Solar Magnetic Moment and Cosmic-Ray Effects Associated with Solar Flares*

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A close correlation between solar flares and small cosmic-ray intensity increases has recently been established by the Climax, Colorado, neutron monitor data. The correlation, however, is restricted only to those flares which occur when the station lies within a certain interval of local solar time. This has been explained by supposing that the new cosmic-ray particles approach the earth preferentially along the earth-sun line, before deflection in the terrestrial magnetic field takes place. In the present paper, this evidence is used to establish an upper limit to a possible solar magnetic dipole field. Allowance is made for the fact that the dipole field may be seriously perturbed by local fields near the sun; but on the assumption that the dipole field predominates far from the sun (at distances greater than one-fifth the earth-sun distance), the upper limit on the solar dipole moment is 5×10^{32} gauss-cm^3.

ANALYSIS of the neutron-monitor data for Climax, Colorado, has revealed that small cosmic-ray intensity increases are frequently associated with solar flares.[1] Although small in magnitude, these events resemble the large cosmic-ray increases which on rare occasions in the past have been observed to accompany large solar flares.[2] Aside from its inherent interest in demonstrating a solar influence on cosmic radiation, the new evidence has an important bearing on the question of the magnitude of a possible solar dipole field. It is this aspect of the problem which we shall consider here.

The association between small flares and cosmic-ray intensity increases is found to be pronounced only for those flares which occur when the cosmic-ray detector lies within a certain interval ("impact zone") of local solar time.[1] For the Climax detector, the center of the impact zone is at $\sim$4 A.M. and the width of the zone appears to be no larger than ±2 hours. For flares which occur when the detector lies outside of the impact zone, there is no measurable cosmic-ray effect.

This local time, or longitude dependence of the cosmic-ray effect, has been interpreted along the following lines.[1] If the new cosmic-ray particles which give rise to the intensity variation approach the earth from a specified direction (in particular, if they approach along the earth-sun line), they will be deflected in the terrestrial magnetic field and will strike the earth at calculable "impact points," whose locations depend on the magnetic rigidity. For particles which arrive vertically at the latitude of Climax, one such impact point (which involves particles of rigidity 4 Bv) occurs at 4 A.M. local solar time. The impact points spread out into impact zones of finite width when one takes into account the whole range of zenith angles of arrival at the earth. The zones will be further widened if the particles approach the earth over a range of angles with respect to the earth-sun line.

Not only the small cosmic-ray increases associated with solar flares, but also the four large solar-flare events seem to fit this picture.[1] We shall therefore consider it established that the cosmic-ray particles which are produced[3] on or near the sun in connection with solar flares, and which reach the earth, approach essentially along the earth-sun line before they are deflected in the short-scale terrestrial field. The width (±2 hours) of the 4 A.M. impact zone at Climax implies that the particles make an angle of at most 30° with respect to the earth-sun line in the geomagnetic equator.

It is difficult to reconcile this evidence with the large solar dipole moment (6.5×10^{33} gauss-cm^3) implied by the cosmic-ray latitude cutoff observed at the earth.[4,5] For this value of the dipole moment, the earth would not be accessible to 4-Bev particles coming from the vicinity of the sun unless they are produced at very large heliomagnetic latitudes. Even in this case it appears very doubtful that in the vicinity of the earth the orbits are preferentially directed along the earth-sun line.[6]

However, during solar-flare periods one might well expect that local magnetic fields seriously perturb the dipole field near the sun, so that the above arguments lose their force. For example, Forbush *et al.*[7] have suggested the possibility that the interaction of sunspot fields with the general solar dipole field produces a "tunnel" through which particles can escape the vicinity of the sun at low heliomagnetic latitudes. Nevertheless, in the cases considered by them, and perhaps in general, it appears that the simple dipole field becomes predominant at distances greater than about one-fifth the sun-earth distance r_e. At any rate,

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1 John Firor, preceding paper [Phys. Rev. **94**, 1017 (1954)].
2 Forbush, Stinchcomb, and Schein, Phys. Rev. **79**, 501 (1950).
3 Although we speak of the new particles as being "produced," we also have in mind the possibility that the cosmic-ray intensity variations may be due to the acceleration ("modulation") of pre-existent cosmic radiation by fields in the vicinity of the sun. Our discussion does not depend on the distinction between production (*de novo*) or modulation.
4 J. A. Van Allen and S. F. Singer, Nature **170**, 62 (1952).
5 Neher, Peterson, and Stern, Phys. Rev. **90**, 655 (1953).
6 In this connection, see C. Stoermer, Astrophys. Norv. **1**, 116 (1935) for plots of typical dipole orbits.
7 Forbush, Gill, and Vallarta, Revs. Modern Phys. **21**, 44 (1949).

we shall make this assumption; i.e., we suppose that for distances greater than $r_1=r_e/5$, the orbits are those appropriate to a pure magnetic dipole.

One can, however, imagine a special kind of magnetic perturbation which might be appreciable all the way out to the earth, namely, a neutral, ionized beam of particles from the sun, which carries with it a magnetic field. In fact, it has been suggested[8] that an induced electric field associated with the magnetic field is responsible for the acceleration of particles to cosmic-ray energies during solar disturbances. However, the ion beam travels very slowly. Unless the emission of beam particles had begun many hours before the emission of the cosmic-ray particles, the latter would overtake the beam before the distance r_1 is reached.

We also assume that the new cosmic-ray particles which give rise to the intensity variation at the earth are produced somewhere within the sphere of radius r_1, although we need not consider the details of the process or of the trajectories inside the sphere. Finally, we assume that the earth lies in the plane of the heliomagnetic equator.

Consider now a particle, of rigidity 4 Bev, which emerges from the sphere and reaches the earth. We have seen that in the vicinity of the earth the particle travels essentially along the earth-sun line. The entire trajectory between r_1 and r_e can therefore be considered, in good approximation, to lie in the plane of the heliomagnetic equator.

Making use of the well-known Stoermer integral of motion, we can write

$$-R_1 \cos x_1 + 1/R_1 = -R_e \cos x_e + 1/R_e,$$

where $R=r(cp/eM)^{\frac{1}{2}}$. The solar dipole moment is designated by M, p is momentum of the particle, and x is the angle between the velocity vector and a reference vector which points eastward about the solar dipole axis. Letting $f=r_1/r_e=R_1/R_e$, we find that

$$R_e^2 = (-1+1/f)/(f \cos x_1 - \cos x_e).$$

The smallest possible value of R_e (hence the largest possible value of M) is now obtained by setting $\cos x_1 = 1$ and $\cos x_e = -0.5$ (this corresponds to the upper limit of 30° which the experimental observations set for the angle between the earth-sun line and the direction of motion near the earth). For $f=r_1/r_e$ we have adopted, as an upper limit, the value one-fifth. Inserting these numbers, we find

$$R_e^2 > 5.71,$$

or

$$M < 5\times10^{32} \text{ gauss-cm}^3.$$

This upper limit on the solar dipole moment is one order of magnitude smaller than the value implied by the cosmic-ray latitude cutoff at the earth.

It is best, however, to recall again the two most important assumptions which have gone into the present calculation. We have assumed that: (1) the new cosmic-ray particles have been generated at distances from the sun no greater than $r_1=r_e/5$; (2) at distances between r_1 and r_e the solar dipole field is not seriously perturbed by any other large-scale field.

The first assumption is supported by the very fact that the new cosmic-ray particles associated with small solar flares always approach the earth from the same general direction (the earth-sun line) within a fairly small cone; i.e., the "source" region for each event always lies within a fixed cone of small aperture. The most reasonable choice for the source region is of course the sun and its vicinity. The second assumption is more difficult to justify and our result must therefore rest explicitly on its validity. Nevertheless, we note that if the solar dipole moment were appreciably larger than the upper limit which we have set, it would require very special kinds of perturbation fields in order to give rise to orbits which, in the vicinity of the earth, are preferentially directed along the earth-sun line. As it is, even the "tunnels" postulated by Forbush *et al.*[7] would develop only under unusual circumstances. On the other hand, the cosmic-ray effect which we are considering is a frequently-occurring phenomenon.

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[8] K. O. Kiepenheuer, Phys. Rev. 78, 809 (1950).