PAPER 38

SOLAR PRODUCTION AND MODULATION OF COSMIC RAYS, AND THEIR PROPAGATION THROUGH INTERPLANETARY SPACE

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ABSTRACT

The principal characteristics for changes of cosmic ray intensity as a function of time and primary particle energy are reviewed for those intensity variations which are thought to be of non-terrestrial origin. These variations are either (*a*) temporary increases of cosmic ray intensity arising from the *de novo* production of cosmic ray particles in the vicinity of the sun in association with some solar flares, or (*b*) the modulation of extra-solar cosmic radiation within the interplanetary volume by a modulation mechanism related to solar activity.

The study of these variations for low-energy cosmic ray particles is also a unique tool for the investigation of interplanetary magnetic fields and other properties of interplanetary space. As an example, the cosmic ray events associated with the giant solar flare of 23 February 1956 have been studied. The experimental evidence shows that interplanetary magnetic fields must exist for the storage and redistribution of the solar flare cosmic ray particles. A more specific model indicates that disordered magnetic fields lie mainly beyond the orbit of the earth and that diffusion through these irregular magnetic fields is the prominent mechanism for particle storage. In addition, this cosmic ray intensity increase was fortunately superposed in such a way upon a change of intensity arising from a modulation mechanism that it is possible to restrict the kinds of models which account for modulation of cosmic ray intensity within the interplanetary volume.

I. INTRODUCTION

Cosmic ray intensity variations with time have been observed for over 25 years, but only recently has it become clear from experiments that many of these variations are, indeed, changes of primary particle intensity—changes which occur outside the atmosphere and beyond the geomagnetic field. These variations have been correlated with properties of the sun, and it is now obvious that the principal changes observed in the primary cosmic ray spectrum are connected with solar phenomena: the intensity variations have a solar origin [1]. For example, the occasional and transient increases of cosmic ray intensity at the time of large solar flares represent solar cosmic ray production. On the other hand, changes of intensity such as the recurring 27-day variations, or sharp changes in the level of intensity the order of 20%, as well as gradual changes in the spectrum over the 11-year solar cycle all appear to have their origin in the solar modulation of pre-existent cosmic radiation in the interplanetary medium. Hence, there exist within the solar system both, (*a*) *de novo* production of cosmic rays at the sun, and (*b*) the modulation of extra-solar cosmic radiation within the interplanetary volume.

We know that the cosmic ray spectrum undergoes the largest changes with time at low-particle energies, with the magnitude of the variations becoming vanishingly small for energies in excess of 40–50 Bev (Billion electron volts). We conclude that this dependence upon particle energy, along with the change in numbers of particles reaching the earth, requires the presence of magnetic fields of non-terrestrial origin to account for modulation by the sun. The search for a theory of how solar connected phenomena produce cosmic ray modulation effects have led us to re-examine the conditions which prevail in interplanetary space, particularly with regard to these magnetic fields and their description.

Indeed, we use the cosmic ray particles of low magnetic rigidity as a unique 'tool' to study the electrodynamics of the interplanetary medium. Cosmic rays from solar flares are probes for investigating the prevailing conditions at the time of the flare, and place limits upon the magnitudes and configurations of interplanetary magnetic fields and ionized gases. As we shall later show, the solar flare cosmic ray particles will also help us to understand the modulation mechanism.

The application of cosmic rays to problems of the interplanetary medium are not restricted to the study of intensity changes. They have also been used as probes to determine the earth's outer magnetic field distribution. In fact, only recently have we found that the outer geomagnetic field *effective for cosmic rays* is significantly different from earlier predictions—a problem bearing on the question of an inclined and rotating magnetic dipole field interacting with an extensive, ionized gas. However, our discussion in this paper shall be directed to the specific case of cosmic radiation from the solar flare of 23 February 1956, and its implications for a description of the interplanetary medium and cosmic ray modulating mechanism. For this study I wish to acknowledge the collaboration of P. Meyer and E. N. Parker of our laboratory [2].

The fifth large increase of cosmic ray intensity known to occur in association with a solar flare took place on 23 February 1956. This was the largest of all the intensity increases since they were first observed in 1942 [3, 4], and it undoubtedly will be the most studied. From these earlier events it was evident that the particles producing the intensity increase occurred predominantly in the low energy portion of the cosmic ray

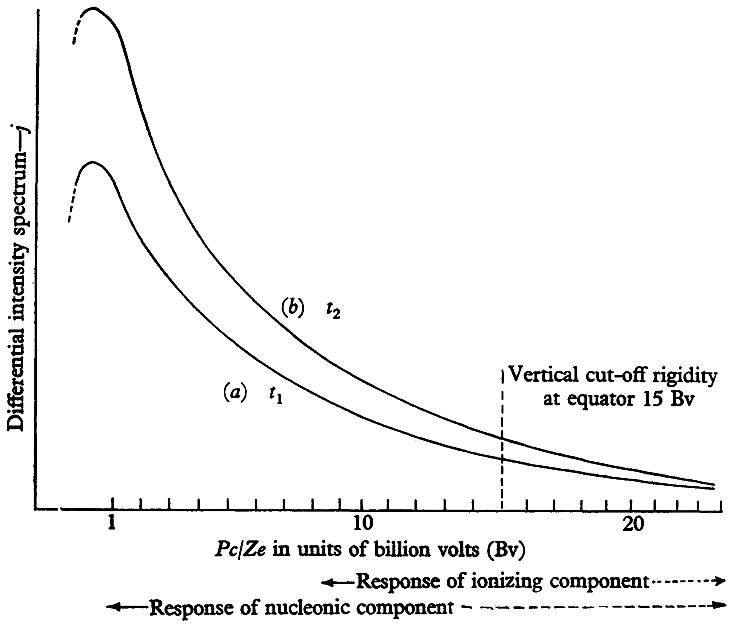

Fig. 1. The range of detector responses for the secondary particles arising from the primary cosmic radiation.

spectrum. Therefore, detectors which respond to the secondary radiation from the low energy portion of the primary cosmic ray spectrum are of special interest in studying the energy spectrum of flare particles. Over the past 8 years a neutron intensity monitor has been developed and used for investigations of this kind at low energies, since more than 0·75 of all cosmic ray particles to which it is sensitive fall within a magnetic rigidity range where we may use the geomagnetic field as a particle rigidity analyser.

To measure changes in primary cosmic ray intensity during the flare we record the intensity of the secondary, nucleonic component generated by the primary radiation. The nucleonic component intensity is indirectly measured by the amount of local neutron production within a pile structure of lead and paraffin. Since we know the response of the neutron detector

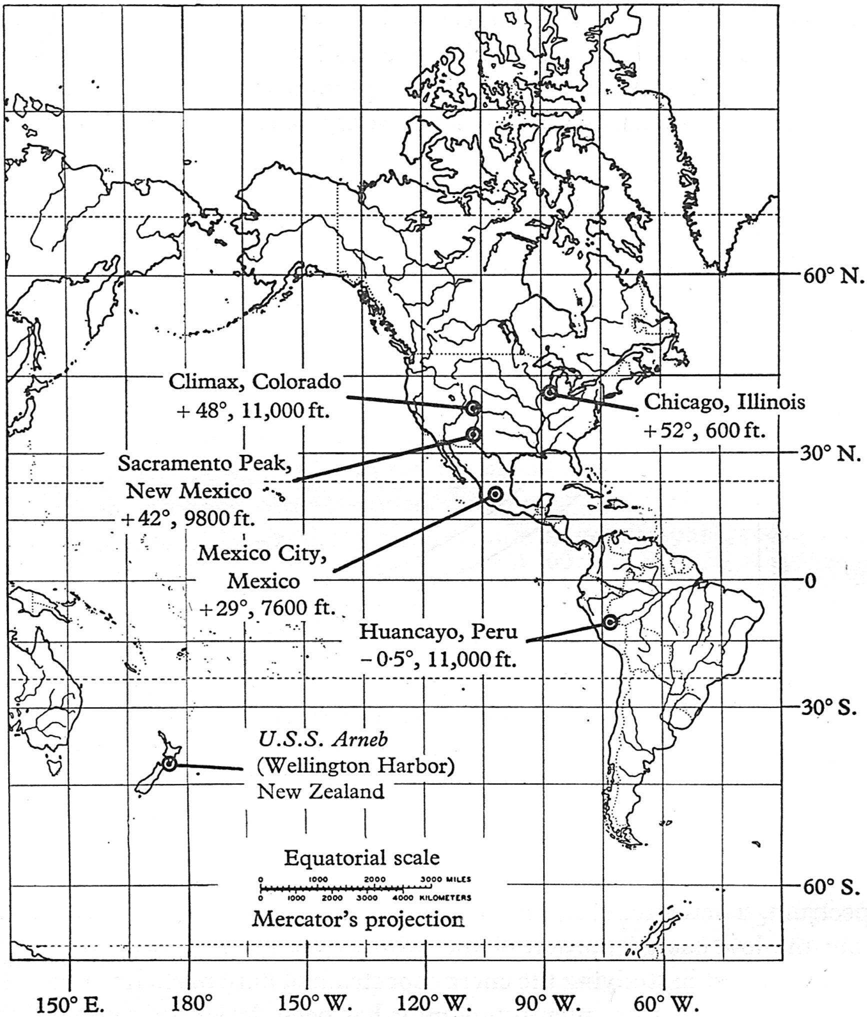

Fig. 2. Locations of neutron intensity monitors established by the University of Chicago.

for the normal cosmic ray spectrum as a function of geomagnetic latitude and atmospheric depth, we may extrapolate any changes of observed intensity to the top of the atmosphere. In this way we deduce the changes in primary intensity. Fig. 1 shows the differential cosmic ray spectrum—

number of incident particles as a function of magnetic rigidity—and illustrates how the nucleonic component extends observations over the range of low magnetic rigidity particles inaccessible to ion chambers or counter telescopes. We have established a network of neutron pile monitors to exploit these principles. Locations of the continuous observing stations are shown on the map, Fig. 2. At the time of the flare the sixth neutron monitor, identical with the units at Chicago and Climax, was returning with the U.S. Antarctic Expedition and was operating in the harbor of Wellington, New Zealand. In addition, neutron detection apparatus was

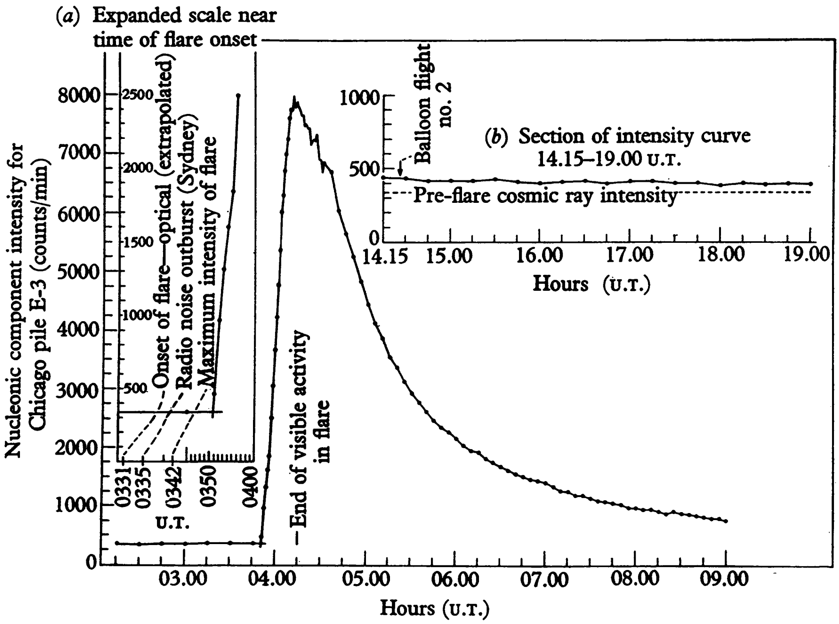

Fig. 3. The neutron intensity as a function of time for Chicago at the time of the 23 February 1956 flare.

carried by a balloon over Chicago during the cosmic ray increase. Thus, the flare of 23 February is of interest since there exists for the first time the means for studying the flare particle intensity as a function of both time and particle rigidity.

We shall report here on the analysis of our experiments and its bearing on the flare particle spectrum, the propagation of the high-energy flare particles in the interplanetary medium, and the relationship of this cosmic ray event to solar phenomena.

The neutron intensity as a function of time outside of impact zones is shown in Fig. 3 for Chicago, and in Fig. 4 for Wellington Harbor. These two widely separated stations yield precise information on the time of onset, the rate of rise, the maximum intensity and the rate of decline of the temporary increase. In Fig. 5 we display the intensity at all six stations as a function of time.

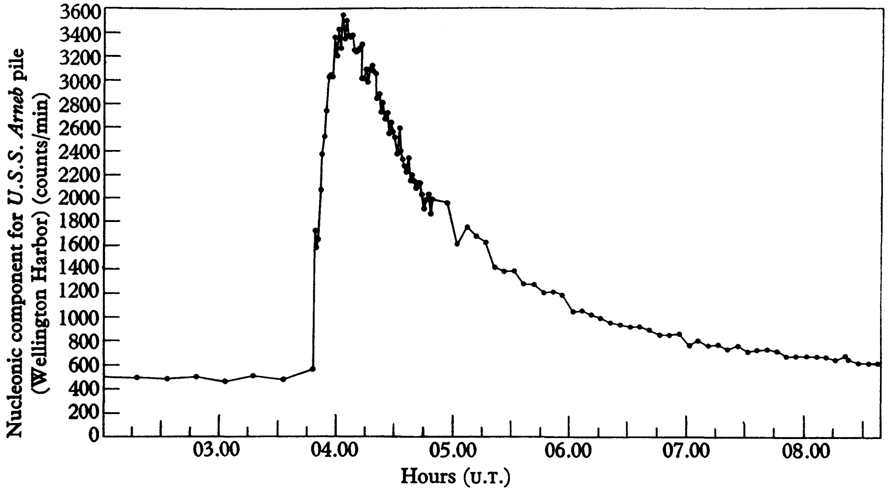

Fig. 4. The neutron intensity as a function of time for Wellington at the time of the 23 February 1956 flare.

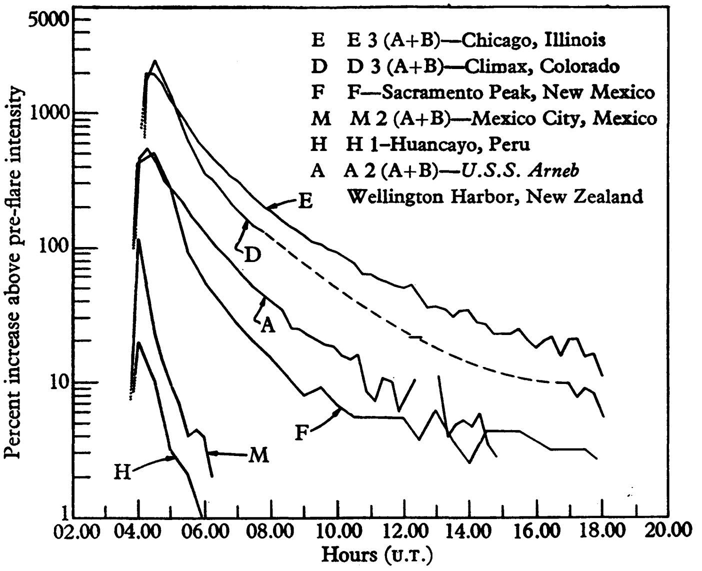

Fig. 5. The increase of intensity for the six neutron monitors.

Before undertaking an analysis of the flare particle spectrum, we wish to point out several conclusions which may be drawn directly from the experimental data in Figs. 3–5. They are:

(1) The temporary increase of cosmic ray intensity represents the acceleration of particles to cosmic ray energies in the vicinity of the sun. No hypothesis of focusing, particle storage at the sun or terrestrial phenomena can account for this enormous increase of cosmic ray intensity.

(2) The incident cosmic radiation which produces the 'tail' of the intensity curve at low energies most probably represents particles scattered back to the earth from many directions in the solar system. This conclusion is supported by the evidence that the radiation continues to arrive for more than 15 hr after all indications of activity in the solar region have disappeared. The lack of intensity increases superposed on the flare intensity curves for Chicago, Climax and Sacramento Peak, near 0400 and 0900 local time impact zones, is further strong evidence that the particles at those times were not coming directly from a 'point' source in the direction of the sun.

(3) To preserve the relatively sharp increases of cosmic ray intensity after onset as shown in Figs. 3 and 4, the particles must have traversed relatively uncomplicated orbits—hence it is unlikely that the scattering regions we have invoked to account for the 'tail' could lie inside the orbit of the earth. If the scattering region had been distributed both inside and outside the orbit of the earth the time for rise to maximum intensity would have been the same order of magnitude as the time for decline to background intensity.

On the other hand, since at onset both Chicago and Wellington were in non-impact zones,* the anomalously large scale of the effect measured there could reasonably be accounted for by requiring that the particles arrive more or less isotropically. Hence, although the orbits are not complicated they must involve at least some scattering, with the scatterer located outside the orbit of the earth. This requires that no appreciable magnetic fields lie between the sun and the earth at the time of the flare.

(4) Particles with energies in excess of 15 Bev, and probably 20–30 Bev, were produced at the time of the flare. We derive this result from the relatively large increase of intensity at the geomagnetic equator (Huancayo, Peru) where the minimum energy for arrival of protons from the vertical is ~ 15 Bev.

From the experimental data we have also obtained the flare particle spectrum. There are two assumptions underlying our analysis. First, we

* Note added after the conference: Reference [5] shows that impact zones of high order do exist for Chicago and Wellington.

assume that the incoming radiation is isotropic, and hence we restrict our analysis to the period following the intensity maximum where the incoming radiation becomes isotropic. From this assumption it then follows that we may use Störmer theory in determining geomagnetic cut-off as a function of latitude for the flare particles. Secondly, we assume that the composition of the incoming radiation is not significantly different from the composition of the normal cosmic radiation. Primary neutrons as the

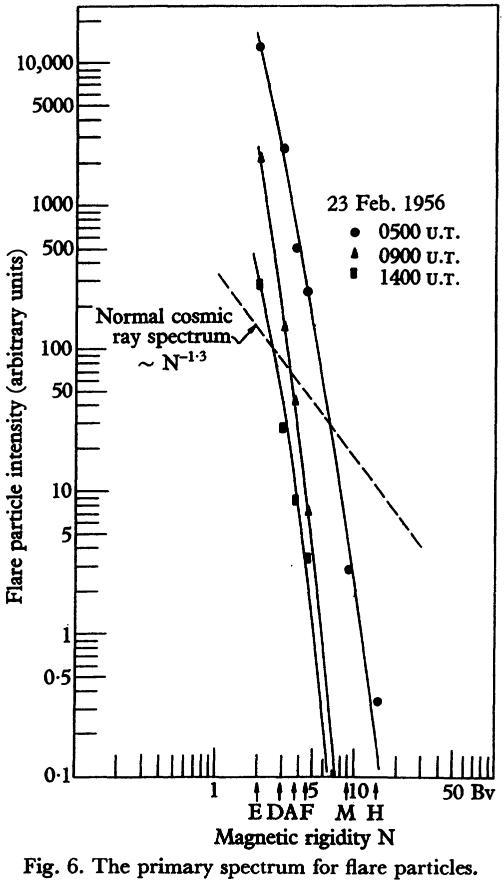

Fig. 6. The primary spectrum for flare particles.

main component are excluded since the flare increase was observed at full intensity on the night side of the earth. The problem then reduces to whether electrons, protons or alpha particles constitute the principal flare radiation. Though electrons may possibly be abundant in the primary flare spectrum, their contributions to the secondary nucleonic component can be estimated to be less than 1 %, assuming that they are just as abundant in the primary radiation as the protons.

The contribution of alpha particles or heavier nuclei to the primary intensity is a more difficult problem, but our analysis of the magnitude of the flare increases at Sacramento Peak, Climax and Chicago proves that the greatest intensity increase at low magnetic rigidity arises almost entirely from protons.

With the above assumptions we have constructed the primary spectrum for flare particles after the first hour of the flare. The results are given in Fig. 6. The spectra follow approximately the power law N^{-7}, although there is evidence that the high rigidity particle intensity tends to decrease more rapidly with time than the intensity for low rigidities.

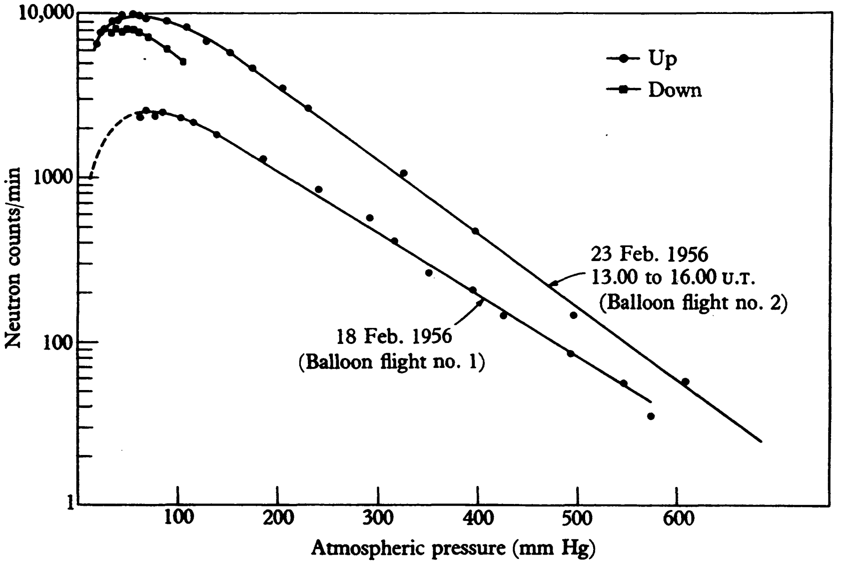

Fig. 7. Balloon flights using neutron detectors. Flight no. 1 was prior to the flare. Flight no. 2 followed the flare.

In Fig. 7 we show the results of two balloon flights: number 1 prior to the flare and number 2 obtained during the progress of the cosmic ray intensity increase. Our analysis shows that the primary spectrum was strongly peaked near magnetic rigidities of 2–4 Bev at 14.30 hour U.T. This is in agreement with the independent observations from the neutron monitor network.

The large difference in onset times of > 5 min between detectors located in impact zones (or at the equator) and detectors outside of impact zones can reasonably be explained by assuming shorter path lengths for the particles arriving in impact zones over those arriving outside of impact zones.

Sittkus *et al.* [6] have suggested that this difference in onset time arises from some reflecting region beyond the orbit of the earth. In this way the particles arriving at regions outside of impact zones will have undergone scattering. This time difference leads to a radius of closest approach for the scattering region to the sun with the value 1·4 to 1·7 a.u.*

3. MODEL FOR THE INTERPLANETARY VOLUME

We now direct our attention to the explanation of the cosmic ray flare effect. It is clear from the experiments that there are several physical conditions within the solar system which must be satisfied in order to develop an explanation for the observations on 23 February 1956. These conditions may be summarized as follows:

(1) There exists a magnetic field-free region extending outward past the orbit of the earth to approximately $r \sim 1{\cdot}5$ a.u.

(2) There is a boundary region which scatters cosmic ray particles back into the field-free region.

(3) Since the particle intensity declines only slowly after reaching maximum intensity the boundary region must be a barrier for the escape of particles from the 'field-free' region.

(4) The decline of intensity follows a power law $t^{-3/2}$ as shown in Fig. 8 and not an exponential function of time. Consequently, the barrier is continuous around the field-free region, and is not thin.

(5) It then follows that the field-free region is a volume surrounded by a barrier of finite thickness for the escape of cosmic ray particles into the galaxy.

This description of the interplanetary volume derived from experiment suggests that the cosmic ray flare particles diffuse through the barrier from the field-free region. If we let $J(E)\,dE$ represent the *density* of cosmic ray particles with energies in the range $(E, E+dE)$, then we shall assume that $J(E)$ varies according to the diffusion equation

$$\frac{\partial J(E)}{\partial t} = K(E)\nabla^2 J(E), \tag{1}$$

where $K(E)$ is the diffusion coefficient for particles of energy E. We find that there is a solution to the diffusion equation which may have the same $t^{-3/2}$ dependence on time which we found from experiment, Fig. 8; namely,

$$J(E) = \frac{c}{(\pi K t)^{3/2}}\, e^{-r^2/\pi K t}. \tag{2}$$

* Note added after the conference: It is shown in reference [5] that the differences in onset times are not due to reflexions. The onset time is a smooth function of particle energy over a spread of >9 minutes in onset time.

Eq. (2) is the special solution of Eq. (1) where a burst of radiation is instantaneously released at $t=0$ and at the origin ($r=0$) of an infinitely extensive diffusing medium. This is a problem well known in the theory of heat conduction. If we observe the change in particle density near the source (small values of r) then $J(E) \propto t^{-3/2}$ for all energies.

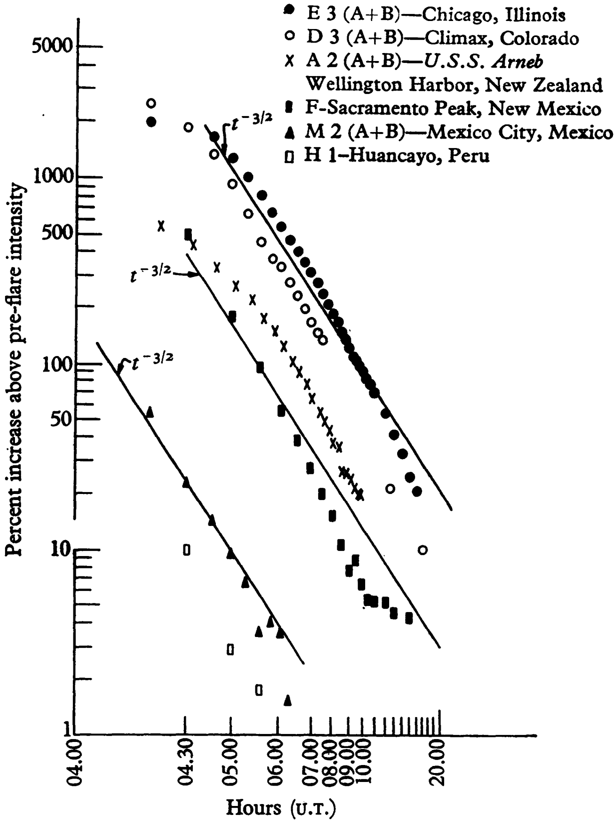

Fig. 8. The decline of cosmic ray intensity follows a power law approximately $t^{-3/2}$ except for late times where the decline approaches an exponential function.

Obviously, this is an over-simplification of the physical conditions if for no other reason than that we know the diffusing region has an inner boundary at $r \approx 1{\cdot}5$ a.u. and does not exist for $0 \leqslant r \leqslant 1{\cdot}5$ a.u. Therefore, for simplicity in developing a model we shall assume that the 'field-free' region is a spherical cavity of radius $a = 1{\cdot}5$ a.u. From Fig. 8 we also know that the function $t^{-3/2}$ does not hold at high energies and, for later times, even at low-particle energies. This indicates, as we shall later show, that the diffusing medium is not infinite in extent. For a barrier of finite

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thickness we shall assume the outer boundary is spherical and at radius b in order to preserve a simple model. These simplifying assumptions lead us to the picture shown in Fig. 9 for the cross-section of the inner solar system.

Although the model proposed here rests upon the experimental data from the February 1956 flare, it is important to note that the requirement for a field-free region $r > 1{\cdot}0$ a.u. in extent, a scattering region and a delay in the eventual escape of the flare particles from the solar system were

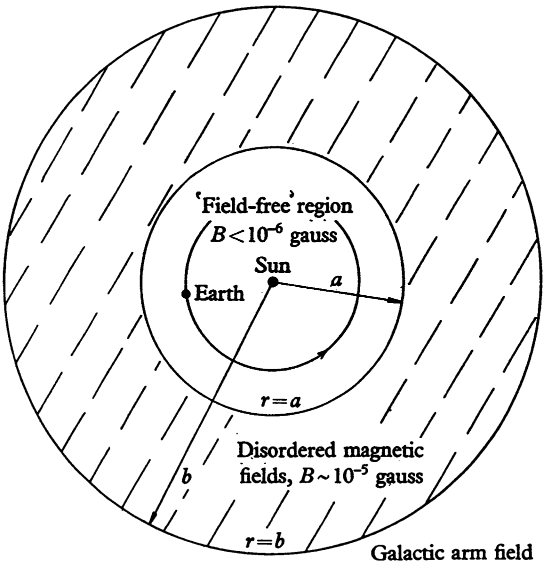

Fig. 9. An idealized model for the distribution of disordered magnetic fields in the solar system.

already deduced from the earlier flare events. [1]. Hence, we hope that the hypothesis proposed here may be extended to all flare particle observations.

We estimate b from the observed deviation of the intensity from $t^{-3/2}$ for large values of t: $b \approx 5$ a.u. We have also obtained two independent estimates of $K(E) = c/3\ L(E)$ where

$$L(E) \approx \frac{E_0\left[\frac{E}{E_0}\left(\frac{E}{E_0}+2\right)\right]^{\frac{1}{2}}}{ZeB}.$$

We note that $K(E)$ is approximately proportional to E for particle energies of several Bev or more.

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If we assume that L is the same order of magnitude as the radius of curvature of the particles in the disordered barrier field then the r.m.s. field intensity $B \cong 2 \times 10^{-5}$ gauss.

Highly ionized field-free clouds of gas may sweep back any ordered solar or galactic magnetic fields which would otherwise pervade the entire interplanetary space [7, 8]. We have assumed that the barrier is represented by these tangled fields piled-up over a region forming a shell with inner radius 1–2 a.u. We do not know the degree of stability of such a barrier against penetration by ordered fields, but we do know from simple hydromagnetic concepts that the time constants are the order of months, or more. For our purposes it is sufficient to point out that the flare event was preceded by months of intense solar activity which should be capable of forming the special conditions required for the barrier region.

4. THE SUPERPOSITION OF FLARE PARTICLES ON A COSMIC RAY MODULATION EFFECT

In view of the severe restrictions we have placed upon magnetic fields and scattering within the solar cavity at the time of the flare it is especially important to understand the origin of the isotropic and rapid decrease of

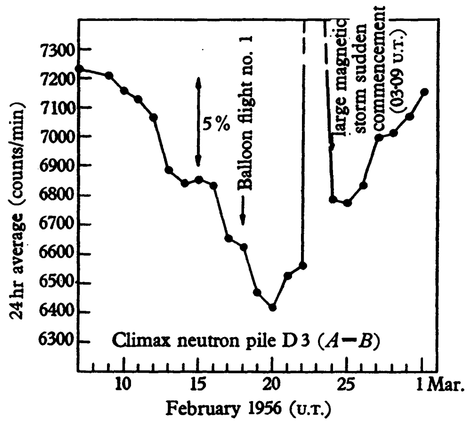

Fig. 10. The decrease of cosmic ray intensity which began before the flare event.

cosmic ray intensity (Forbush-type decrease) which began ~ 10 days prior to the flare event and continued beyond the period of the flare (see Fig. 10). In recent years experiments have shown that this isotropic decrease is not of terrestrial origin, and hence, the mechanism producing it must lie

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outside the geomagnetic field. Experiments have also shown that the magnitude of this phenomenon is a function of particle rigidity and is a modulation of the pre-existent cosmic radiation by a solar-controlled mechanism [9].

We have discussed elsewhere the possibility for distinguishing among the several hypotheses of cosmic ray modulation by studying the superposition of the flare particle spectrum on the modulated pre-existent cosmic rays [10]; we treat the flare particles as probes for studying electromagnetic conditions in interplanetary space.

The experimental evidence cited above supports modulation by magnetized and ionized clouds. Also the escape of the flare particles from the solar system is strong evidence for the presence of diffusion. The question then arises: How is it possible for these cloud-like regions to expand outward from the sun carrying their tangled magnetic fields without introducing such serious scattering within ~ 1 a.u. that the observed features of the cosmic ray flare event would be destroyed? The magnetic field intensity and scale length of the model clouds proposed by Morrison [11] to account for a rapid intensity decrease and continuing low intensity level ($\sim 10\%$ decrease at climax) are more than an order of magnitude too large to permit observation of the flare event. An alternative explanation [12], wherein the magnetized cloud is captured by the earth and is supported outside the geomagnetic field, namely, a geocentric cloud, does not meet with these objections. For the geocentric model we find that with scattering and diffusion limited to regions near the earth, there is negligible effect on the flare particle orbits.

Let us consider how diffusion of cosmic ray particles through ionized clouds containing twisted and knotted fields may introduce changes of total cosmic ray intensity. For purposes of illustration, we assume that the diffusing region is of infinite extent and thickness y, and that the full galactic intensity is observed in region (1), Fig. 11 (*a*). Then a detector placed in region (2) after the system has reached equilibrium will detect the full galactic radiation intensity. If, however, region (2) is initially free of radiation, and the galactic radiation begins to diffuse through the scattering barrier, the detector will observe that:

(1) The intensity rises asymptotically to the galactic intensity.

(2) The rigidity dependence of the spectrum is changing and approaches the spectrum of the galaxy.

The flux of particles $F(x, y, z; E)$ in region (2) arising from a gradient in the cosmic ray particle density $J(x, y, z; E)$ for the mean free path

$L(x, y, z; E)$ of magnetic scattering centres ($L \ll y$) in the twisted fields region may be written:

$$F(x, y, z; E) = -\frac{L}{3} \nabla[VJ]$$

for particles of velocity V.

This is the mechanism proposed by Morrison to account for the intensity variations. A magnetized cloud of ionized matter is ejected from the sun, expanding to an enormous volume which initially contains no cosmic radiation in its inner regions, Fig. 11 (*b*). If, then, the earth sweeps into

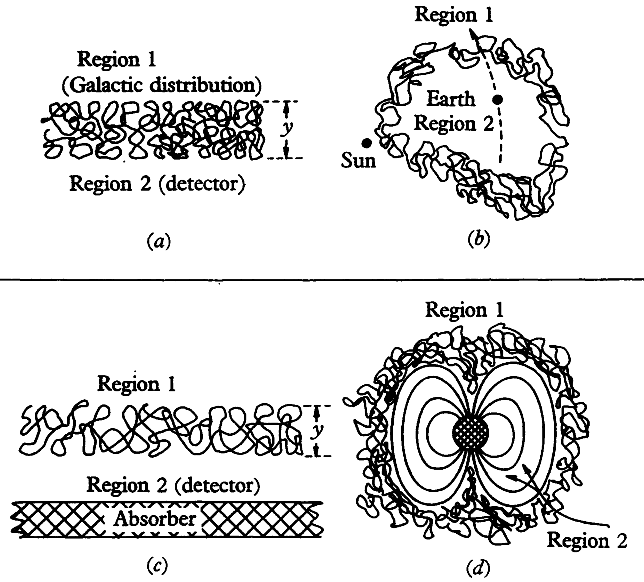

Fig. 11. Concepts for the diffusion and capture of cosmic ray particles.

this volume, a detector will measure a sharply reduced intensity. The outward moving cloud also 'sweeps out' preferentially the low-energy particles due to its velocity V'. The time to reduce the total intensity for reasonable field intensities is the order of a day or more with the time for recovery to normal intensity the order of days.

On the other hand, if we introduce an *absorber* in region (2) which is capable of removing particles as fast as they diffuse through the barrier, as in Fig. 11 (*c*), it is clear that:

(1) A much less efficient barrier-diffusing region is needed to produce reductions of total intensity.

(2) The intensity will remain low so long as the barrier is present.

Now for a diffusing barrier having the scale size of the solar system, there are no large absorbers capable of producing this effect. But if the diffusing barrier is placed around the earth overlying the earth's magnetic field, then the earth becomes the absorber, Fig. 11 (*d*). This latter proposal forms the basis for the theory developed recently by Parker. It is capable of explaining the sharp Forbush-type decreases, the low rigidity cut-off and its variation with the solar cycle, the 11-year cycle of intensity, all with fields the order of 10^{-5} gauss in the barrier region. The model then becomes a local, geocentric, model. This is in contrast with a barrier centered about the sun and extending throughout the solar system in all directions, i.e. a heliocentric model.

For this geocentric model the earth and its outer field is surrounded by an ionized gaseous nebula of low density retained by gravitational forces but buoyed at an equilibrium distance above the geomagnetic field by the pressures between the geomagnetic field, B(terr.), and the fields in the ionized clouds, B(cloud), i.e.

$$\frac{B^2\,(\text{terrestrial})}{8\pi} \approx \frac{B^2\,(\text{cloud})}{8\pi}.$$

This model meets the objections raised by the Morrison model which requires both fields 10^{-1}–10^{-3} gauss and places special conditions on the times at which particles from a solar flare may be detected at the earth.

A theory for the solar modulation of cosmic ray intensity, based upon these principles, is consistent with and a strong argument for the indirect association found between cosmic ray intensity variations and geomagnetic storms, since the interactions of highly ionized gas clouds of solar origin, with or without twisted magnetic fields, are expected to produce observable and transient effects on the geomagnetic field when captured by the earth. These interactions are only now beginning to be studied.

5. CONCLUSION

By extending the study of cosmic ray intensity variations to the low-energy portion of the primary cosmic ray spectrum it becomes clear that the dominant mechanism for both (*a*) modulation of extra-solar radiation, and (*b*) the temporary storage of solar cosmic rays is cosmic ray diffusion through disordered magnetic fields in interplanetary space. The distribution of these disordered fields throughout the interplanetary volume is not known, except that tangled fields surrounding the earth satisfy the conditions for modulating cosmic ray intensity, and disordered magnetic fields beyond the earth's orbit enclosing a field-free region between the sun and the earth are required to account for the diffusion of solar flare-produced cosmic rays away from the vicinity of the sun and earth. The r.m.s. magnetic field intensities required to account for the observed changes in the primary cosmic ray spectrum are no greater than the order of 10^{-5} gauss in the vicinity of the orbit of the earth. The strong correlations between solar activity and the observed changes in the cosmic ray spectrum both for short and long-time scale phenomena leave no doubt as to the solar origin of these magnetized clouds; however, their production and life-history is an unsettled problem.

It is not difficult to imagine that the major geomagnetic storm effects may also find their explanation in the collision of magnetized clouds with the permanent geomagnetic field, and their occasional capture by the field. All of our evidence relating cosmic ray intensity variations to major geomagnetic disturbances support the view that cosmic ray and geomagnetic field variations are linked by a solar-produced mechanism, presumably the production of magnetized clouds in special regions of the sun.

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Discussion

Eckhartt: I would like to make some comments concerning the question of onset times. As you pointed out there should be a difference in onset times between stations lying within the classical impact zones and those stations lying outside. We have chosen a number of stations where the times of onset were rather sharply defined. For each of these stations we determined the geomagnetic deflexion of cosmic ray particles arriving from zenith in the momentum range up to 10 GeV/c, using Malmfors's curves. Thus we got the initial directions far away from the earth of these flare cosmic ray particles which finally arrive at the chosen stations from zenith directions. These initial or asymptotic directions will be represented by a vector. The end-point of this vector is thought to rest in the center of the earth, whereas the arrow point of the vector is determined by a latitude angle and by a longitude angle in the geographic system of the earth. This is the same manner in which Brunberg demonstrates the asymptotic directions on his globes. In the two-dimensional representation of Fig. 12 we look upon the northern hemisphere. The geographic latitude is

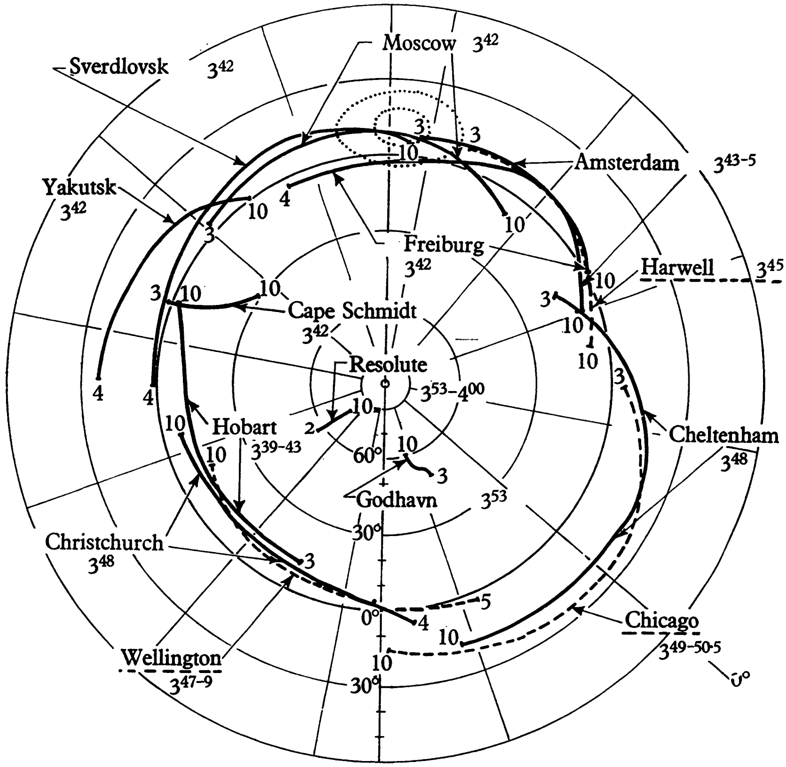

Fig. 12. The asymptotic directions for arrival from the zenith at the chosen stations. The directions towards the sun at the beginning of the solar flare are indicated by the dotted lines at the top of the figure. The time of onset of the cosmic ray increase is written next to the name of each station.

represented by the length of the radius, the geographic longitude by the azimuth angle. For example, take a proton of energy 3 GeV which arrives at Chicago from the zenith. This particle has an asymptotic direction far away from the earth defined by the direction from the earth's center to the point 40° E of Greenwich and 5° S which is shown on Fig. 12. The small figures at the ends of each curve denote the value of the momentum at the particular point. Other values and points have been computed. Thus, the curves represent a smooth interpolation of the asymptotic directions for arrival from the zenith at the chosen stations for particles in the range of momenta denoted by the small

https://doi.org/10.1017/S0074180900237947 Published online by Cambridge University Press

figures. But for the low energies in question and for the chosen stations these curves may be representative even for arrival from other small zenith angles. Most of the stations shown here are equipped with ionization chambers. Only the dashed lines refer to stations with neutron monitors or a shower detector at Harwell. At the very moment of the beginning of the flare the sun, as seen from the earth in an angular diameter of 15 and 30° respectively, is given by the dotted lines at the top of the figure. When a curve intersects this area the corresponding station lies in one of the classical impact zones. The time of onset of the cosmic ray increase is written next to the name of each station. You see that Hobart, lying far outside the impact zones, had such an early onset as 3^{39}–3^{43}. The same is valid for the Russian stations Yakutsk and Sverdlovsk.* In general, the stations whose asymptotic directions are between $\pm 90°$ with respect to the direction towards the sun seem to have started earlier, than those stations whose asymptotic directions point away from the sun.

This was my first remark. Let me now present some of the results measured by our own GM directional telescopes. These are declined 30° to the north and to the south. During the whole flare increase the north pointing telescope recorded more particles than the south pointing one. Since particles measured by the two inclined telescopes are almost equally affected by the atmosphere the ratio between the measured pulse rates becomes a measure for the ratio of primary flux above the atmosphere. On Fig. 13 we show the ratio between the relative increases of the north and south pointing telescopes at Stockholm and at Rome. We see that the north pointing telescope measured about 10 % more particles than the south pointing telescope did. This seems to be in conflict with your assumption of isotropy a certain time after the onset of the flare. We interpret our results in the following way. The asymptotic directions—these are the directions of the particles far away from the earth—lie very close to each other for momenta below 10–12 GeV/c. This means that particles below this energy come from nearly the same directions outside the earth's magnetic field. Therefore, there must have been particles with momenta higher than 10 or 12 GeV/c. For the second, the number of particles with higher momenta must have been different for the different asymptotic directions. Isotropic distribution among all asymptotic directions could not cause any difference in the counting rates. Different onset times for the two telescopes would certainly only have affected the first hour's result. If one looks now upon the difference in angles between the direction towards the sun and the asymptotic directions from which the particles have come in order to be measured by our north pointing telescope, one arrives at the values 50 and 70° for momenta 20 and 10 GeV/c respectively. A value of about 6×10^{-6} gauss is found for a mean magnetic field in the interplanetary space which would have caused this deflexion, assuming that the particles are coming from the vicinity of the sun. This value is somewhat higher than the upper limit you have chosen.

Alfvén: I think that if one takes into account only the stations which Professor Simpson showed in his diagrams, then the results could be interpreted with his

* Note added after the conference: According to a recent publication in *Nuclear Physics*, **1**, 585, 1956, the times of onset at the Russian stations should be altered to: Moscow 3^{38}, 3^{40}, Sverdlovsk 3^{40}.

model. On the other hand, if one includes all the stations which are available, for example also the Soviet and Japanese stations, the whole picture changes altogether. As Eckhartt showed in his diagrams we do not get radiation only from the direction of the sun. We also get radiation from other directions. It is very important that the first moment when the increase in cosmic ray intensity is observed on the earth is, as far as could be judged, simultaneous for beams coming from all directions. This is very clearly seen from the recordings of the Soviet stations.

I think the general picture we get here when we include all the stations shows how important is international collaboration and I am very glad of the initiative taken by Gold and Elliot to collect all the data.

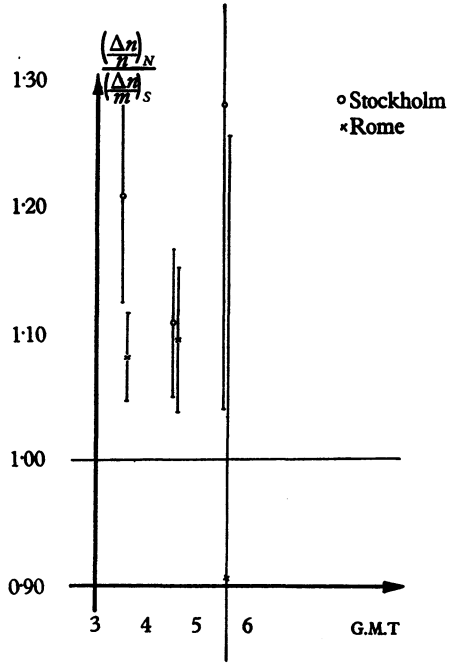

Fig. 13. The ratio between the relative increases in pulse rates of the north and south pointing telescopes at Stockholm and at Rome.

Simpson: Just one remark concerning the whole question of energies. At the high energies the asymmetries certainly seem to exist at the beginning of the flare and are very important. However, after the first hour, most of the particles in the field are coming in below 5 BeV and the arguments given here are based on these very low energies. See also reference [12] of the preceding paper.

Alfvén: You cannot possibly conclude that there is a field-free region between the sun and the earth.

Simpson: I have defined the region containing an average field of 10^{-6} gauss or less as a 'field-free' region, and have included the earth's orbit in this region. The boundary region would begin beyond the earth's orbit.

Singer: The solar flare increase on 23 February 1956, was a special case in that it occurred during a Forbush decrease. Statements about the interplanetary field must take account of this. My own view on the Forbush decrease is that it is produced by a turbulent magnetic field which is expanding and therefore decelerating the cosmic radiation. I think that the results that Eckhartt presented which I have not seen before support this point of view.

Elliot: Simpson suggests that the anisotropy might be due to difference in energy between primary particles recorded by telescopes and neutron monitors. I do not agree with this view because I think they very nearly measure the same thing. In the neutron monitor roughly half of the particles are protons and these same protons must be recorded by the counter telescope of the type which Eckhartt has used. I do not see that one can contribute any difference in primary energy to these two types of recording.

Simpson: That is correct. I just want to say that the onset time differences and the asymmetry constitute very crucial points. Most of the particles we have studied were primaries in the region 2–4 Bev, near geomagnetic cut-off energies, and the time for first arrival, i.e. onset time, appears to be a function of particle energy. See also reference [12].

Parker: Professor Alfvén's objection that the observed directions of approach of the primary particles from the solar flare cannot be accounted for by the field-free ($B \leqslant 10^{-6}$ gauss) space is easily avoided by tangled magnetic fields localized about the earth.

Alfvén: Can you construct such a field and what is the order of magnitude of that?

Parker: A rough value would be 10^{-2} gauss in regions at a distance of several earth's radii. Such a possibility is not ruled out even though it conflicts with your theories.

Alfvén: But observations are well interpreted by the electric field model which I proposed yesterday.

Parker: I do not think that observations could pick out a unique theory.

Ferraro: If an interplanetary field is responsible for the influx of cosmic ray particles on the anti-meridian and post-meridian sides of the earth by magnetic deflexion, as Professor Alfvén reports, would we not expect a difference between the time arrivals of particles at the earth in different localities? Is this the case?

Simpson: Also there is the problem of the long storage times observed. How can your model store particles long enough?

Alfvén: In the magnetic field you will have a diffusion outwards.

Parker: We have calculated the diffusion rate of a field of 10^{-5} gauss and it comes out too large by a factor of 10.

Alfvén: I do not believe this. It depends on the shape of the field.

Sarabhai: Dr Simpson has listed a number of variations under modulations of cosmic ray intensity. He has further stated that in these modulations, low energy primaries are more affected than high energy primaries. I would like to point out that this type of energy dependence is by no means always present. As shown by Neher, intensity increases have sometimes been observed for intermediate energies without equally large changes at low energies. Furthermore, the energy dependence in the different types of variations is not the same.

Some years ago, the Chicago group reported the small flare effect in the cosmic ray nucleonic component. Little has since then been heard of this important effect. Has this been confirmed in later measurements? How does the small flare effect fit into the model proposed by Dr Simpson?

Simpson: With respect to the effect of small flares I will say that the apparatus was put into operation just as we came to the declining period of the solar cycle. We have about 15 months period to look for flares. There are about 66 flares available to work with; a statistical treatment is necessary in order to look for a small pulse. The results were just exactly as reported. There seems to be about 1 % pulse in the impact zones and nothing evident outside the impact zones. A statistical study, however, is weak because one wants observations for at least one whole solar cycle and we certainly propose to follow this up. But this now requires waiting well into the maximum of the present solar cycle in order to get enough new data. There are two points that one has to consider. First, one may ask if all flares of the same character produce cosmic ray particles arriving here. Secondly, there is the question whether they strictly follow the simplest paths of impact zones worked out by Schlüter and Lüst, and Firor.

Biermann: Would it not seem from the collective evidence we have heard that only a small fraction of the flare radiation everywhere observed on the earth comes directly from the sun? In that case the original outburst must have been of rather short duration (almost a few minutes) and that the 'cavity' was filled quite rapidly. The observed time differences of the onset at various stations would then mainly reflect the irregularities and general shape of the reflecting and diffusing boundary of the cavity assumed by Dr Simpson.