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ON THE VARIATIONS OF THE PRIMARY COSMIC RAY INTENSITY*

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ABSTRACT

To construct a model for producing the observed variation in the cosmic ray intensity we consider primarily the Forbush decrease and the general decrease of the cosmic ray intensity during years of solar activity. These are larger variations than the diurnal and 27-day variations and require more drastic assumptions; thus they will better serve to establish a unique model.

It is assumed that the sun does not emit cosmic ray particles except during the time of a solar flare. Thus, decreases in the cosmic ray intensity are to be interpreted as a solar effect which inhibits the arrival of galactic cosmic ray particles at earth. Since the intensity of low rigidity primary cosmic ray particles is observed to vary more than the intensity at higher rigidities, the inhibition has generally been assumed to be caused by magnetic fields.

The necessary depression of the cosmic ray intensity requires both a barrier, to impede their arrival, and a removal mechanism within the barrier, to prevent eventual statistical equilibrium (with uniform particle density). Quantitative development indicates that a heliocentric magnetic dipole, a heliocentric cavity in the galactic field (Davis, *Phys. Rev.* **100**, 1440, 1955), and a heliocentric interplanetary cloud barrier (Morrison, *Phys. Rev.* **101**, 1397, 1956) all encounter serious difficulties in explaining the observed effects, one reason being the ineffective removal that is available.

It is shown that a geocentric magnetic cloud barrier does not encounter these difficulties: it is proposed that during the years of solar activity the terrestrial gravitational field captures magnetic gas of solar origin from interplanetary space, which is then supported by the geomagnetic field; the removal by absorption by the earth is sufficiently effective that only a relatively thin barrier need be maintained; the occasional capture of new magnetic material accounts for the abrupt onset of the Forbush decreases, and the slow decay (0·5 years) of the captured fields for the smooth variation of the mean cosmic ray intensity with the sunspot cycle.

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* Assisted in part by the Office of Scientific Research and the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, U.S. Air Force.

This paper is a summary of the results of a number of formal calculations [1, 2, 3] of the propagation of cosmic ray particles through interplanetary space, and represents a critical analysis of the functioning of the general classes of models that have been proposed to account for the variations in the primary cosmic ray intensity observed at the earth. By focusing our attention on the more extreme of the variations [4], we will be able to eliminate many hypothetical models and arrive within fairly narrow limits at a situation which seems to account in a natural way for the observations.

The largest observed fluctuation in the cosmic ray intensity is the appearance and disappearance of the low energy cut-off with the sunspot cycle. During periods of sunspot activity the energy spectrum of the primary cosmic ray particles drops off rapidly at energies below 1 or 2 GeV/nucleon; to form what is known as the *low energy cut-off*. As solar activity declines during the approach of a sunspot minimum, immense quantities of low energy primary particles gradually appear, to entirely obliterate the cut-off [5, 6] and noticeably increasing the number of particles at all energies up to 30 GeV or more; above 30 GeV the percentage increase is so small as to be unobservable. Isotropy obtains at all times. During the return of solar activity following the minimum the low energy particles disappear bit by bit at irregular intervals of time and after a few years the total number of incoming cosmic ray particles has decreased to the pre-minimum value, exhibiting the low energy cut-off.

The most abrupt fluctuation in the cosmic ray intensity is the Forbush decrease, where the world-wide primary cosmic ray intensity may decrease by as much as 10 % in as little time as 5 or 10 hr and remain low for days or months. Again the variation is largest at low energies and represents a variation in the total number of particles rather than a change in the energy of the individual particles. Only small deviations from isotropy are observed during the onset of the decrease; complete isotropy prevails following the onset.

It is difficult to understand how the above variations can be the result of emission of cosmic ray particles by the sun, and it is generally assumed that they are the result of depression of the general galactic cosmic ray field by processes of solar motivation within the planetary system. The observation that the variations are greatest for particles with low magnetic rigidity and vanishingly small at high rigidities, and the observation that the variations are a result of a change in the number of particles, rather than in particle energies, lead us to the conclusion that the variations result from magnetic deflexion of the particles by interplanetary fields.

The steady form and world-wide character of the depression of the cosmic ray intensity during times of solar activity implies that the deflexion is a statistical process and is not produced by one or two individual regular magnetic fields. Presumably, therefore, the diffusion equation represents a rough approximation to the propagation of the general cosmic ray density through space [7]. We let $j(E, \mathbf{r}, t)\, dE$ represent the number of particles/sec/cm²/steradian with energies in the interval $(E, E+dE)$ at the position $\mathbf{r}$ and time t. We regard the irregular interplanetary magnetic fields as a diffusing medium with coefficient of diffusion $\kappa(E)$ and general velocity field $\mathbf{v}(\mathbf{r})$. Then

$$\frac{\partial j(E, \mathbf{r}, t)}{\partial t} = -\nabla . [j(E, \mathbf{r}, t)\ \mathbf{v}(\mathbf{r})] + \kappa(E)\ \nabla^2 j(E, \mathbf{r}, t). \qquad (1)$$

From elementary kinetic theory the diffusion coefficient κ is equal to $\frac{1}{3}wL$ for particles with velocity w and mean free path L. We define the scale $l(\mathbf{r})$ as the mean distance over which the interplanetary magnetic field does not change sign; we let B represent the mean value of the field density over a region of scale $l(\mathbf{r})$. It can be shown [2] that

$$L \simeq L_0 \left\{ 1 + \left[\frac{\pi M w c}{2 l B q (1 - w^2/c^2)^{\frac{1}{2}}} \right]^2 \right\},$$

where L_0 is the mean free path for passage between regions of field, and M and q are the particle mass and charge.

The formal analysis of the cosmic ray intensity throughout interplanetary space, justifying the exclusive use of (1), has been given elsewhere [1, 2, 3]. The quantitative results may be summarized by the following considerations:

(*a*) Formal solution of the equations of motion of a charged particle moving in general hydromagnetic fields, varying slowly over space and time as compared to the radius of curvature of the particle trajectory and the Larmor frequency, or abruptly as in a shock wave, show [3] that a particle will experience no increase in its kinetic energy except by the betatron effect [8] and by Fermi's mechanism [9, 10, 11]; both these mechanisms are estimated to be negligible in interplanetary space, in agreement with the observed fact that the cosmic ray intensity variations do not involve changes in the individual particle energy.

(*b*) The solution of the equations of motion in slowly varying hydromagnetic fields shows that particles can be neither excluded from the solar system nor stored within the solar system by large-scale regular fields, such as a heliocentric magnetic dipole or a heliocentric cavity in the general galactic field[9] unless the large-scale field has very nearly mathematically perfect symmetry and regularity[2]. To significantly trap or exclude particles the field density must not deviate from perfect symmetry by more than one part in 10,000. We believe that the observed solar activity with the associated magnetic and/or material emission from the sun would not allow such regular large-scale fields to occur.

On the basis of (*a*) and (*b*) we conclude that in interplanetary space the diffusion equation (1) represents the complete influence of the sun on the cosmic ray particles of galactic origin; the sun is responsible for the production and motion of the interplanetary magnetic fields, represented by $\kappa(E)$ and $\mathbf{v}$.

In order to lower the cosmic ray intensity at earth for the long years of solar activity we must, of course, postulate a tangle of interplanetary fields to impede the arrival of galactic particles. However, unless we can soon remove the particles which manage to diffuse through the tangled interplanetary barrier, then, no matter how dense the barrier, an equilibrium state will soon be achieved and $j(E, \mathbf{r}, t)$ will be uniform throughout interplanetary space with just the cosmic ray intensity found in the interstellar space outside. Therefore, if we wish to depress the cosmic ray intensity for long periods, we must have a removal mechanism inside the interplanetary field barrier to complement the functioning of the barrier; the more effective the removal mechanism, the less dense need be the barrier, etc.

Now the sun is the major absorber of cosmic ray particles in the solar system; the planets and the interplanetary densities of 10^3 atoms/cm^3 are negligible. The sun will absorb a particle confined within the orbit of earth in about 1·5 years. The interplanetary barrier, associated with this solar removal, of sufficient density to produce the observed depression of the intensity would involve closely packed tangled fields of about $0{\cdot}5 \times 10^{-2}$ gauss surrounding the entire inner solar system. The origin of such a dense interplanetary field is difficult to understand. If it were present between the sun and the earth, we would not expect to see the burst of cosmic ray particles that is observed to accompany some solar flares; we would not expect the almost daily arrival of auroral particles. If the field were present outside the orbit of earth we could not explain the rapid decay of the enhanced cosmic ray intensity following a solar flare; the decay suggests[1] fields of only 10^{-5} gauss. Hence, we do not regard an interplanetary cloud barrier of $0{\cdot}5 \times 10^{-2}$ gauss as likely.

If we wish to use an interplanetary magnetic barrier more diffuse than $0{\cdot}5 \times 10^{-2}$ gauss, then we must have a more effective removal mechanism than solar absorption. If we assume that the interplanetary magnetic fields have been ejected from the sun with velocities of the order of 2000 km/sec, then the cosmic ray particles within the orbit of earth will be swept out once each day instead of once each 1·5 years. The field densities need be only 10^{-5} gauss. However, the fields must be ejected more or less isotropically from the sun (even small leaks in the outward rushing cloud barrier nullify the effect); hence we would not expect to be able to see the sharp rise and the terrestrial impact zones [12] of the cosmic ray bursts from solar flares which requires that $B \lesssim 10^{-6}$ gauss inside the orbit of earth [1]. With outward rushing clouds we would expect the general depression of the cosmic ray intensity at earth to depend critically on the day-by-day activity on the observable face of the sun. Hence, we do not believe that there exists such an outward rushing (2000 km/sec) interplanetary cloud barrier of 10^{-5} gauss.

Let us turn our attention from the general depression of the cosmic ray background during years of solar activity to the transient Forbush decrease. The most striking feature of the Forbush decrease is the 5 or 10 % drop in the intensity (as seen in neutron detectors) occurring in as little time as 5 hr. Following such a drop the intensity may level off and remain low for days. Such an abrupt drop implies interplanetary magnetic clouds carrying fields of $0{\cdot}5 \times 10^{-2}$ gauss, and traveling past earth at 2000 km/sec. Unfortunately we cannot easily reconcile the abrupt drop with the immediate levelling off of the intensity. But even if we overlook these difficulties and use, as originally proposed by Morrison, the somewhat more diffuse field of 10^{-3} gauss, which can produce a decrease only over about 20 hr, we cannot explain how it was possible to observe the abrupt onset of the solar flare of 23 February 1956 while in the minimum of a Forbush decrease: earth was supposedly in the middle of a large magnetic cloud of 10^{-3} gauss; the abrupt onset and terrestrial impact zones required that $B \lesssim 10^{-6}$ gauss.

We wish to suggest on the basis of the above failures of heliocentric models involving tangled interplanetary fields that the observed depressions in the cosmic ray intensity are not heliocentric in origin and do not occur throughout interplanetary space. The most obvious alternative is, of course, that the variations are geocentric in origin and occur only locally about our planet.

We point out that if earth were surrounded by a diffuse cloud of tangled magnetic field ($\sim 3 \times 10^{-2}$ gauss, internal scale of 250 km, and material density 5×10^{6} atoms/cm^3 or less) then we would observe about a 50 % reduction in the intensity of 2 GeV primaries, with less reduction at higher energies and more at lower energies. The tangled field of such a geocentric cloud should extend out to a distance of several earth's radii. Because the solid bulk of earth absorbs a large fraction of the particles penetrating such a geocentric barrier, the necessary barrier is relatively diffuse and will not obliterate the observed terrestrial impact zones for particles of solar origin. Nor would such a small barrier delay or smooth out the abrupt onset of solar flare particles.

Let us suppose, therefore, that the terrestrial gravitational field occassionally captures passing interplanetary magnetic gas. We suggest that during the gradual onset of solar activity following a sunspot minimum the earth captures and builds a tangled magnetic cloud around itself; since earth is never far from the equatorial plane of the sun, the sun need only eject magnetic matter near its equatorial plane to produce such a cloud. The decay time for the captured magnetic fields is of the order of 0·5 years. Hence, freshly ejected matter need be captured by earth only every month or so to maintain a more or less steady depression of the observed cosmic ray intensity. The geocentric magnetic cloud will gradually disappear when solar activity declines at sunspot minimum. Quantitative calculation [2] shows that the observed depression in the abundance of cosmic ray particles at all energies is easily explained by the accumulation of such a cloud.

If we assume that the capture of passing interplanetary cloud material is not always a continuous process, but that occasionally a relatively large amount may be accumulated by the terrestrial gravitational field all at once, then we can readily account for the Forbush decrease with its abrupt onset and levelling off for long periods following the initial decrease. It is an observed fact that the depression of the cosmic ray intensity during a Forbush decrease initially is not uniform over the earth, but gradually becomes so. The initial non-uniformity is expected from the probable condition that the capture of the new magnetic material is not uniform around the earth; then following capture the material gradually spreads out, arranging itself in a smoother and more or less equilibrium state. Only a local geocentric model can account for the observed non-uniformity.

Now consider the limitations of the calculations on which the geocentric model is based. Given a particular statistical distribution of tangled magnetic fields around earth it is not difficult to calculate the resulting reduction in the cosmic ray intensity; the above description of the expected cosmic ray effects is based on such calculations. However, the dynamics of the capture and formation of a geocentric magnetic cloud form a complex mathematical problem which is beyond our present means to handle in a general way. We can show that the weight of such a cloud is so small that it is easily supported by the geomagnetic field without significant magnetic effects occurring at the surface of earth, but we can do little more that is not merely speculation. Therefore, we would like very much to obtain an indication of the presence and structure of the geocentric magnetic cloud which is independent of the cosmic ray observations. Unfortunately with the complex thermodynamic structure of the solar atmosphere, the immense quantities of interplanetary hydrogen, and the dubious thermodynamic state of the geocentric gas, one is led to the conclusion that even such obvious measures as rocket observations at high resolution of the solar L_α line may not yield unambiguous results.

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Discussion

Singer: I agree that the mechanism that Morrison proposed probably does not work, because it is a transient mechanism and it requires a high field. But I do not think that your mechanism will work either; rather particles have to be decelerated by an electric field. You have stated an objection to the electric field mechanism which would lead to a (non-observed) anisotropy. This applies to the picture of a polarized beam; my own view is that particles are decelerated by expanding turbulence set up by beams or clouds. This cloud, when coming from the sun, must expand and give an inverse Fermi effect (to be published in *Phys. Rev.*). The electric field effects are very efficient due to the Liouville factor: $i \propto Dp^2\beta c$, where i is the directional intensity in flux, D the density in phase space, p the momentum of the particle and βc, which has been put in here for the sake of completeness, is usually equal to one. The reason for putting β in here is that I want to explain the production of a knee. In this deceleration mechanism, which I have in mind, when the energy loss is such as to make a particle non-relativistic, we get $\beta c < 1$. Since in a turbulent gas the gas density and the magnetic field are coupled, the ionization loss now becomes important and this is a removal mechanism which I think is most effective for low-energy particles forming a trap and a knee.

Parker: We have looked into both the inverse betatron effect and ionization loss and concluded that they were not sufficient to produce it.

Singer: Let me make a remark about measurements. According to your view the cosmic ray intensity during a Forbush decrease should be low in the top of the atmosphere and should rise when you get out several earth radii. According to my point of view the cosmic ray intensity would be low until you get out of the solar system. Further: according to your view there should be no shift in the position of low energy cut-off, whereas I should find a northward shift in the knee. Concerning these different points of view I will say that one might at the moment be able to decide this by measurements near the poles.

Can you hold your cloud also near the earth at the magnetic pole so that it completely surrounds the earth?

Parker: It should completely surround the earth and perhaps be slightly thinner at the poles because the earth's field is denser there.

Ferraro: I would like to ask you about the leading ideas of the size of that cloud with a magnetic field of about 10^{-2} gauss.

Parker: This is a tangled field and the scale of the inhomogeneity which we estimated from cosmic ray intensities was about 300 km. The cloud would be of the order of 2–3 earth radii thick.

Ferraro: What is the inner boundary?

Parker: For the inner boundary I can only give you a lower limit of half an earth's radius above the earth's surface. It may be more than that.

Ferraro: But in that case if you get variations in the magnetic field would you not expect to observe this at the earth?

Parker: We have tried to estimate the effects which will be produced by the magnetic field we have assumed and we find that there are two competing effects. The orders of magnitude are difficult to estimate; I am sorry I cannot give you a definite reply to your question.

Schlüter: May I ask whether the fast rising time of a few minutes during a big flare is compatible with this model?

Parker: Yes. The transit time through this cloud around the earth is of the order of a fraction of a second. The effect that it will produce is that it deflects in a random way and impedes the particles coming in. A 1 GeV particle is seriously impeded but particles of 4 or 5 GeV come through with not more than 30° deflexion.