especially to obtain the counting rates in the "2000" hour impact zone. For this zone—as well as for background radiation—the asymptotic values for orbits at infinity depend critically on the rigidity. This increases the integration time on AVIDAC by a factor 10 over orbit integrations for the "0900" hour zone. Hence, it was not practical to determine the counting rates in the higher order impact zones and for background radiation.

[14] G. Pfotzer [Proceedings of Varenna Conference on Cosmic Rays (to be published)] finds a spectrum near N^{-4} from his analysis of the anisotropic radiation. This spectral form will change the computed cosmic-ray intensities in the various impact zones which we report here but does not change the results of our analysis.

"2000" hour region and background zone for both hemispheres will critically depend upon the magnetic rigidity of the arriving particles. For the longitude band centered at "2000" hour the delay in onset time, Δt, with respect to prompt onset, is shown in Fig. 6. We have expressed the time delay over a particle energy range of 1–10 Bev, assuming that the incoming particles are principally protons. The delay in onset time appears to be a smooth function of primary-particle energy.

IV. ORIGIN OF THE DELAYS IN ONSET TIMES FOR THE ARRIVAL OF SOLAR COSMIC RAYS

If the impact zones at the earth during the early portion of the flare event are even approximately correct, then the first high-energy particles arrive ahead of successively lower-energy particles so that the time difference Δt depends upon particle energy, and may be as large as $\Delta t = 9$ minutes for particles differing in energy by an order of magnitude. We therefore seek a physical explanation for this effect and the phenomenon associated with it.

Differences in transit time arising from the range of β for the particles account for less than 10% of the effect. Also the time spent in the geomagnetic field, even for complicated orbits belonging to higher order impact zones, is less than 0.1 second. We are then led to either (a) possible differences in the production time for cosmic-ray particles within the flare, or (b) mechanisms operative during the propagation of the particle between the flare region and the geomagnetic field. There are not, at present, any arguments for delayed production of the low-energy particles in the visible flare region[15,16]; indeed, it is likely that even for a rapid acceleration process the low-energy particles will tend to appear in the source first, or at the same time as high-energy particles. If we tentatively discard time delays during production, we then consider mechanisms which may produce the effect during cosmic-ray propagation outside the flare volume.

In addition to the differences of onset time Δt for cosmic-ray increases observed at the earth, there exists the elapsed time between production and first detection of particles which may be even larger than the difference in onset times. We define the elapsed time from the beginning of production at the sun to the first arrival at the earth as the *initial transit time* t'. It is clear from the four earlier large cosmic-ray flares that this time may be many-fold the value of the transit time for electromagnetic radiation, and it is this time delay which has already been discussed in the literature. Thus, Δt is the dispersion arising from the time delay in transit t' and is a function of particle energy as shown in Fig. 6. (This dispersion may also be a function of t'.)

The value of t' for particles of a given energy depends upon our assumptions regarding the time of solar production. In this paper we shall consider the time of maximum energy per unit volume of the flare as the time when cosmic-ray production begins.[17] For the February, 1956 flare this would correspond to maximum light output and to the time approximately 0342 U.T. If solar radio emission should turn out to be the dominant mechanism for cosmic-ray production, it would be necessary to specify the time for initial production as 0335 U.T., thus increasing t' so that it would be approximately equal to the dispersion time.

We shall now discuss possible explanations for the time delays and begin by considering the dispersion effect in time, Δt.

The alternatives are not numerous. Assuming prompt production of all particle energies within the flare volume, we are left with the problem of invoking suitable magnetic fields in order to increase the effective lengths of the low-energy particle trajectories relative to the high-energy particles. We also require temporary storage of the short burst of radiation, since the observed arrival of solar-flare particles for more than 16–18 hours is difficult to attribute to continuous production in the flare region. Interplanetary magnetic fields appear to be the most likely means for charged-particle storage. The question then arises: do the magnetic fields invoked for storage also introduce the observed spread in onset times at the earth? The possibility, that the interplanetary volume is pervaded by a uniform magnetic field,[2,3] yields spiraling orbits which may introduce some spread in the arrival times of particles, but arguments given in Sec. VIII indicate that a uniform field does not satisfy the experimental observations. A second possibility is the assumption of disordered magnetic fields located outside the orbit of the earth in the form of an enclosing barrier to provide temporary storage—a model which appears to fulfil some of the requirements for the late development of the cosmic-ray flare event.[1]

Although we have shown that "reflection" of charged particles from the inner boundary of such a barrier field cannot be the origin of the onset time delay Δt, we shall consider other ways by which the spread of onset times may be produced by particle diffusion through irregular magnetic fields.

If we make the tentative assumption that irregular fields are extended throughout the region within the earth's orbit, we see that a burst of radiation at the sun containing particles of all energies will diffuse outward through the field and that, since the diffusion mean free path will in general be a function of particle

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[15] We have already shown that the kinetic energy stored in solar, cosmic-ray particles exceeds 3×10^{30} ergs for the flare of February 23, 1956.[1] This would imply that if the efficiency for cosmic-ray production were as high as 1%, as seems improbable, the total flare energy exceeds 3×10^{32} ergs. We know that the flare was seen in white light and hence was of comparable intensity to the photospheric background[16]; these observations are consistent with the total flare energy being confined to the visible flare region.

[16] Notuki, Hatanaka, and Unno, Publ. Astron. Soc. Japan 8, 52 (1956).

[17] The total energy output of the flare in nonradio emission is at least of the order 10^{32} ergs, whereas the total energy emitted in the radio spectrum is of the order 10^{25} ergs.

energy, there may develop significant differences in the arrival time between the first high-energy and low-energy particles.

However, continuous diffusion throughout the region between the sun and earth cannot represent the physical conditions at the time of onset on February 23, 1956. Enough diffusion to produce the observed time delays leads to the smearing out of impact zones[18] and, contrary to observations, there would be a unique onset time for all observed intensity increases. We, therefore, discard uniform diffusion between the sun and the earth.

The remaining possibilities for using diffusion to produce the time delays require that the diffusion be restricted to either a region around the sun or one around the earth. Even though some diffusion near the earth is likely, and is a possible way to account for the large Forbush-type decrease of total intensity underway prior to the onset of the flare event,[1] the earth would have to be immersed in a much larger volume of disordered fields to produce the observed diffusion-time differences $\Delta t=9$ minutes than the volume required to produce the observed Forbush decrease. Also, the requirements on the scale size of the disordered magnetic-field region and the retention of observed impact zones at the earth are mutually exclusive.

The flare of November 19, 1949 provides an independent argument against the time differences arising from disordered fields in the vicinity of the earth. At that time there was no evidence for a Forbush decrease having occurred prior to the flare. (The Carnegie Institution ionization chambers displayed a 1% decrease in intensity below the average for the period.) Even so, the time delay between the arrival of the first high- and low-energy particles was approximately 11 minutes as we shall indicate in Sec. V.

Consequently we explore solar particle diffusion in the vicinity of the sun.

V. DIFFUSION OF SOLAR COSMIC RAYS OUT OF THE GENERAL SOLAR MAGNETIC FIELD

Babcock has demonstrated beyond doubt that the sun possesses a general magnetic field.[19] He has shown that the field intensity near the photospheric surface is of the order 1 gauss. However, irregularities in the general field are certain. From the Babcock data there are obvious irregularities, and eclipse pictures taken at various phases of the solar cycle emphasize the changing distortion of the general field in the solar corona throughout the solar activity cycle. From independent solar-terrestrial observations there is extensive evidence that ionized matter in the form of streams and clouds emanate from deep in the solar atmosphere—these bursts of ionized matter inevitably squeeze and spread the general field in such a way as to produce small-scale irregularities.

In view of these arguments we shall assume as a working model that, although when observed as a large-scale phenomenon the general solar field is roughly coherent, it is not a "good" dipole field—it is a general field containing more or less random small-scale irregularities extending from photospheric level out to 50–100 solar radii.[20] We now ask how cosmic-ray particles in the energy range 1–30 Bev will propagate out of this solar field from the visible flare region. Trapping orbits will have very short lifetimes because the magnetic-field irregularities will scatter the particles into ever-changing orbits. Indeed, if the general solar field were sufficiently perfect to sustain trapping orbits, it is difficult to see how low-energy cosmic rays could ever escape from the vicinity of the sun,[21] without invoking special effects.[22] The fact that a high yield of low-energy cosmic rays exists is a strong argument that the field is not a perfect dipole. Furthermore, the flare produces an enormous outburst of radiation and matter which may extend one solar radius, or more, above the photosphere. Cosmic-ray particles may then be carried in this outburst from regions of intense magnetic fields to the higher corona where the general solar field is weaker before the diffusion we discuss here becomes effective.

If the magnetic-field irregularities are distributed throughout the solar corona, they may be considered to be scattering centers for charged particles of cosmic-ray energy with successive scatterings leading to more or less isotropic diffusion of particles in the general solar field. In the following discussion we shall assume that the propagation of charged cosmic-ray particles away from the solar flare region may be treated as particle diffusion out of the general solar magnetic field. The time required for a low-energy particle to travel through a diffusing medium is in general longer than for a high-energy particle, and it is this possibility that we invoke to generate the delay in arrival time of the flare particles at the earth.

Sekido and Murakami[23] have proposed that the magnetic field around the sun be a trapping field for flare particles in order to account for the initial transit time t' defined earlier. We wish to point out that from our preceding arguments it would be difficult to sustain trapping orbits because of field imperfections and that, in addition to the bulk time delay t', we must explain the dispersion time difference Δt. For these reasons we

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[18] For example, particles starting out from the sun in the direction of the earth will arrive over a solid angle >5 radians at the earth.

[19] H. W. Babcock and H. D. Babcock, Astrophys. J. **121**, 349 (1955).

[20] R. Lüst and A. Schlüter, Z. Astrophysik **38**, 190 (1955). These authors found a similar radius for the region which should rotate with the sun.

[21] For a proton of 2 Bev/c in a field of 10^{-2} gauss, the Larmor radius is $=7\times10^{8}$ cm, which is 10^{-2} solar radius.

[22] Forbush, Gill, and Vallarta, Revs. Modern Phys. **21**, 44 (1949).

[23] Y. Sekido and K. Murakami, Proceedings of the International Conference on Cosmic Rays, Guanajuato, Mexico, 1955 (unpublished).

prefer to try exploring diffusion rather than trapping as the dominant mechanism in the vicinity of the sun.[24]

From the observed spread of the main impact zones we assume that the source, or diffusing region, centered at the sun extends out at least 50 solar radii. To simplify the calculations the diffusing region shall be represented as a spherical envelope of radius r' concentric with the sun. If the photospheric radius is r_0, then $r_0 \ll r'$. All particles that enter the volume defined by $r < r_0$ are absorbed. In addition to the symmetry of the model, we also assume that the diffusion coefficient $\kappa(E)$ throughout the envelope is constant and nonzero, i.e., $\partial\kappa(E)/\partial r = 0$. The particle density, $J(E)$ is represented in the diffusion equation as:

$$\partial J(E)/\partial t = \tfrac{1}{3}cL(E)\nabla^2 J(E), \tag{1}$$

where $\kappa(E) = \tfrac{1}{3}cL(E)$, $L(E)$ being the scattering mean free path.

The solutions of the spherically symmetric diffusion equation have already been considered for several cases.[1]

Since the scale size of the flare region is r_f, where $r_f \ll r_0$ we may assume that the particles are injected instantaneously at $t=0$ into the solar envelope at $r \approx 0$. Then the particle density, at time $t > 0$ and at $r \gg r_0$, is

$$J(E) = \frac{A}{(\pi\kappa t)^{\frac{3}{2}}} \exp\left(-\frac{r^2}{\pi\kappa t}\right). \tag{2}$$

From the exponential factor we see that $(\kappa t)^{\frac{1}{2}}$ is proportional and comparable to the distance l beyond r_0 to which particles of a given energy have diffused in the time t.

If the relative distances that particles of energies E_1, E_2 travel in the times τ_1, τ_2 are represented as lengths l_1, l_2, then

$$\frac{l_1}{l_2} = \left[\frac{\kappa_1\tau_1}{\kappa_2\tau_2}\right]^{\frac{1}{2}} = \left[\frac{L(E_1)\tau_1}{L(E_2)\tau_2}\right]^{\frac{1}{2}}. \tag{3}$$

In general, for an irregular magnetic field whose root-mean-square B is decreasing as $\sim 1/r^3$, the lower energy particles will experience diffusion out to greater radial distances than will high-energy particles, i.e., if $E_1 < E_2$, then $l_1/l_2 < 1$.

However, to simplify the problem we let $l_1/l_2 = 1$ so that the distances for particles of all energies to escape are equal; the time differences we calculate for particles of energy E_1 and E_2 will, therefore, tend to be a lower limit for the true time differences with the assumption

$$L(E_1)\tau_1/L(E_2)\tau_2 = 1. \tag{4}$$

Our next task is to obtain an explicit function $L(E)$, and the discussion which follows is directed towards that end. We know very little about the properties of the general solar field and its extension out to great distances. However, there is sufficient qualitative evidence to limit the number of possibilities. (1) Irregularities in the field we have already discussed. (2) The irregularities have a much smaller scale size than the scale size of the general solar field near the photosphere ($\sim r_0$) since the over-all character of the field is one of order. (3) The regions between strong, small-scale irregularities are not field-free, i.e., between collisions with irregularities the particle trajectories will have Larmor radii $\rho_0(B)$.

If we call λ the scale size for an irregularity capable of deflecting a particle of relativistic energy, then $\lambda \ll r_0 = 7\times10^{10}$ cm. If ρ_i is the Larmor radius of the particle inside a scattering region, the scattering process will depend upon the relative magnitudes of ρ_i and λ. Since, on the average, the general solar field will be present throughout the diffusing volume, the scattering centers may be concentrations of the field or regions of depressed field intensity; i.e., $\rho_i > \rho_0$ or $\rho_i < \rho_0$, where ρ_0 is the Larmor radius in the average field at radius r.

These conditions are stated relative to the energy of the charged particle undergoing the scattering. For a sufficiently high-energy particle $\rho_i > \lambda$ under all conditions; for a sufficiently low-energy particle $\rho_i < \lambda$ under all solar conditions. The energies to be considered here are within the range 1–20 Bev. As one possible case the irregularities in magnetic-field intensity may be treated as concentrations of strong fields interspersed with regions of very weak fields. Then for sufficiently large and dense concentrations $\rho_i < \lambda$ and $\rho_i \ll \rho_0$ so that the particles over a wide range of energies will undergo wide-angle deflections in collisions with these irregularities. Under these conditions the scattering mean free path $L(E)$ depends very little, if at all, upon particle energy. But if this diffusion is the main process which leads to the differences in onset time at the earth, we know from Fig. 6 that the process is strongly energy-dependent and the limiting case $\rho_i < \lambda$ does not apply to solar conditions at the time of the February, 1956 flare. We are led to the conclusion that $\rho_i \geqslant \lambda$.

The general question of how cosmic-ray particles diffuse through a plasma cloud containing a disordered magnetic field has already been considered by Morrison[25] and by Parker.[26] The conditions we have assumed for the field irregularities in the solar envelope approximate closely the case for the transmitting scattering centers described by Parker. From the work of Morrison and Parker, we find that for

$$\begin{aligned} \rho_i > \lambda, &\quad L(E) \propto \rho_i^2 L_0/\lambda^2, \\ \rho_i \approx \lambda, &\quad L(E) \propto \rho_i L_0/\lambda, \end{aligned} \tag{5}$$

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[24] L. I. Dorman and, independently, G. Pfotzer [Proceedings of Varenna Conference on Cosmic Rays (to be published)], have also suggested that there may be a diffusing region in the vicinity of the sun. The magnetic clouds near the sun which Dorman invokes to produce his "scatter" radiation could be modified to explain the dispersion effect.

[25] P. Morrison, Phys. Rev. **101**, 1397 (1956).

[26] E. N. Parker, Phys. Rev. **103**, 1518 (1956).

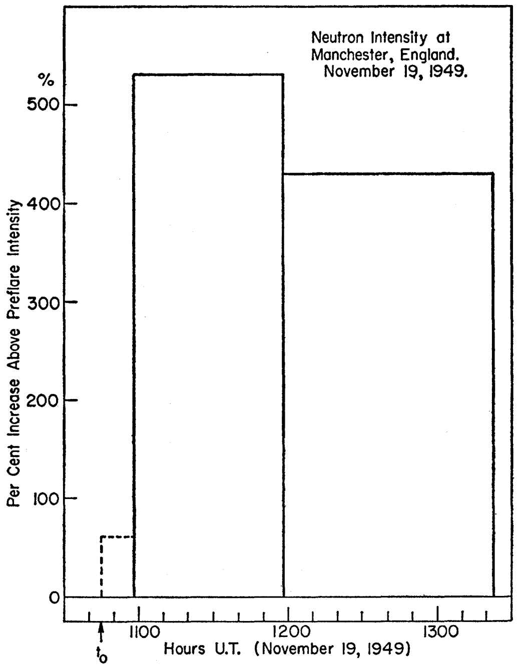

FIG. 7. The percent increase above preflare intensity, shown as a dashed line, represents events which occurred very close to 1055–1058 U.T.

where L_0 is the mean free path *between* scattering centers and is here taken to be independent of particle energy in first approximation. Since

$$\rho_i=E_0\left[\frac{E}{E_0}\left(\frac{E}{E_0}+2\right)\right]^{\frac{1}{2}}\Big/(ZeB), \tag{6}$$

where E_0 and E are the rest and total particle energies, respectively, we may write for the ratio

$$L(E_1)\tau_1/L(E_2)\tau_2=1;$$

$$\left[\frac{E_1}{E_0}\left(\frac{E_1}{E_0}+2\right)\Big/\frac{E_2}{E_0}\left(\frac{E_2}{E_0}+2\right)\right]^n=\frac{\tau_2}{\tau_1}, \tag{7}$$

where

$$n=1 \quad \text{for} \quad \rho_i>\lambda,$$
$$n=\tfrac{1}{2} \quad \text{for} \quad \rho_i\approx\lambda,$$
$$n\to 0 \quad \text{for} \quad \rho_i<\lambda,$$

for $E_1<E_2$, $\tau_1>\tau_2$.

TABLE I. Rate of cosmic-ray intensity increase as a function of onset time.

	t_0	Time for intensity to increase to 50% t_m
Prompt arrival	0344	4 min
Cheltenham	0348	6 min
Chicago	0349	8 min
Ottawa	0353	11 min

If we call τ' the transit time, assumed independent of particle energy, from the outer boundary of the solar diffusing envelope to the orbit of the earth, and Δt the difference in the observed onset times for particles of energy E_1, E_2 we may write

$$\tau_2+\Delta t+\tau_2'=\tau_1+\tau_1'. \tag{8}$$

All particles are relativistic and travel with the velocity c. Since we have assumed that the envelope radius, r', will be independent of particle energy, then $\tau_1'=\tau_2'$ and $\tau_2+\Delta t=\tau_1$.

If $R=\tau_2/\tau_1$, then

$$\tau_2=\frac{R}{1-R}\Delta t. \tag{9}$$

From experimental observations we have the time of onset as a function of geomagnetic cutoff energy for five different geomagnetic latitudes, all in the region of the spread-out "2000" hour zone, as shown in Fig. 6.

The ratio R is best determined for a wide spread in Δt and particle energy; the Ottawa and Huancayo[27] data are, therefore, used to obtain the value τ_2 for the diffusion time out of the solar envelope for particles of energy 10 Bev or greater. It then follows that, using the two end points of the curve in Fig. 6, we can calculate the values for Δt under the alternate assumptions $\rho_i>\lambda$ or $\rho_i\approx\lambda$. The results are shown in Fig. 6 where it appears that $\rho_i\approx\lambda$ is the better assumption. The errors of $\Delta t=\pm 1$ minute do not justify further approximations in the calculations, especially in view of the fact that the effective solar-envelope radius must be a function of particle energy.

An order-of-magnitude estimate can now be obtained for the radius of the solar diffusing envelope from the high-energy particles $E\geqslant 10$ Bev which have prompt onset at the earth: $\tau=2.6$ minutes for these particles, therefore, $r'\leq\tau c$ and $r'\approx 0.3$ au. This represents an approximately 35° source in the sky. Independent estimates of the source size from the width of the "0900–0300" hour impact zone require a source of at least this size as noted in Sec. VI.

If diffusion through the general solar magnetic field accounts for the dispersion in onset times Δt, then there are two consequences which follow for the behavior of the cosmic-ray intensity during the first minutes of the increase of intensity. First, the rate of rise of cosmic-ray intensity following t_0 must be a function of the lateness of onset time over the entire energy range. The time required for the intensity to rise to 50% of maximum intensity is given in Table I for each station. These results are in the right direction and of the correct magnitude for agreement with the diffusion hypothesis. Second, for any given energy, the growth of intensity at the outer boundary of the envelope will at first be gradual: the increase of intensity everywhere at the earth should, therefore, have a "foot" on the curve for

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[27] S. E. Forbush (private communication).

TABLE II Cosmic-ray intensity increases at polar stations.

	Estimated geomagnetic latitude	Geographic longitude	Time of onset U.T.	Time of maximum intensity U.T.	Detector and absorber
Mawson[a]	−73	65°E	Est. 0344-50	<0358	Vertical; 10 cm Pb
MacQuarie Island[a]	−61	160°E	Est. 0344	0400	Vertical; 10 cm Pb
Cape Schmidt[b, c]	+63	180°E	0344	0358	Ionization; 12 cm Pb
Kiruna[d]	+68	20°E	Est. 0344	<0400	Vertical; no absorber
Godhavn[e]	+80°	55°W	0353-4	<0420-30	Ionization; 12 cm Pb
Resolute[f]	+83°	100°W	0353	0415	Vertical; 14 cm Pb

[a] See reference 28.
[b] See reference 5.
[c] See reference 8.
[d] See reference 32.
[e] See reference 27.
[f] See reference 7.

intensity increases. This is observed in some cases and has been defined here as the gradual pre-onset increase t_0*. For example, the preflare increase began about 0341 U.T. and amounted to 20% (ionization) at Hobart, Tasmania,[28] and 10% (ionization) at Freiburg.[6] For low energies and late onset the foot is also evident in the Ottawa neutron intensity data, Fig. 3.

If this explanation for the observed dispersion in arrival times of particles is correct, then these dispersion effects must have occurred at the time of previous cosmic-ray intensity increases. For example, on November 19, 1949, the ion chamber at Climax, Colorado was in an impact zone with onset time $t_0 = 1045$ U.T.[29] Whereas the neutron detector at Manchester, England[30] was in a higher order region. For Manchester we see from Fig. 7 it is unlikely that the onset was earlier than about $t_0 \approx 1055$; hence $\Delta t \approx 10$ minutes.

The simplified model for a solar diffusing envelope which we presented here to account for the dispersion effect is undoubtedly, in nature, a mixture of magnetic field regions, since not only are there the field irregularities in the envelope, but also radially stretched magnetic fields in the equatorial regions, in addition to the enormous channel of disordered fields produced by the giant flare itself. Hence, each flare event may display some differences in the energy dependence of Δt and apparent source size. The magnitudes of t' and Δt for the five great flares may depend upon how far into the corona the flare burst carries the production region before diffusion outward takes place.

Because of diffusion, cosmic-ray particles may reach the back side of the solar envelope and escape. There may be, therefore, a difficulty with the model since few increases of cosmic-ray intensity have occurred without an observed solar flare. Perhaps the outward diffusion is limited more to a radial diffusion channel than we suspect at present.

VI. COSMIC-RAY EFFECTS IN THE POLAR REGIONS

For the first time cosmic-ray detectors were located in both polar regions, and in this section we consider the main results derived from the data in Table II. We define the polar regions by the limiting latitudes $> \pm 60°$. The intensity curve at Mawson[28] is shown in Fig. 8 where it is clear that no matter what onset time is assumed, the maximum intensity must occur before 0358 U.T. This fact, along with the restriction for a reasonable rate of intensity increase, limits the probable onset time to a range near the prompt onset time $t_0 = 0344$ U.T. Thus, the intensity increase at Mawson is of the impact-zone type. This agrees with the calculated position of the "0900" hour impact zone at −70°, as shown in Fig. 4(b). Lüst, Schlüter *et al.*, also found

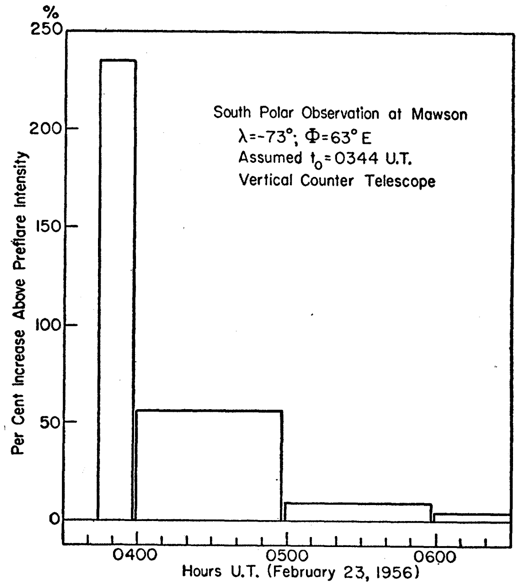

FIG. 8. The cosmic-ray intensity at Mawson, Antarctica.

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[28] A. G. Fenton *et al.*, Nature **177**, 1173 (1956). We are indebted to Dr. Fenton for his review of the ionization data.

[29] Forbush, Stinchcomb, and Schein, Phys. Rev. **79**, 501 (1950).

[30] We are grateful to Dr. H. J. J. Braddick and Dr. N. Adams for providing us with more accurate data on the neutron-intensity increase at Manchester (November 19, 1949) than has heretofore been published.

connecting orbits in this region at high latitudes.[31] By similar arguments the intensity increase at Macquarie Island[28] and at Kiruna, Sweden,[32] should be in impact zones.

As we earlier noted for Fig. 4, the Cape Schmidt[5] ion chamber behaves as though it were in an impact zone, but from Fig. 4(a) we see that this would only be true if the source size were very large. Consequently, this station establishes the boundary condition for source size at 0344 U.T. The prompt onset at Cape Schmidt cannot arise from very high-energy particles passing relatively undeflected from the sun.[8] We know that the energy spectrum of solar particles is steep and from impact-zone theory that only particles of greater than 10 Bv rigidity reached Tokyo from the direction of the sun. But particles above 10 Bv rigidity produced only a 10% increase at Tokyo.[33] Since the maximum intensity at Cape Schmidt was approximately 215% above normal, the incoming radiation was of lower energy.

These four stations provide strong evidence for impact-zone effects in both polar regions and are in agreement with reasonable extensions of the calculations for the zones shown in Figs. 4(a) and 4(b). In contrast with this the intensity increases at Resolute and Godhavn show that only late-arriving particles contribute to the onset of the increases at these stations.

There is convincing evidence that the particle intensity observed at Resolute[7] and Godhavn[27] is not restricted to these regions but rather extends over the entire North Polar region and Cape Schmidt.

First, an examination of the intensity increase at Cape Schmidt shows that it may be represented roughly by the sum of two components: (a) a moderately high-energy component producing an intensity-time curve similar to that observed at lower latitude stations such as at Yakutsk[5] or Freiburg and including the promptly arriving particles, and (b) the radiation curve as a function of time for Godhavn with a slight reduction in intensity which takes into account the difference in geomagnetic latitudes of these two stations. It should be noted that after the first hour of the flare, Cape Schmidt and Godhavn data are remarkably similar.

Second, from Fig. 3 we note that for more than an hour, changes of intensity in the Ottawa neutron pile and the Godhavn chamber are identical, within experimental errors, if the percent increase at Godhavn is increased by the factor 50 to account for detector response. It is highly unlikely that the detailed shape of the intensity-time curves would be the same unless the radiations reaching the two sites were identical in composition and intensity with time.

Third, the counter telescopes at Resolute and at Ottawa showed almost identical behavior under 14 cm lead.

From these three arguments we conclude that the radiation which began to arrive at Ottawa after 0353 U.T. was also admitted at Resolute, Godhavn and Cape Schmidt and, hence, over a wide range of polar latitudes and longitudes.

Within the South Polar regions, due to insufficient data, the only evidence for late-arriving radiation continuing beyond the first hours of the flare event is derived from the Mawson telescope, where the intensity remained above normal level for more than six hours; this was a period which certainly took the telescope outside the impact zone shown in Fig. 4(b), even if the width of the zone is expanded by 4 hours. The time above normal preflare intensity was about the same as for Resolute, and it suggests that the radiation arriving at late times in both polar regions followed the same intensity-time curve.

From this discussion we conclude for the flare of February 23, 1956, that there were impact zones extending into the lower polar regions for the promptly arriving particles, and that after about 0353, the kind of radiation arriving at Ottawa extended throughout the north polar and probably the south polar regions. At late times, especially after 0500 hour U.T., the highest total particle intensities are found in the polar regions. Experimental results indicate that the polar radiation at late times is composed of the entire radiation which has access to the earth. The four previous large cosmic-ray increases support this view since the intensity at Godhavn at late times is always farther above preflare intensity than any other comparable ion chamber anywhere in the world.

VII. TRANSITION FROM IMPACT ZONE EFFECTS TO ISOTROPIC INCIDENCE

Since Godhavn and Resolute are located at latitudes inaccessible to the solar source, the polar observations show that the radiation reaching Ottawa and Godhavn was beginning to come from directions other than the sun after 0353 U.T. During the following hours there was no further evidence that the incoming radiation arrived from a preferred source position except for small anisotropies measured at high energies in Stockholm[34] and Rome.[35] We believe that this anisotropic effect after the first hour may arise from the north and south telescopes observing particles of different energies. If so, the observed steep particle spectrum will produce appreciable differences in intensity between the two telescopes. Also, the telescope anisotropy persisted for more than a quarter revolution of the earth which suggests that there was not a unique position for the apparent source.

We argue, therefore, that the period following 0353

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[31] Lüst, Schlüter, and Katterbach, Nachr. Akad. Wiss. Göttingen, 8 (1955).

[32] A. Sandstrom (private communication).

[33] Y. Sekido (private communication).

[34] D. Eckartt, Proceedings of the Conference on Cosmical Electrodynamics, Stockholm, Sweden, 1956 (unpublished).

[35] F. Bachelet and A. M. Conforto, Nuovo cimento 3, 1153 (1956).

U.T. represents the transition from a preferred source direction to isotropic incidence.

In Sec. V we made the simplifying assumption that the source size was constant, and independent of particle energy. However, if our calculations of the impact-zone locations are even approximately correct, then the solar cosmic rays came from a region which included the position of the sun. The size of this diffusion source for different particle energies may be estimated, both from the longitude spread of the merged first and second zones in Asia and Europe, and from the time for particles to diffuse out of the source. At the time of prompt onset (0344 U.T.) the source as observed at the earth was less than 1 radian in solid angle. However, for approximately 1 Bv magnetic-rigidity particles first arriving about 0353 U.T. the source would appear to occupy an exceedingly large solid angle. It is at this time, we believe, that the transition from particle arrival in impact zones to more or less isotropic incidence begins.

VIII. CONSEQUENCES OF THE DISPERSION EFFECT AND IMPACT ZONES FOR PROPAGATION IN UNIFORM FIELDS

Recently Ehmert[2] and Hayakawa *et al.*[3] have suggested that the region including the sun and the earth was pervaded at the time of the flare by a more or less uniform magnetic field along which the solar cosmic rays may propagate to the earth.[36] We shall consider here briefly the implications which (a) the existence of impact zones and (b) the dispersion effect have upon this hypothesis during the early stages of the cosmic-ray intensity increase.

The first step is to show how particles moving in a uniform field will be distributed just outside the influence of the terrestrial magnetic field near the time of prompt onset, t_0, and at later times, $t_0+\Delta t$. The second step is to find out what distribution the particles will have within the magnetic field and at the top of the atmosphere for these respective times. We shall give here only the main features and principal effects.

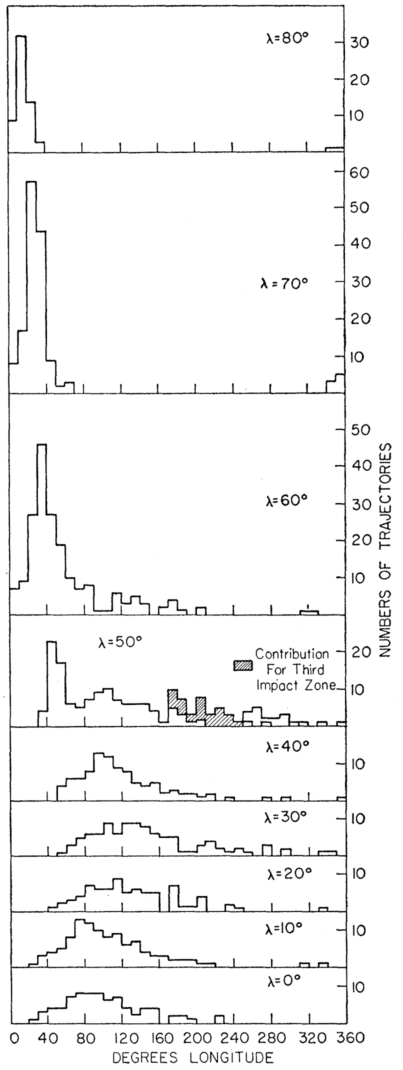

FIG. 9. The locations of impact zones inside the terrestrial field from a "line" source of particles outside the field and covering $\leq 180°$ in the sky. This type of source is predicted for propagation of flare particles in uniform magnetic fields, within which lie the sun and earth.

Call φ the angle between the direction of the magnetic-field lines of force and the sun-earth line, l. Charged particles with a wide range of magnetic rigidities are assumed to be emitted isotropically by the flare into this magnetic field; we define α as the angle which a particle trajectory makes with respect to the field lines. We also assume that all particles are relativistic and travel at the same velocity, $v=\beta c$. Then the time to travel along the field in the sun-earth direction is $t=l\cos\varphi/\beta c\cos\alpha$. Clearly, if $\varphi=0$ particles of *all* energies traveling along the line will reach the earth. But if $\varphi\neq0$, then only particles above a lower rigidity limit $N'(=pc/Ze)$ may reach the earth, and only at late times. If we define ρ to be the radius of curvature of the trajectory projected on the plane perpendicular to l, then there is a value $\rho'(=l\sin\varphi)$ determined by φ which establishes the lower rigidity limit N' for solar particles observed at the earth. Particle trajectories with a radius of curvature less than ρ' will not reach the earth at any time.

To account for the prompt onset time t_0, high-energy particles are required to move along a small spread of orbits about l. As time elapses, $t>t_0$, particles will begin to approach the earth with $\alpha\rightarrow90°$ to form an apparent particle source in the sky which lies in a plane approximately 90° with respect to the sun-earth direction, but this depends upon the bending of the field lines between the sun and earth. Thus, the apparent source moves from a position coincident with the sun at t_0 to a position approximately 90° away from the sun by approximately

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[36] If the uniform magnetic-field model is modified to produce a field which diverges from the sun to the earth, the observed storage of particles becomes a problem. At late times storage is difficult, and the spectrum is expected to become rapidly steeper with time, a result which does not agree with the observations.

$t=0353$ U.T., if the arrival of particles in forbidden zones is to be explained by this model.

We have investigated the distribution of impact points at the top of the atmosphere for this line source. The results for half the sky are shown in Fig. 9. It is clear that the impact zones are remarkably well defined and, since the line source must persist for as long as there are solar cosmic-ray particles stored in the uniform field, the impact-zone effect at the earth as shown in Fig. 9 will remain for hours after its initial formation.

We believe that the experimental observations argue against a uniform magnetic field pervading the sun-earth region at the time of the flare.

First, the uniform-field model does not produce delays in onset times of the kind shown in Fig. 3. The time delays must arise in a uniform field from the spiral trajectories of the particles, rather than from the difference in velocities of the particles, since this latter effect is less than 10% of the observed dispersion. Then, for the initial burst of solar cosmic rays, the first arriving particles were those of all energies which travel along the field direction, i.e., for $\alpha\approx 0°$. Since the transit time is $t'=l/\beta c \cos\alpha$ for small values of φ, the radiation first reaching the earth contains particles of *both* low and high energies. Similar conditions will exist for a slowly diverging or radial magnetic field.

On the other hand, Ehmert[2] has suggested that the time delay comes about by making φ large and by invoking the progressive shift of the apparent source from the sun direction to a position in the sky far from the sun—as we have noted above. This requires that the impact zones be well defined at all times during the shift of the apparent source, and for later times. It also requires that very low-energy particles (<6 Bev for protons) have no access to the earth at any time during the intensity increase. Neither of these requirements appear to be fulfilled by the observations.

Second, for times in excess of $t_0=0353$ U.T. the uniform-field model requires the presence of a line source which produces impact zones distributed as shown in Fig. 9. During the rotation of the earth, many stations on the earth have access to the main impact zone at some time during the decline of solar cosmic-ray intensity. At these times the intensity is predicted to be substantially greater than at other times. No effects of this kind have been reported, and we conclude that the intensity was almost completely isotropic in the vicinity of the earth at later times.

Once the transition to nearly isotropic conditions occurs, the storage mechanism takes over the further propagation of the solar-produced particles.

The experimental evidence, both for early and late times in the development of the solar flare effect does not exclude the possible existence of a uniform or radial magnetic field lying between the sun and earth, even for a field intensity as large as 10^{-5} gauss at the orbit of the earth. However, the experiments indicate that even if these field distributions are present, they do not account for the dispersion effect or isotropy and storage at late times. This problem of cosmic ray storage by magnetic fields in interplanetary space extending beyond the orbit of the earth has been discussed elsewhere,[1,37] and will not be discussed further here.

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[37] J. A. Simpson, Nuovo cimento (Supplement, 1957).