On the Mechanism of Sudden Increases of Cosmic Radiation Associated with Solar Flares

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A FEW sudden large increases of the intensity of cosmic radiation taking place soon after the appearance of a solar flare have been observed.[1] Most solar flares are not associated with such an increase. When the two phenomena appear together, the intensity of cosmic radiation begins to increase about an hour after the appearance of the solar flare, rises rapidly to its maximum value and then decreases rather slowly back to its normal value (Fig. 1). The whole process lasts for about a day. It appears only at high and intermediate geomagnetic latitudes. About a day after the appearance of the flare a magnetic-storm is felt all over the world, the intensity of cosmic radiation decreases and then slowly rises back to its normal value. We shall not be concerned in this paper with the magnetic storm effect.

1. In the following we shall attempt to give a preliminary theory of sudden increases of cosmic radiation associated with the appearance of solar flares. For the sake of clarity, we shall consider the following questions in turn:

(a) Is there any way that charged particles (protons and electrons) can be accelerated up to cosmic radiation energies (of the order of 10 Bev) by solar phenomena connected with the appearance of flares?

(b) If the answer to the previous question is in the affirmative, how do such particles escape from the sun?

(c) If such an escape is possible, can such particles reach the earth?

2. Question (a) has already been studied and answered affirmatively by W. F. G. Swann,[2] who solved, in relativistic mechanics, the problem of acquirement of cosmic-ray energies by charged particles, through the agency of variable magnetic fields associated with sunspots. It is well known that flares nearly always appear at the same location as sunspots. Swann assumes that the magnetic field of a sunspot varies linearly with time and inversely as the distance from the spot center. According to Cowling,[3] the field does not vary linearly with time except over an interval small compared with the time required for the field to reach its full value. Further, at sufficiently large distances, the field of a pair of spots of opposite polarities is that of a dipole.

The orbit of a charged particle being accelerated in the variable magnetic field of a sunspot is unstable both in the radial and the axial directions and pulls away from the plane and axis of the spot in a few seconds.

On the basis of Swann's results, and making the modifications suggested above, we compute that the maximum energy acquired by protons in the variable magnetic field of the pair of sunspots, which accompanied the solar flare of July 25, 1946, was 7.3 Bev, although probably most of the protons accelerated had an energy not exceeding 6 Bev. This pair had the following characteristics: spot radius, 28,000 km; time required to reach maximum value of the magnetic field, 6 days (0.518×10^6 sec.); maximum field, 3800 gauss.

3. Regarding the second question (b), we must bear in mind that, if there is a permanent magnetic field of the sun of dipole moment 10^{34} gauss-cm^3, such as would account for a cut-off of the energy spectrum of primary cosmic radiation at about 2 Bev and correspondingly would place the knee of the latitude effect at about 50° geomagnetic latitude; then, because of the forbidden region of Störmer, particles having energies as computed in paragraph (3) can never leave the surface of the sun except at very high solar latitudes and then only over a small range

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[1] S. E. Forbush, Phys. Rev. **70**, 771 (1946); H. V. Neher and W. C. Roesch, Rev. Mod. Phys. **20**, 350 (1948).

[2] W. F. G. Swann, Phys. Rev. **43**, 217 (1933).

[3] T. G. Cowling, Monthly Notices, Roy. Astr. Soc. **106**, 218 (1946).

of latitude.[4] The sunspot pair of July 25, 1946, appeared at latitude 23° N, so that no particles of energy 7.3 Bev or less could escape from the sun, unless special means of exit are available.

Such means are provided by the combined action of the permanent field of the sun and the transient field of the pair of sunspots. As has already been pointed out, the field of the pair of sunspots drills a tunnel through the forbidden region of Störmer through which particles can then escape.[5] The existence of this tunnel depends on the relative strength and orientation of the permanent and the transient dipoles, and on the ratio of their field strengths as a function of distance. It is assumed that the sun's permanent dipole coincides with the axis of rotation. Leaving out for the present the details of the calculation, it can be shown that the tunnel exists over a distance from the pair of sunspots such that the ratio of the permanent and transient magnetic field strengths is not constant. This condition seems to be necessary but not sufficient. Thus it is only seldom that the conditions for the existence of the tunnel are all satisfied, which explains

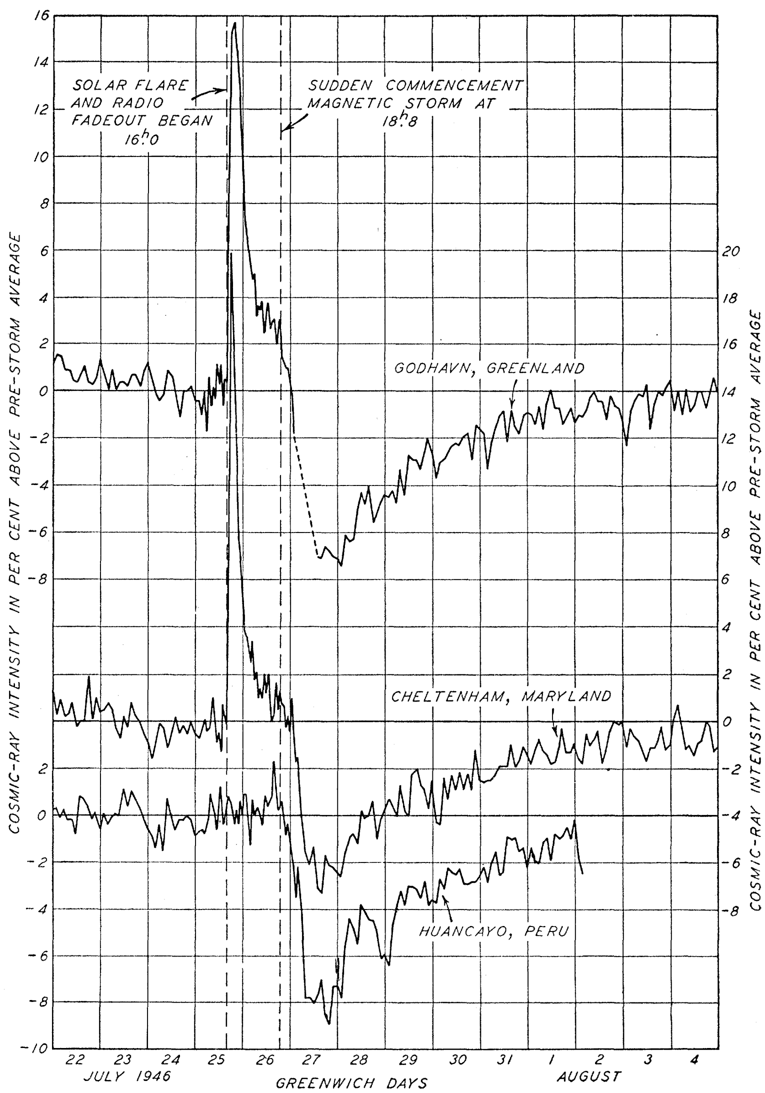

FIG. 1. Sudden increase of cosmic-ray intensity following solar flare of July 25, 1946.

[4] M. S. Vallarta, Nature **139**, 839 (1937).
[5] M. S. Vallarta and O. Godart, Rev. Mod. Phys. **11**, 180 (1939).

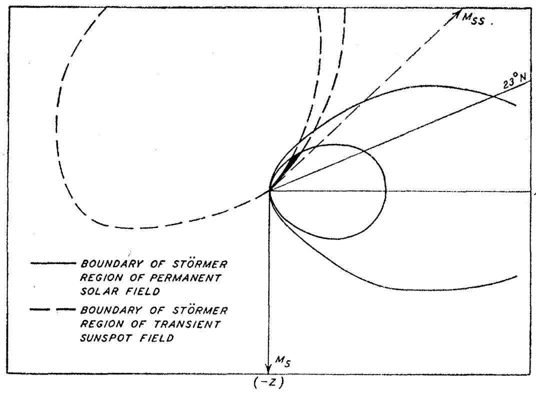

FIG. 2. The tunnel on July 25, 1946 at 17^h GMT and at longitude 13° E.

why solar flares are seldom accompanied by an increase of cosmic-ray intensity.

The tunnel is usually very long and narrow. For the pair of sunspots of July 25, 1946, its length turns out to be 27 million km. Its aperture is between 2 and 3 degrees in latitude and not over 70 degrees in longitude. Conditions are illustrated in Figs. 2 and 3. The tunnel is shown in dark and the cross-hatched area corresponds to the region where the ratio of the variable to the steady field is constant and therefore the tunnel is closed.

A solar flare without a corresponding increase of cosmic radiation occurred on February 6, 1946. Figures 4 and 5 illustrate the conditions obtaining then. It is seen that there was no tunnel available anywhere. Therefore, the particles accelerated by the variable magnetic field of the sunspots could not leave the surface of the sun.

The variation of permanent (H_s) and transient magnetic field (H_{ss}) as a function of distance from the sunspots at 16^h GMT on July 25, 1946, is shown in Fig. 6. It is seen that the end of the tunnel is just about, where $H_{ss}/H_s=\text{const}$.

The data related to three flares we have studied are collected in Table I.

4. We now turn our attention to question (c). The tunnel through which particles must leave the sun is long, narrow, and extends over a limited range of solar longitude. Such particles can reach the earth only after traveling through the magnetic field of the sun, the earth, and the transient sunspot field. Therefore, they can arrive at the earth only along certain directions, and, by Liouville's theorem, with an intensity equal to what they had when they left the sun. During solar flares accompanied by an increase of cosmic radiation, one would therefore expect important departures from isotropy as observed at the earth. Such departures would occur only at certain points on the earth and only in certain directions.

Whether particles acquiring energy and leaving the sun by processes such as contemplated here will actually reach the earth cannot be decided without integrating the equations of motion. This laborious task will require the use of modern electronic computing machines. We intend to study this problem in the near future.

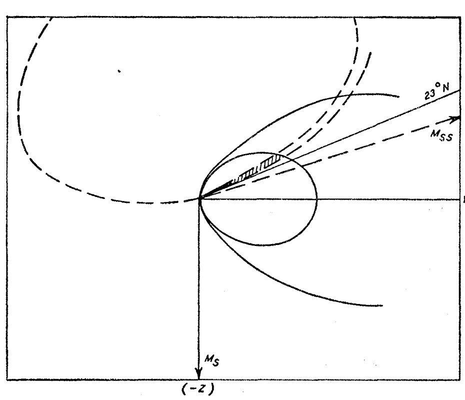

FIG. 3. No tunnel on July 25, 1946 at 17^h GMT and at longitude 103° E.

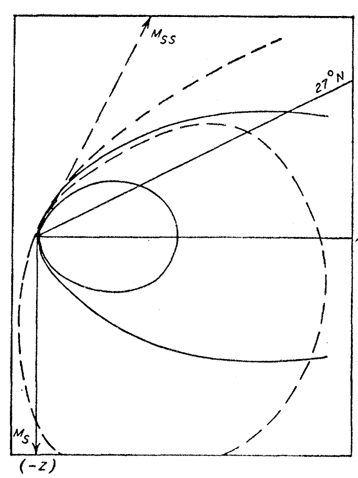

FIG. 4. No tunnel on February 6, 1946 at 16^h GMT and at longitude 13° W.

TABLE I. Data on three flares.

No.	1	2	3
Date	Feb. 28, 1942	Feb. 6, 1946	July 25, 1946
Magnetic Moment gauss-cm^3	7.8×10^{30}	3.5×10^{31}	3×10^{31}
Direction cosines:*			
α	0.01	0.11	−0.33
β	−0.90	0.97	0.90
γ	0.43	0.22	0.29
Spot diameter km	58000	52000	56000
Build-up time—days	≃6	≃6	≃6
Maximum field gauss	4800	3800	3800
Solar latitude—degrees	7N	27N	23N
Solar longitude—degrees	7E	13W	13E
Time hours GMT	12	16	17
Energy Bev	8.2	6.8	7.3
Energy Störmers (protons)	0.39	0.35	0.37
Minimum geomagnetic latitude	22	34	30

* Note: Z axis along negative permanent dipole, X axis in central meridian.

5. The transit time for a particle of energy about 10 Bev traveling from the sun to the earth in the combined magnetic fields of the sun, sunspots, and earth would be of the order of magnitude of one hour, in agreement with observation.

The tunnel would shut off gradually as the relative magnitude and orientation of the permanent and transient dipoles changes. It seldom would stay open for longer than one day.

Particles can acquire energy so long as the sunspot field is changing with time. The duration of particle emission would in general be determined by the combination of two factors: time during which the sunspot field is changing, and time during which the tunnel stays open. It appears that seldom would it be greater than one day. These conditions are well illustrated by the solar flare of February 25, 1942. Unfortunately, the orientation of the sunspot dipole could not be determined with good accuracy. However, from the information available to us we infer that a very narrow tunnel opened up for a short time late on February 27 or early on February 28,

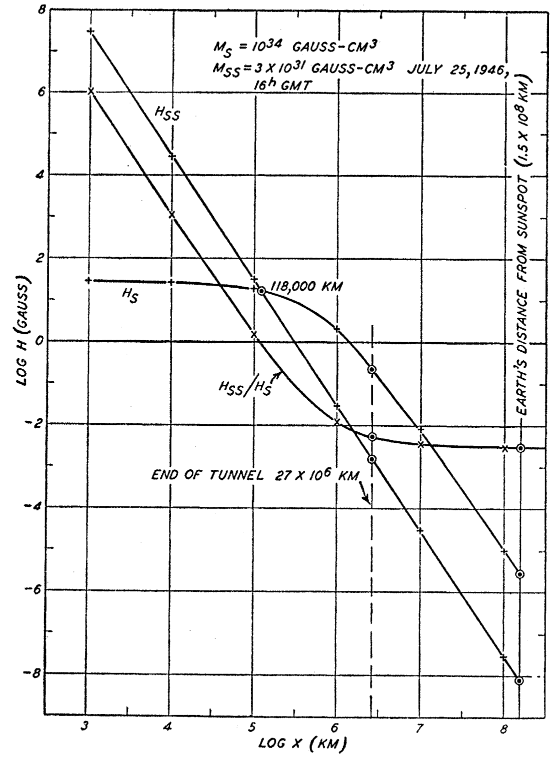

FIG. 6. The variation of permanent and transient fields as a function of distance from the sunspot.

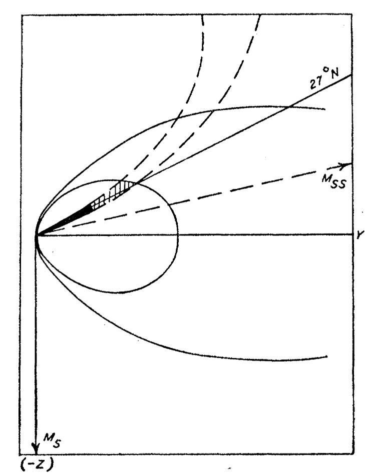

FIG. 5. No tunnel on February 6, 1946 at 16^h GMT and at longitude 77° E.

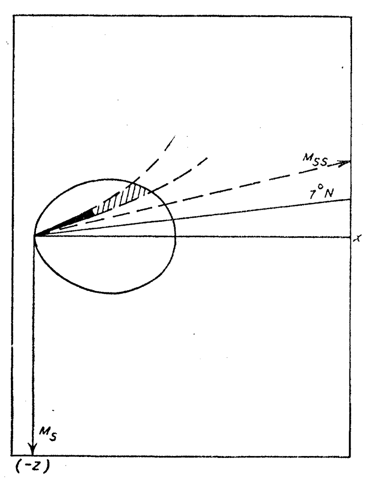

FIG. 7. No tunnel on February 25, 1942 at 18^h GMT and at longitude 43° E.

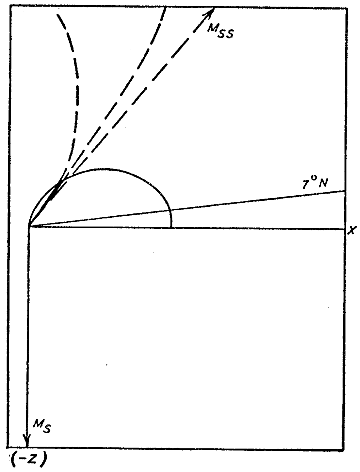

FIG. 8. The tunnel on February 27, 1942 at 21^h GMT and at longitude 15° E.

shut off late on February 28 and opened up again for a brief time on March 1 (Figs. 7 to 10). There was an increase of cosmic radiation on February 28 and again possibly a smaller one on March 1.

The energies imparted to particles by variable magnetic sunspot fields are in general of the order of magnitude of 0.3 to 0.4 Störmer. Hence, such particles can reach the earth only at intermediate and high latitudes. The sudden increases

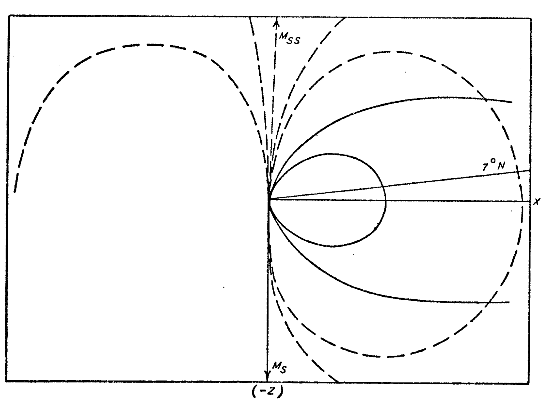

FIG. 9. No tunnel on February 28, 1942 at 12^h GMT and at longitude 7° E.

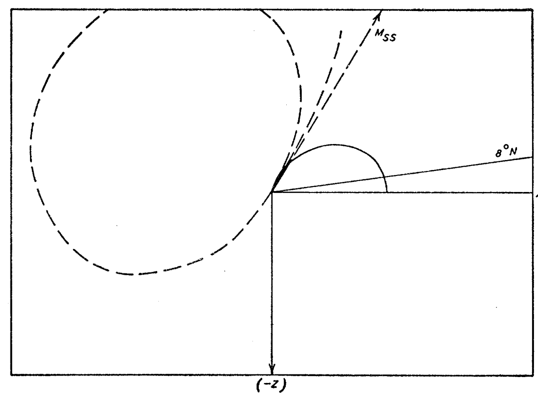

FIG. 10. Narrow short tunnel on March 1, 1942 at 22^h GMT and at longitude 11° W.

of intensity following solar flares should not be detected, in general, at equatorial latitudes in agreement with observation.

Particles of either positive or negative sign may be accelerated by variable magnetic fields of sunspots.

While it seems certain that particles of cosmic-ray energy can be occasionally ejected from the sun, it is not proved that all primary cosmic rays are generated by similar processes taking place in the stars.

The fact that very few flares are accompanied by sudden increases of cosmic radiation seems to provide a sound argument for the existence of a permanent solar magnetic field. Otherwise *all* flares would be expected to be associated with such increases. The role of the flare appears to be that of providing a supply of charged particles which are then accelerated by the variable field of the sunspots.

Finally, it should be emphasized again that the mechanism responsible for changes in the intensity of cosmic radiation during magnetic storms is clearly different from that which is connected with sudden increases of intensity which follows the occurrence of some solar flares and which is studied in this paper.[6]

[6] S. E. Forbush, see reference 1.