teristics for solar protons?

Singer: i) This is an important point and will effect the proton-alpha ratio at the low energy end of the spectrum. This should be calculated and compared with observations.

ii) Diffusive deceleration is the only mechanism I can think of which can affect cosmic rays of this high energy substantially without making unreasonable demands on the properties of the magnetic scattering centers.

iii) Not necessary, but this work has not been carried out yet.

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN Vol. 17, SUPPLEMENT A-II, 1962
INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-5-17. Modulation of the Cosmic Ray Intensity by the Interplanetary Magnetic Field

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Introduction

At the present time there exists a number of rather different models of the interplanetary field, each of which tends to emphasize some particular characteristic as the prime cause of the cosmic ray intensity variations. Alfvén, for example, has laid particular stress on the importance of electric fields, and the effects of these fields have been worked out in great detail by Dorman. The kinds of magnetic configurations which have been proposed show a wide variety. According to Morrison, the plasma motions in the solar system, and consequently the field also, are highly turbulent so that the galactic cosmic rays can only reach the earth by a process of diffusion. The picture that has been particularly advocated by Gold, on the other hand, is quite different. He argues that the outward motion of the solar material must drag out the photospheric fields into long tongue-like configurations in which the field distribution is rather regular. When the earth is enveloped by such a magnetic tongue or bottle, we observe a drop in the galactic cosmic ray intensity corresponding to the Forbush decrease. A configuration of this kind also provides direct paths for the charged particles linking the earth to the sun, thereby facilitating the propagation to the earth of particles accelerated in solar flares.

Parker takes the view that the outward streaming of solar material is not restricted to times of exceptional activity but takes place all the time, constituting the so-called 'solar wind'. This wind stretches the photospheric fields out radially into a configuration which is relatively smooth within the earth's orbit but becomes turbulent a fraction of an astronomical unit beyond it. The outward motion of the disordered part of the field provides a barrier to the incoming cosmic rays, but this barrier operates in a rather different way to that envisaged by Morrison. In Morrison's model the intensity inside the diffusing region slowly builds up and, given sufficient time, it would eventually reach the full galactic intensity. If, however, the diffusion time is long enough, we shall see variations in intensity at the earth caused by changes in extent and density of the magnetic barrier. In Parker's model the magnetic scattering centres are in continual outward motion and the inward diffusion of the cosmic rays is counteracted by outward convection so that in the steady state there is a subnormal cosmic ray intensity inside the barrier. Singer has pointed out that if the sun is indeed surrounded by an expanding cloud of turbulent field then cosmic rays inside this cloud will lose energy by what he calls an "inverse Fermi process", which is similar in principle to the cooling of a gas by adiabatic expansion.

It seems likely that all these ideas will ultimately have to be incorporated to some extent into the final picture. The problem at the present time is to determine their relative importance. Each of the proposals mentioned above has its own particular merit, but none in itself seems to be entirely adequate to account for all that we know at present about the cosmic ray intensity variations.

Dipole-like Field Model

I have tried to construct a simple semi-quantitative model of the interplanetary magnetic field incorporating some of these ideas and which would be capable of explaining at the same time the eleven-year intensity variation, the Forbush decrease, and the solar daily variation (Elliot[1]). This model is based on the belief that the eleven-year intensity variation is fundamental, whilst the Forbush decrease and the daily variation are of secondary importance, and that all three are primarily the result of the screening action of the magnetic field. The first point I would like to make concerns the symmetry of this field. We know that the variation in intensity observed over the twenty seven day rotation period of the sun is generally small compared with the amplitude of the eleven-year variation, as can be seen from the neutron data in Fig. 1. This implies that the magnetic field producing the long-term variation must have a fair

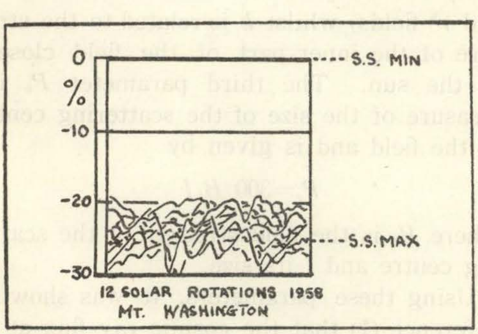

Fig. 1. Superposition of the neutron intensity variations during 12 solar rotations in 1958.

degree of axial symmetry. Consequently, isolated tongues of magnetic field generated by the outward motion of solar material from regions of strong magnetic field near sunspots, for instance, can hardly be responsible for the basic eleven-year variation. A highly turbulent field of the kind proposed by Morrison would of course fulfil the symmetry requirement, but the field strengths required by his model ($10^{-3} \rightarrow 10^{-2}$ gauss) appear to be incompatible with those detected by Pioneer V ($10^{-5} \rightarrow 10^{-4}$ gauss in general). The dipole-like field of ~ 1 gauss observed in the photosphere is also much too small to explain the changes in cosmic ray intensity, and in any case it appears to pass through zero at sunspot maximum when the depression in cosmic ray intensity is greatest (Babcock[2]).

Unless the measurements of the field strength in the photosphere are grossly wrong there appears to be no alternative other than a field generated by axially symmetric currents flowing in the corona. The location and extent of these current systems is not crucial from the cosmic ray point of view.

If the field beyond the earth's orbit were completely regular and unperturbed it would produce a sharp lower limit to the magnetic rigidity required by a cosmic ray particle if it is to reach the earth from infinity. The values for this minimum rigidity P_{min} would be

$$P_{min} \sim 48\ B_e r_e \text{ volts, for a dipole field of moment } M_s$$

whilst the corresponding value for field falling off as $1/r^2$ turns out to be

$$P_{min} \sim 84\ B_e r_e \text{ volts}$$

where B_e is the magnetic field strength at the earth distant r_e from the sun.

We know that the modulation of the cosmic ray intensity does not take the form of a sharp cut-off in the primary spectrum. Instead, we have a reduction in intensity over a wide band of primary energies (Elliot *et al.*[3]). This can be accounted for by the presence of inhomogeneities in the large scale field produced by the outward motion of solar plasma. These inhomogeneities introduce a degree of scattering, enabling the galactic particles of low energy to diffuse through the field into regions which would otherwise be forbidden to them. In the absence of any other effect, the ultimate result of this diffusion would be to fill the forbidden regions with cosmic rays at the full galactic intensity. Competing with this diffusion process, however, there is absorption by the sun. The magnetic lines of force extend from the scattering region near the ecliptic plane to the neighbourhood of the sun and some will in fact connect directly with the solar surface. Consequently, a particle scattered in the right direction can reach the surface of the sun and be absorbed there. This is the converse process to the propagation of solar flare particles out to the earth and beyond. The appearance of these particles at the earth is a good indication that from time to time at any rate such paths leading into the sun do exist. The intensity of the cosmic rays at any given distance from the sun is determined, therefore, by the competitive processes of diffusion and absorption, so that we have a steady state in which the intensity of particles in the forbidden regions lies somewhere between zero and the full galactic intensity.

The field close to the sun must be extremely complicated because of the photospheric fields and the violent hydromagnetic motions in the inner corona. As has been pointed out above, however, some lines of force from the large scale external field must connect rather directly with sunspot fields as shown in Fig. 2.

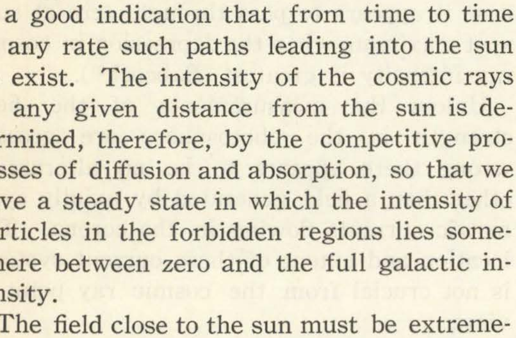

Fig. 2. Lines of force from large scale external field connect with sunspot magnetic fields, thereby providing connecting paths between flare regions and the earth.

According to this picture, a major part of the interplanetary field arises from a stable static configuration of lines of force in the form of closed loops which do not in general intersect the solar surface.

Should it turn out that the large scale field has a net outward motion, this would mean that we should have removal of cosmic rays by outward convection as well as by absorption in the sun. There seems reason to believe, however, that convection is not very important in the modulation process. If it were, the reduction in cosmic ray intensity within the solar system would be a function not only of the magnetic rigidity of the particle but also of its velocity. Consequently, at the low energy end of the spectrum, where the particles have values of β appreciably less than unity, we should expect protons and α-particles with the same magnetic rigidity, but different values of β, to be reduced in intensity by different amounts. It is extremely important to determine to what extent convective modulation does exist, and for this purpose it is essential to obtain simultaneous and accurate measurements of the intensity variations of low energy protons and α-particles. The existing evidence seems to show that the modulation at low energies is a function of rigidity only (Webber[4]). We must conclude, therefore, that convection is relatively unimportant and that we are dealing with a field which is essentially static.

Quantitative Discussion of the Model

In reference (1) a dipole field was assumed and this field was specified by three parameters. The first of these, M_s, is the dipole moment of the current system generating the field. The second, αk, is the probability of absorption per scattering collison. The quantity α is determined by the geometry of the large scale field and has the value unity for a dipole field (it is different for r^2 and r^3 fields) whilst k is related to the structure of the inner part of the field close to to the sun. The third parameter P_o is a measure of the size of the scattering centres in the field and is given by

$$P_o = 300\ B_i\, l$$

where B_i is the field strength in the scattering centre and l its size.

Using these parameters, it was shown in reference (1) that the cosmic ray flux at the earth φ_E, is related to the galactic flux φ_∞, by the relation

Table I.

Intensity of Nucleonic Component at Mt Washington relative to that ot sunspot minimum	M_s (gauss cm^3)	αk	P_0 (GV)	Corresponding field strength at the earth, B_E in gauss	
				Dipole	$1/r^2$ field
0.98	1.0×10^{35}	0.05	0.50	3.0×10^{-5}	1.5×10^{-5}
0.96	1.2×10^{35}	0.08	0.60	3.6×10^{-5}	1.8×10^{-5}
0.92	1.5×10^{35}	0.15	0.75	4.5×10^{-5}	2.2×10^{-5}
0.86	2.0×10^{35}	0.25	1.00	5.9×10^{-5}	2.9×10^{-5}
0.75	3.0×10^{35}	0.30	2.00	8.9×10^{-5}	4.5×10^{-5}

$$\varphi_E=\varphi_\infty\left[\frac{Pr_e^2}{45M_s}\right]^{\gamma(P)} \qquad (1)$$

where

$$\gamma(P)=\frac{1}{4}\left[\left\{1+4\alpha k\left(\frac{P_o+P}{P}\right)\right\}^{1/2}-1\right],$$

P is the magnetic rigidity of the particle and r_e the radius of the earth's orbit.

The three parameters M_s, αk and P_o all depend on the degree of solar activity and reach their highest values at sunspot maximum. An estimate of the range over which they vary has been obtained by fitting the modulation function given by Equation (1) to the observed rigidity dependence of the eleven-year cosmic ray intensity variation.

Table I shows the relationship between these parameters and the intensity of the nucleonic component of the secondary radiation at Mt Washington which has been taken as the base line.

The Forbush Decrease

According to Equation (1) the cosmic ray flux is a function of distance from the sun, and in reference (1) it was pointed out that

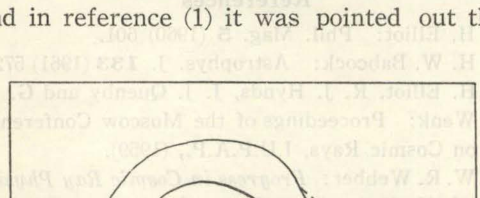

Fig. 3. Distortion of contours of equal cosmic ray intensiiy at the time of a Forbush decrease.

a Forbush decrease could be interpreted in terms of the outward motion of solar plasma carrying the interplanetary field and its associated cosmic ray flux with it. Thus the contours of equal cosmic ray intensity are distorted in the way shown in Fig. 3 and at such a time the earth finds itself in a region of subnormal intensity. It was shown in reference (1) that this simple picture of the Forbush decrease, together with the values of the parameters determined from the eleven-year variation, gives very nearly the correct energy dependence. This is illustrated by the two examples in Fig. 4.

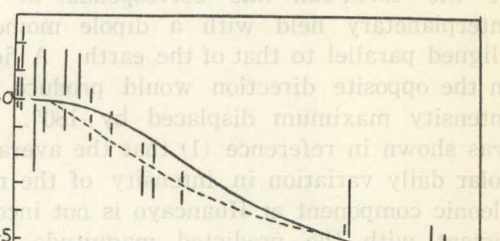

Fig. 4. Latitude dependence of Forbush decrease normalized to value 1.0 at high latitudes.
—— Calculated. - - - Observed for July 1959 event (Carmichael and Steljes).
Vertical lines indicate observations for event of March 25/26, 1958.

Anisotropies in the Primary Radiation

The existence of a gradient in the cosmic ray flux in interplanetary space implies that the radiation will not in general be completely isotropic. Fig. 5 shows the relation between the direction of anisotropy, the flux gradient, and the magnetic field direction to be expected on the basis of the present model. The degree of anisotropy can be calculated roughly from the values of the parameters M_s, αk and P_0 already deduced from the eleven-year variation. The *direction* of anisotropy, however, depends on the *direction*

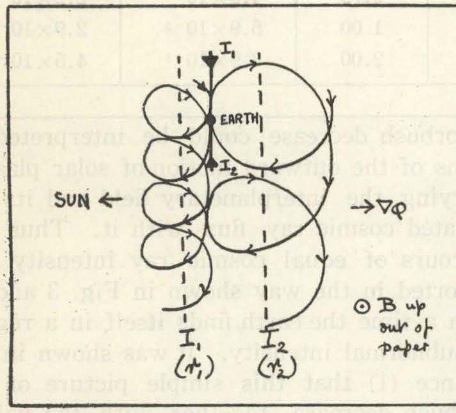

Fig. 5. Anisotropy produced by a cosmic rar flux gradient in a magnetic field.

of the magnetic field. Maximum intensity incident from the direction at 90° to the east of the earth-sun line corresponds to an interplanetary field with a dipole moment aligned parallel to that of the earth. A field in the opposite direction would produce an intensity maximum displaced by 180°. It was shown in reference (1) that the average solar daily variation in intensity of the nucleonic component at Huancayo is not inconsistent with the predicted magnitude and phase of the primary anisotropy provided the interplanetary field direction is taken to be the same as that of the earth. The eleven-year intensity variation itself of cource provides no information as to whether the field direction is parallel or anti-parallel to that of the earth.

Although the long term average characteristics of the daily variation remain rather constant there are, from time to time, large short term changes particularly in association with Forbush decreases. Considerable changes in both degree and direction of anisotropy are to be expected at these times since, according to the present model, the Forbush decrease is the result of a large scale deformation of the interplanetary field. In particular, this model affords a simple interpretation of the large anisotropy which is often observed at the beginning of a Forbush event.

Fenton *et al.*[5], in an analysis based on twenty-two events, showed that the intensity is first depressed for particles arriving from directions lying between 30° and 120° west of the earth-sun line and that maximum depression occurs at about 90° to the west. The interpretation of the Forbush decrease discussed above provides a simple interpretation of this phenomenon if we accept the field direction already deduced from the cosmic ray solar daily variation. As we have already seen (Fig. 5) the cosmic ray intensity from the direction 90° west of the sun is characteristic of that for particles with their guiding centres at a distance r_1 from the sun, whereas that at 90° to the east corresponds to a distance r_2. It follows, from this picture, that at the beginning of a Forbush decrease there will be a delay in depression of the intensity from the east of the sun relative to that from the west. This delay will correspond roughly to the time it takes the solar plasma to cover the distance (r_2-r_1). This distance will, of course, be a function of energy, being greatest at high energy.

References

1) H. Elliot: Phil. Mag. **5** (1960) 601.
2) H. W. Babcock: Astrophys. J. **133** (1961) 572.
3) H. Elliot, R. J. Hynds, J. J. Quenby and G. J. Wenk: Proceedings of the Moscow Conference on Cosmic Rays, I.U.P.A.P., (1959).
4) W. R. Webber: *Progress in Cosmic Ray Physics* VI, N. Holland Publishing Co. (to be published) (1961).
5) A. G. Fenton, K. G. McCracken, D. C. Rose and B. G. Wilson: Canad. J. Phys. **37** (1959) 970.

Discussion

Simpson, J. A.: The experiments with Pioneer V (see II-4-32) to determine the intensity gradient in space for both the eleven year intensity decrease and the Forbush decrease clearly are in disagreement with Elliot's theory by at least a factor of five to ten, if it is agreed that our measurement were concluded under typical interplanetary and solar conditions. Therefore, the validity of these measurements as a test for his model center on this latter point.

Although there are fluctuations in intensity and gradient for the 11 year variation at solar maximum, they are all small compared to the large scale change of intensity and gradient taking place between solar minimum and maximum. Also the fluctuations in the direction of the gradient in space are likely to be small during the period of our measurements.

Ehmert, A.: Concerning the gradient of cosmic ray intensity on solar distance, I want to point out that Dr. Simpson's interpretation of the excellent valuable measurements on Pioneer V seems to me somewhat doubtful. Fig. A gives on the upper curve the relation of intensity in Pioneer V to that N measured at Chicago with neutron monitor (to get read of modulation influences). But we know that percent deviation by any Forbush decrease as for the primaries outside the earth's field twice that for neutron intensity at Chicago or Lindau. If $P/N_1+2(N-N_1)$ had been drawn, as necessary the points would run along the smooth curve in the upper part of Fig. 1, as the point aligns the smooth curve on the lower part of Fig. 1. This being direct neutron record at Lindau. This means a dependence of cosmic rays on the distance R of the sun $P \sim R^{1.3}$ near the earth, that is to say a very large gradient. That is very important for all theories discussed here and we hope this may soon be clarified by further measurements.

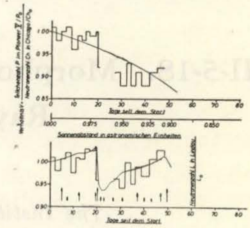
Fig. A.

Parker, E.N.: How do you reconcile this model with the apparent lack of cosmic ray intensity gradient in interplanetary space, as observed from Pioneer V by Fan, Meyer, and Simpson, and how do you reconcile the model with the reversal of polarity of the solar polar fields, as observed by Babcock.

Elliot, H.: i) I do not think that a single measurement of the kind made by Pioneer V is sufficient to establish the magnitude of the average gradient, I believe that much more observational data is required in this connection. I would maintain that at the present time there is no inconsistency between observation and measurement.

ii) The field at sunspot maximum is not related to the solar polar field which in any case pass through zero intensity at this time. I believe that these fields are important at sunspot minimum however and there is evidence in this connection for a reversal of phase of the solar daily variation as between the 1944 and 1954 minima.

Gold, T.: Why does it follow from the small effect of solar rotation that the fields have axial symmetry? The excluding effect could be further out and non-rotating.

Elliot: What you say is absolutely true. The model I do here is dependent on field rotating. If the field does not rotate however, the earth nevertheless holds this field during the course of year. The annual variation is a little bit small, indeed it is smaller than for 27 day variation relative to the full modulation.

Gold: The storage times of solar particles of comparable energy to those excluded in Forbush events are only a few hours. The exclusion time required if the sun itself is to have removed particles, is something like one year, the rate of removal being given by the flux at the solar surface area. It is a serious inconsistency that these times are so different.

McCracken, K. G.: I would like you to amplify the details of your model in relation to the following experimental facts.

1) For an axially symmetric magnetic field, the direction of the diurnal anisotropy will be either 90° to the east, or the west of the sun. In fact, it takes intermediate values on a great number of occasions. In particular, there was a continuous migration of this direction from approximately towards the sun, to one 90° east of the sun between 1954 and 1958.

2) For those events for which sufficient data are available to permit positive identification, the arrival directions for cosmic rays generated in solar flares lie close to the plane of the ecliptic, and furthermore, are inclined by some 50° to the west of the sun. For a "dipole like" field, I would think that we would expect the solar cosmic rays to come from directions roughly perpendicular to the plane of the ecliptic.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-5-18. Morphology of Solar Flare Effects on Cosmic Rays and Sub-Cosmic Rays

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Morphological studies of energetic solar protons are presented in an energy range of Mev to GeV by using cosmic ray records and polar cap absorption data. The solar protons could be classified by order of energy into the four groups: (1) cosmic ray unusual increase, (2) cosmic ray small increase and polar cap absorption of (3) fast and (4) slow types, being classified, respectively, in terms of the propagation time of the particles from the sun toward the earth. A clear distinction is recognized on their characters between a group of the unusual increase and the fast-type PCA and another group of the small increase and the slow-type PCA. These two groups are related to different solar regions where different accelerations of particles occur. This conclusion is based on characteristics of the solar radio noise outbursts associated with these solar proton events and also solar cycle dependencies of the events.

Introduction

This is a review of the morphological studies of energetic solar protons, such as cosmic ray unusual increase, small increase and polar cap absorption events, which were mainly given by several Japanese workers. We have a lot of data concerning the solar flare events by means of the world-wide network of observatories distributed during the IGY 1957–58. Although many interesting studies on the solar flare effects have been made so far, most of them were apt to be restricted to either region of cosmic rays or sub-cosmic rays such as PCA event. If not so, then the studies have concentrated on a special event, for examples, July 1959 event or November 1960 event. At least, the statistical study so as to deal with all of the solar flare events throughout both regions scarecely exists.

The purpose of this report is to investigate the various characteristics of solar cosmic