Variations of the Cosmic Ray Intensity During Magnetic Storms

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Abstract

A simple mechanism has been suggested by H. Alfvén to explain the main features of the variation of cosmic ray intensity during magnetic storms.

Cosmic ray particles are accelerated or retarded in the electric fields of ionized beams, which are sent out from the sun. Particle orbits hitting the earth have been calculated for different momenta and for solar magnetic fields decreasing with distance as r^{-3}, r^{-2} and r^{-1}. The influence on the particles of beams of different length and breadth has been analyzed.

A beam length of a few times the orbital radius of the earth and particles with momenta in the range 20—40 $GeV\ Z/c$ give a time variation in cosmic ray intensity similar to the variation measured during a magnetic storm. This requires a solar magnetic field of 10^{-5} gauss at the earth's orbit.

As discovered by FORBUSH (1937) the typical variation of cosmic ray intensity during a magnetic storm is a decrease of the intensity soon after the beginning of the main phase of the storm. This result was obtained from measurements with ionisation chambers and G-M counters (cf. also WILSON, "Progress in Cosmic Ray Physics", *1952*, Chapter VIII). After the decrease a slow recovery to normal value occurs and during the whole time of the storm there is a pronounced diurnal variation as seen in fig. 1, (SEKHIDO and YOSHIDA, 1950, ELLIOT and DOLBEAR, 1951). The decrease is not proportional to the intensity of the magnetic storm. During some storms no decrease takes place whereas some small magnetic storms have caused rather big decreases in the intensity of cosmic radiation. (TRUMPY, 1953.)

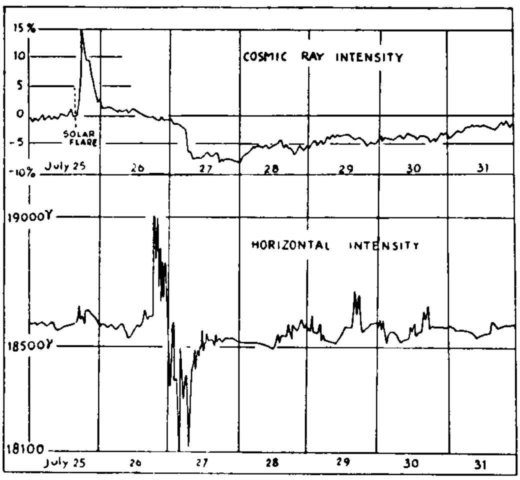


Fig. 1. Typical variation of the cosmic ray intensity during a magnetic storm. (WILSON, 1952, *Progr. in Cosm. Ray Phys.* p. 495.)

An increase in cosmic ray intensity has sometimes been observed approximately one hour after a solar flare and 24 hours before the main phase of the storm *(Progress in Cosmic Ray Physics)*. We shall here not discuss this immediate effect of the solar flare, which is without a doubt a quite different phenomenon.

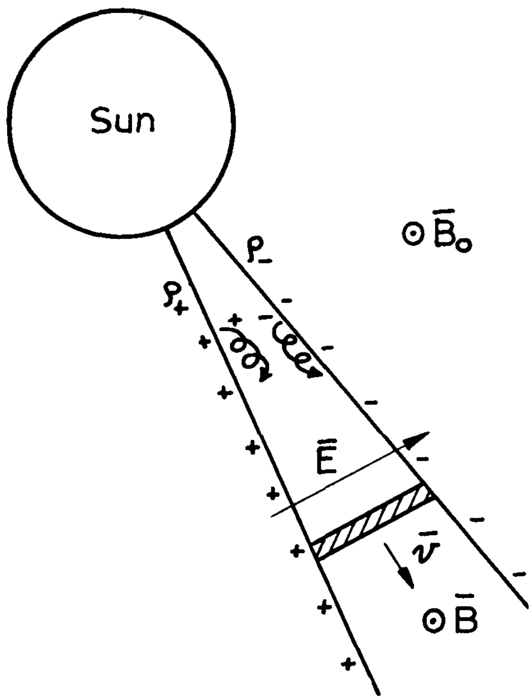
The properties of an ionized beam

ALFVÉN (1949) has suggested that the magnetic storm effect is caused by the electric field of a beam of ionized gas, which is sent out from the sun in connection with a magnetic storm. In order to discuss this problem we shall first give an account of the main properties of such a beam.

We consider the phenomena in the equatorial plane of the sun and assume that a stream of ionized gas is sent out from the sun with the velocity $\bar{v}$, which is of the order of 10^6 m/s, fig. 2. The solar magnetic field polarizes the beam. Seen from a coordinate system which is at rest in relation to the sun the magnetic field strength is supposed to be $\bar{B}$ inside and $\bar{B}_0$ outside the beam. The positive and negative space charges give rise to an electric field $\bar{E}$ across the beam with field strength

$$\bar{E} = -\bar{v} \times \bar{B} \tag{1}$$

and pointing in the same direction as the sun rotates.



Big. 2. The beam of ionized gas, sent out from the sun.

In the combined electric and magnetic fields, charged particles move out from the sun in trochoidal orbits. The radius of curvature of a particle orbit depends on the mass and the energy of the particle but the translation velocity is equal for all particles and given by

$$v = \frac{E}{B} \tag{2}$$

MKS units are used. (cf ALFVÉN, 1950. Ch. II.)

Cosmic rays in the field of the beam

During a magnetic storm the earth passes regions with electric and magnetic fields where the conditions are different from that in other parts of the earth's orbit. Cosmic particles are affected by these fields and the intensity measured on the earth is changed. In the following example we suppose the beam to be very thin so that it can be considered as an electric double layer. Hence the effect on a cosmic particle crossing the beam must be a change of the particle energy. Particles which cross the beam from the negative to the positive side lose energy, and particles moving in the opposite direction gain energy.

The change in energy is $\Delta W = e \int \bar{E} ds$.

However, there are further effects to be considered. The particles reach the earth from all directions (except in the forbidden cones) and they may or may not cross the beam. Furthermore the extension of the beam in the meridional plane of the sun is unknown, as well as the length of the beam in the equatorial plane. We also know little about the solar magnetic field. Nevertheless it is possible to discuss the phenomenon of the magnetic storm variations by means of a study of a simple model, as explained in the following.

The discussion is confined to the phenomena in the equatorial plane of the sun.

Generally the radius of curvature is

$$\varrho = \frac{\sqrt{V^2 + 2\, m_0 c^2 V}}{B}$$

but $B = \frac{M}{r^n}$

and hence $\frac{\varrho}{R_{S-E}} = k \left(\frac{r}{R_{S-E}} \right)^n$

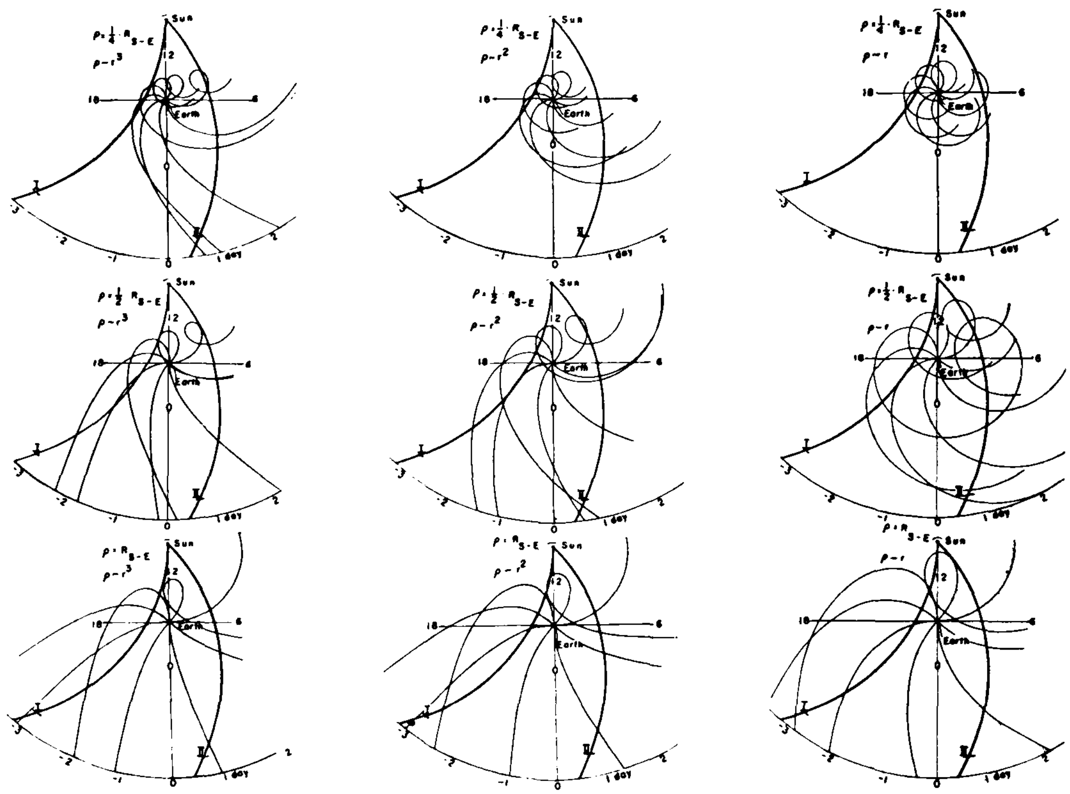


Fig. 3. Charged particle orbits in the solar magnetic field, calculated for different values of k and n.

where r = distance to the sun
B = magnetic field strength at distance r
k and n are constants
R_{S-E} = distance between the sun and the earth
The particle orbits are calculated graphically for
$k = 1$, 0.5, and 0.25
$n = 1$, 2, and 3

and those which hit the earth from the zenith direction at eight different points with the local time 12 h, 15 h, 18 h, 21 h and so on. The magnetic field of the earth is neglected. A correction for this can be applied according to BRUNBERG and DATTNER (1953). In such a way nine diagrams were obtained, each consisting of eight different orbits (see fig. 3).

Then we consider a beam of a geometrical shape as given by CHAPMAN and BARTELS, (*Geomagnetism* vol. II, p. 806). Before the magnetic storm the beam is situated in position I (fig. 4), and moves towards the earth. In order to define the problem it is necessary to introduce the length of the beam. This is arbitrarily put equal to 2 or 3 R_{S-E}.

Starting from these assumptions the variation of cosmic ray intensity during a magnetic storm may be explained in the following way.

Particles crossing the beam either gain or lose energy. Those crossing from the left gain energy, those crossing in the opposite direction lose energy. Finally particles crossing the beam and returning again through the beam do not change their energy.

The deflection of particles in the magnetic field is altered by the change in energy but this is a small effect and has not been taken into account in the present model.

After the beam has passed the earth a decrease in intensity takes place because most cosmic particles reaching the earth have passed the double layer of the beam and hence become retarded. The rays which are least affected are those entering between 12 h and 18 h. (See fig. 4 Beam in position II.) From this it is evident that the beam length plays an important part for the phase of the diurnal variation. It is shown further on that good agreement with observations of cosmic ray intensity during the magnetic storms can be obtained if the beam length is assumed to be three times the radius of the earth's orbit. Other

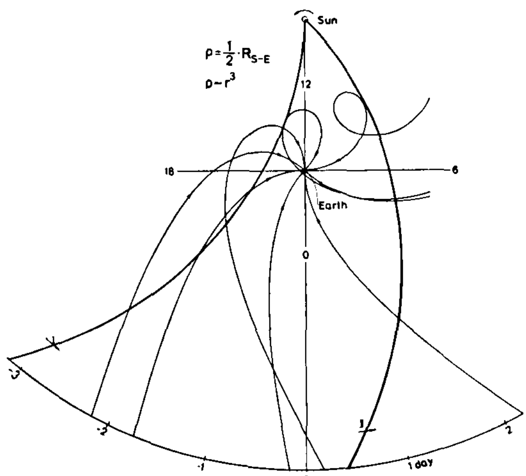


Fig. 4. Charged particle orbits in the equatorial plane of the solar magnetic field.

beam lengths are likely to give similar results, but a more precise discussion requires more data about the phase of the storm time diurnal variation.

The intensity variation

We consider the beam in a certain position and observe particles coming from the zenith to a point on the earth's equator. We follow this point while the earth rotates and the beam moves towards the earth and passes it. The observed intensity varies as for example in fig. 5 depending on the initial position of the beam and the point of observation. The same has been repeated for other initial positions of the beam and similar intensity diagrams have been obtained.

We have so far assumed the beam to be infinitely thin and shall now discuss what happens if the beam has a finite breadth. If the beam is supposed to have a breadth corresponding to an 18 hours arc $(18/24 \cdot 1/365\ R_{S-E})$ of the earth's orbit, a beam with this breadth can be used in fig. 4. We must take into account that a particle which passes only a part of the beam changes its energy in proportion to this fraction of the beam breadth.

The difference between the magnetic field inside and outside the beam produces some change in this picture as pointed out by SWANN (1954) and ALFVÉN (1954). This effect will be studied in detail in a subsequent paper. The results are essentially the same as those obtained here.

The effect of the beam breadth was calculated by integrating the already obtained intensity diagrams of a thin beam in the following way. We assumed a beam breadth such that the earth is enveloped in it for 18 hours and 6 diagrams were plotted, representing the state of things at 3 hours intervals (8 diagrams correspond to 24 hours). We began with diagram 12 h and added diagram 15 h moved 3 hours back. The same was repeated for diagram 18 h but with a displacement of 6 hours and so on. The result is the smoothed intensity curve of figs 6 and 7.

This graphical method has been repeated for magnetic fields decreasing as r^{-2} and r^{-1}, for different radius of curvature, for two values of beam breadth and also for a beam length of twice the orbital radius.

Intensity diagrams with a beam length of 3 times the orbital radius, a beam breadth corresponding to 18 h and 36 h and magnetic fields decreasing as r^{-3} and r^{-2} are most interesting and shown in figs 6 and 7.

Results obtained by the model

Four diagrams have been found which give a variation similar to observed variations in cosmic ray intensity during magnetic storms, figs. 6b, 6e and figs. 7b and 7e. In all cases the beam length is 3 times the orbital radius of the earth and $\varrho = 0.5\, r^n$. In figs. 6b and 7b

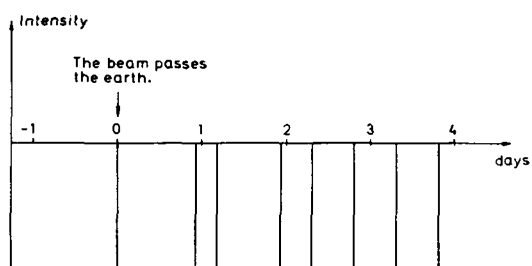


Fig. 5. The variation of the cosmic ray intensity when the beam is assumed to be infinitely thin.

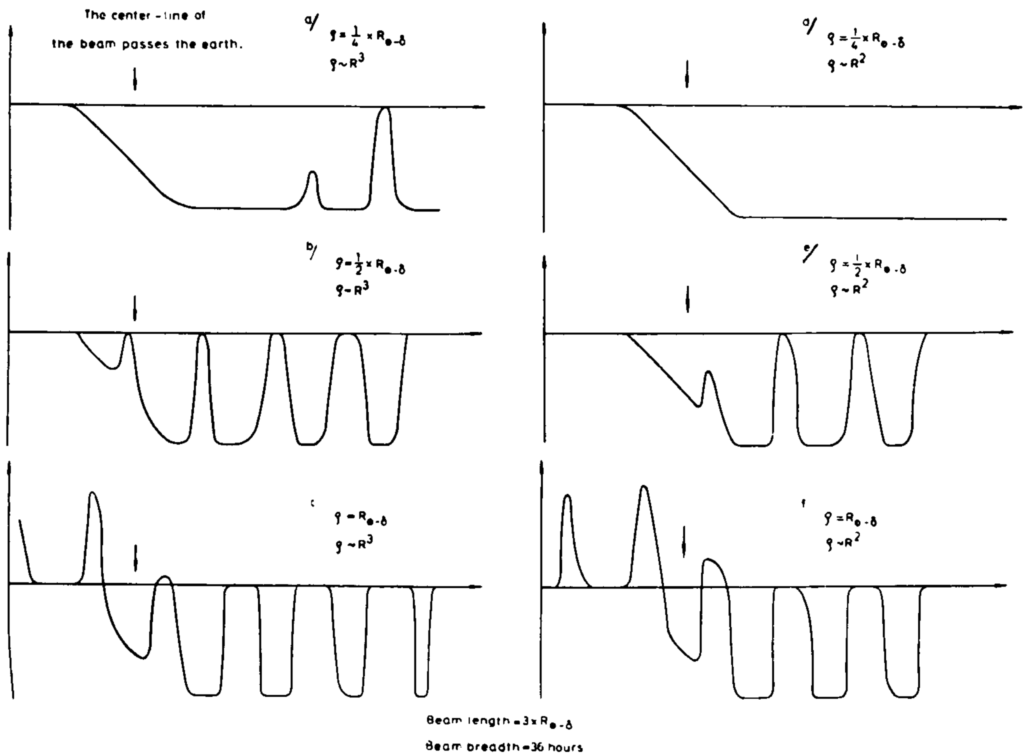


Fig. 6. The variation of the cosmic ray intensity for a beam with a breadth corresponding to an 36 hours arc.

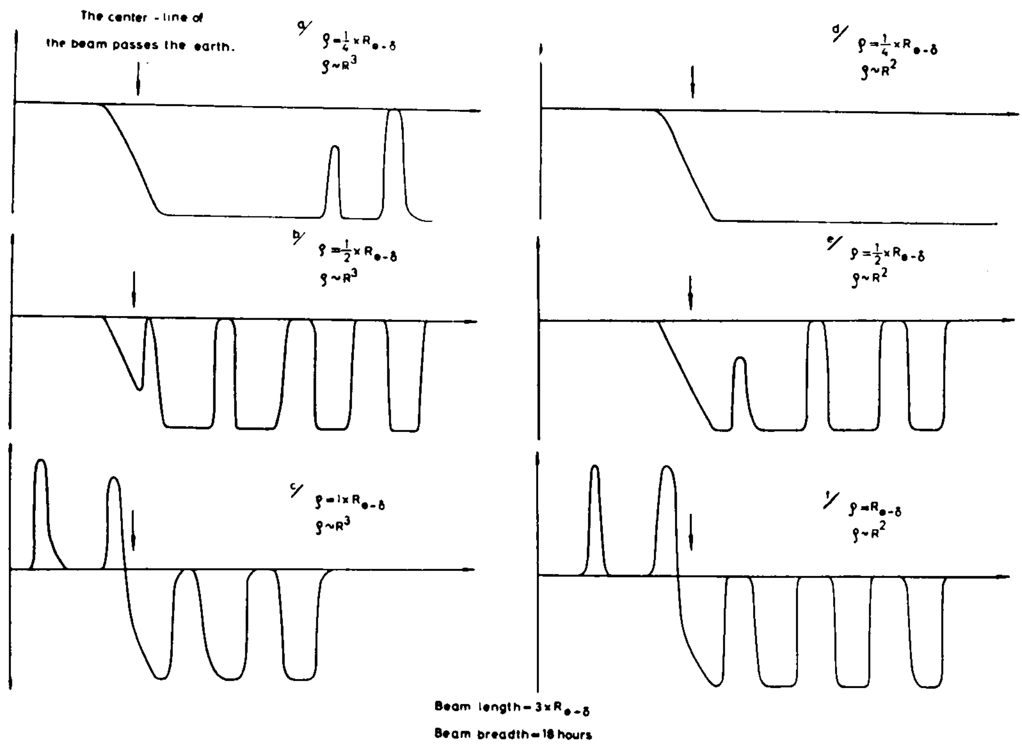


Fig. 7. The variation of the cosmic ray intensity for a beam with a breadth corresponding to an 18 hours arc.

$n=-3$ and in fig. 6 e and 7 e $n=-2$. The breadth of the beam seems to be of little importance for the general appearance of these diagrams.

From the ordinary diurnal variation we know, that the particles which cause the observed diurnal variation have momenta in the range 20 – 40 *GeV Z/c* (BRUNBERG and DATTNER, 1954). It is probable that the diurnal variation during magnetic storms is caused by particles in the same momentum range.

Moreover the analysis of figs. 6 and 7 has shown that the radius of curvature for the trajectories of the relevant particles is $\varrho = \frac{1}{2} R_{S-E}$, where R_{S-E} is the radius of the earth's orbit. Thus we know the energy of the particles and the curvature of the trajectories, and we can deduce the strength of the solar magnetic field at the earth's orbit. The result is

$$B=\frac{p}{\varrho e}=\frac{eV}{c\varrho e}=10^4\cdot\frac{3\cdot 10^{10}}{3\cdot 10^8\cdot 0{,}75\cdot 10^{11}}=$$
$$=1{,}3\cdot 10^{-5}\ \text{gauss}$$

Suppose the solar magnetic field decreases as r^{-n}. Consideration of the model of the present paper gives no possibility to determine exactly the value of n. However, it has been shown that a value of n between 2 and 3 is in agreement with the general appearance of the intensity variation measured during magnetic storms. If the solar magnetic field is 10 gauss at the sun and 10^{-5} gauss at the orbital radius of the earth the exponent n shall be 2.6.

We point out that a 27-day recurrence tendency can be explained by this mechanism if a beam lasts for a rather long time and passes the earth several times.

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