On the Solar Origin of Cosmic Radiation

HANNES ALFVÉN
Kungl. Tekniska Hogskolan, Stockholm, Sweden
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The idea proposed by Teller and Richtmyer that the cosmic radiation is a local solar phenomenon is developed.

It is shown that motion of interstellar matter is likely to amplify a primary interstellar magnetic field up to the value of the order 10^{-5} gauss postulated by Richtmyer and Teller.

According to an earlier suggestion, magnetic storm variations of cosmic radiation are due to electric fields set up within the solar system by the storm-producing beams. It is shown that the long-time effect of the same mechanism may account for the generation of cosmic radiation. It is of special interest that there seems to be some hope to derive theoretically the observational energy spectrum.

I.

At the recent Nuclear Physics Conference in Birmingham, Teller[1] proposed that cosmic radiation should be a local solar phenomenon, the cosmic-radiation particles being trapped by magnetic fields and confined to move in a region around the sun, which is small compared to stellar distances. Strong arguments in favor of this view have been given in the preceding paper by Richtmyer and Teller.[2] This picture requires magnetic fields around the sun, for example just outside the planetary system, which are much stronger than is usually supposed. At first sight there seems to be little reason to assume other fields than the solar dipole field, which is not at all sufficient to keep cosmic radiation trapped and to make it isotropic. We know, however, very little about the magnetic fields in our neighborhood and a closer examination of the problem is necessary.

II. TRAPPING MAGNETIC FIELDS

For the following discussion it is important to consider a process by which a magnetic field may be amplified. Suppose that in an electrically conducting medium with the mass density $=\rho$ there is an externally given magnetic field H_0. If parts of the medium are put into motion with velocity v, the magnetic field is distorted, so that an induced field H' is superimposed on the initial field. In the case of an infinite electrical conductivity the average value of H' increases until the magnetic energy equals the kinetic energy:

$$\frac{H'^2}{8\pi}=\frac{1}{2}\rho v^2. \tag{1}$$

When this limit is reached an equipartition of energy is accomplished and magnetic field energy converted back into kinetic energy. The state characterizing a magneto-hydrodynamic wave is reached.

III.

We shall apply these results to interstellar space around the solar system. Hence we put $\rho=10^{-24}$ g/cm which is the usually accepted value of interstellar density. This gives

$$H'=v(4\pi\rho)^{\frac{1}{2}}=3.5\cdot10^{-12}\,v. \tag{2}$$

A magnetic storm is usually supposed to be produced by a corpuscular beam sent out radially from the sun with a velocity of the order $2\cdot10^8$ cm sec.$^{-1}$. When it passes through the solar magnetic field, the beam will distort the magnetic lines of force and will cause an induced field which may grow up to the order of $H'=3.5\cdot10^{-12}\cdot2\cdot10^8=7\cdot10^{-4}$ gauss. It should also be observed that as the beam consists of ionized gas which has a high conductivity, the magnetic field in the region close to the sun where the beam emanates may in part be "frozen" into the matter of the stream. In this way magnetic field is "transported" outwards.

Both these effects produce magnetic fields in the outskirts of the solar dipole field which are much stronger than the dipole field itself. Considerations of the decay of these fields and the total energy necessary to produce fields of such an extension and strength as to trap cosmic radiation makes it rather dubious, however, if this effect is sufficient.

IV.

For an assumed galactic magnetic field the value 10^{-10} gauss is usually given. The only foundation for this value is that it constitutes the minimum field required to trap cosmic radiation within the galaxy. No other data confirm a value of this order of magnitude. If we start from a low value of the galactic magnetic field and investigate how this value would be transformed by motion of interstellar matter, we find that the final result is given by (1), i.e., the motion increases the magnetic field until equipartition between kinetic and magnetic

[1] E. Teller, Report on the Nuclear Physics Conference in Birmingham, Sept. 14–18, 1948.
[2] R. D. Richtmyer and E. Teller, Phys. Rev. **75**, 1729 (1949).

energy is established. Because of the very large dimensions the decay of the field is slow. Putting $v=3\cdot10^6$ cm sec.$^{-1}$ for the average (relative) velocity of interstellar matter, we find

$$H'\approx10^{-5}\text{ gauss.} \tag{3}$$

This field is likely to be irregular, produced as it is by motion of the interstellar matter. In a field of this order singly charged particles of momentum $p=10^{10}$ gauss cm $(=3\cdot10^{12}$ ev) have a radius of curvature of 10^{15} cm, and for 30-fold charged particles of 10^{16} ev the value is 10^{17} cm. Thus cosmic radiation would be confined to a region around the solar system which is small compared to stellar distances.

The value 10^{-5} gauss seems at first glance to be very high. In fact it is even somewhat larger than the solar dipole field near the earth's orbit. There is at present, however, no argument against this assumption and, as shown by Richtmyer and Teller, a field of this order greatly simplifies the understanding of cosmic radiation. A field of 10^{-6} gauss would give essentially the same result.

V. MAGNETIC STORM VARIATIONS

Before attempting to trace the origin of cosmic radiation we shall discuss the mechanism producing magnetic storm variations. It is well known that these variations cannot be produced by the storm variations of the terrestrial magnetic field. Instead we must suppose that the electric field associated with the storm-producing beam is responsible for them.[3]

Because of its motion in a magnetic field H a storm-producing beam *when seen from a fixed coordinate system* must be associated with an electric field

$$\mathbf{E}=\frac{1}{c}\mathbf{v}\times\mathbf{H}. \tag{4}$$

When the earth is situated within the stream this electric field causes a discharge which hits the earth in the auroral zones, the current system of the discharge producing the magnetic storm field. The voltage difference V_b between the borders of the stream is $V_b=E\cdot d$, where d is the breadth of the beam. With $d=5\cdot10^{12}$ cm and $v=2\cdot10^8$ cm/sec. we obtain (expressing V_b in volts, and H in gauss),

$$V_b=10^{13}H\text{ (volt).} \tag{5}$$

During magnetic storms variations of as much as 10 percent in cosmic radiation intensity are sometimes observed. As the main part of cosmic radiation has an energy of about $3\cdot10^{10}$ ev, V_b must be of the order $3\cdot10^9$ volt. This requires $H=3\cdot10^{-4}$ gauss. This is much more than the solar dipole field, which near the earth's orbit is of the order $2\cdot10^{-6}$ gauss. As pointed out above, the magnetic field in a beam coming from a region near the sun, where the field is much higher, could very well have a stronger magnetic field which is "frozen" into the beam. In fact, if the beam emanates in a region near the solar surface where $H=10$ gauss and moves radially outwards so that its breadth is proportional to the solar distance, this field should for geometrical reasons decrease only to 1/200 of its original value, or to $5\cdot10^{-2}$ gauss. Thus the value $3\cdot10^{-4}$ gauss is not unreasonably high. It should also be compared with the value from (2).

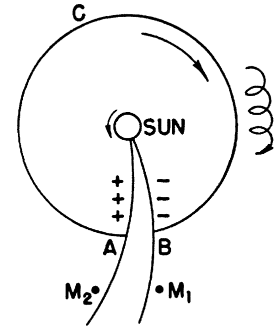

FIG. 1.

It is important to note that in general the field is non-potential. Although the conditions in a meridian plane probably are more important we shall confine the discussion to the equatorial plane (Fig. 1) where the conditions are simpler. The charge accumulated on the sides of the stream tends to produce a current for example along the line ACB. The inductance of this loop is so big, however, that its time-constant τ is very long, possibly of the order of years. When the time during which the beam has been on is short compared to τ there is no appreciable electric field outside the beam, because the field from the charges on the sides of the beam is neutralized by an induced field.

When before a storm the earth has the position M_1 in relation to the beam, positive cosmic-ray particles arriving from the left will be accelerated when traversing the beam. After the storm, positives from the right reaching the earth in position M_2 have in the same way been retarded. This explains the observed increase in cosmic radiation before a storm and the decrease after it. The difference between the two effects may—at least in part—be explained by the geometry of the beam and the particle paths.

VI. GENERATION OF COSMIC RADIATION

The idea that cosmic radiation is produced by induced electric fields has been proposed among others, by Swann,[4] who assumed that the accelera-

[3] H. Alfvén, N ture **158**, 618 (1946).

[4] W. F. G. Swann, Phys. Rev. **43**, 217 (1933); J. Franklin Inst. **215**, 273 (1933).

tion takes place in the electric field generated by the growth of a sunspot magnetic field. A serious objection against this model is that the conductivity of the corona outside a sunspot is so high that the generator is short-circuited. In other words, the electric field must accelerate all particles in the region in question, but the available energy does not suffice to give them cosmic-ray energies. It should also be observed that this model is not reconcilable with a solar origin of the whole cosmic radiation, because fields much stronger and more extensive than sunspot fields must be assumed in order to account for the highest cosmic-ray energies. In the case of the double star generator which has also been proposed to produce cosmic radiation, the acceleration takes place in the space between the stars where the density is much smaller than in the corona, but even in this case the conductivity may be high enough to short-circuit the generator.

The only way to avoid this diffculty seems to be to assume some mechanism which accelerates only particles which already have a high energy. We shall here consider a process of this kind, which takes place in the solar magnetic field. The acceleration is essentially a consequence of the process which we have assumed to be responsible for the magnetic storm variations.[5]

Suppose that no storm-producing beam has been on for a time much longer than the time constant τ of the "electric circuit." Consider the region where the solar dipole field is stronger than the galactic fields. In the solar equatorial plane a positive particle of cosmic-radiation energy may go clockwise either in a circular or a trochoidal path around the sun, the particle energy remaining unchanged.

If suddenly a beam with the voltage difference V_b between its sides is turned on, the particle loses an energy eV_b for every time it passes the beam. No change in energy takes place outside the beam on the way ACB. When the beam has been on for a time which is long compared to τ a potential field is restored so that the particle gains the same energy $eV_a=eV_b$ during the path ACB as it looses when passing the beam. If then the beam suddenly is switched off the particle still gains the energy eV_a when going the distance ACB but does not lose any energy. Hence the net gain per turn is eV_a, which in the above example equals $3\cdot 10^9$ ev. This acceleration goes on for a time of the order τ.

This phenomenon can also be regarded in another way. The beam transports magnetic flux outwards at the rate $H\cdot v\cdot d$. This field must leak back towards the sun, causing an increase of the solar field. The betatron action of this accelerates the particles. In fact when equilibrium is reached the path ACB is cut by the magnetic flux Hvd leaking back, and the voltage V_a induced by this is

$$V_a=\frac{1}{c}vHd$$

which again makes $V_a=V_b$.

The above example with $V_a=3\cdot 10^9$ volt certainly represents an extreme case. In fact, storms changing cosmic-radiation intensity by as much as 10 percent are very rare. Usually the storm effect is less than 1 percent, so the normal value of V_a is probably of the order of 10^8 volts. The total flux F of the solar magnetic field outside the sun is $F=\pi R_0^2 H_p=3.8\cdot 10^{23}$ gauss cm^2, $R_0=7\cdot 10^{10}$ cm being the solar radius and $H_p=25$ gauss the polar magnetic field. In the case of $V=3\cdot 10^9$ volts the outward transport of flux occurs at the rate $Hvd=3\cdot 10^{-4}\cdot 2\cdot 10^8\cdot 5\cdot 10^{12}=3\cdot 10^{17}$ gauss cm^2 sec.$^{-1}$ which shows that it cannot possibly go on as long as 10^6 sec. unless a rapid leaking back occurs. A value of $V_a=10^8$ volt and a time constant of the order of a year ($3\cdot 10^7$ sec.) would probably be more like a normal state.

The maximum energy which a particle can gain is given by the maximum value of Hr in the solar field. For an orbit close to solar equator we have $H=10$ gauss and $r=7\cdot 10^{10}$ cm which gives $p=Hr=7\cdot 10^{11}$ gauss cm and $V=300p=2\cdot 10^{14}$ ev. A heavy nucleus with the charge 30 e could reach $6\cdot 10^{15}$ ev which is of the order of the most energetic particles assumed to cause the extensive showers.

VII.

The kinetic energy W_b transported outwards per second by a storm-producing beam is

$$W_b=\tfrac{1}{2}\rho v^3 S \tag{6}$$

where S is the cross section of the beam. Supposing it to be circular, we have $S=\pi d^2/4$. The value of the beam density ρ is uncertain, but $\rho=10^{-22}$ (near the earth's orbit) is probably a very conservative estimate. With $v=2\cdot 10^8$ and $d=5\cdot 10^{12}$ this gives $W_b=0.8\cdot 10^{28}$ erg sec.$^{-1}$. Comparing this value with Richtmyer-Teller's figures, it is easily seen that the energy which must be converted into cosmic radiation is only a very small fraction of the beam energy.

VIII.

For the acceleration of cosmic-radiation particles two different possibilities should be considered. The first one is that cosmic-radiation particles coming from the outer regions and accidentally passing near the sun are accelerated by the varying field.

[5] E. Fermi, Phys. Rev. **75**, 1169 (1949), has proposed that cosmic rays are produced in extensive electric fields associated with magneto-hydrodynamic waves in interstellar space. It seems at present difficult to judge whether this mechanism or that one discussed in this paper is to be preferred.

The change in energy during one passage is of the order of V_a.

Consider particles of momentum $p=Hr$. The space U to which they are confined is of the order

$$U=(10r)^3=10^3p^3H^{-3}. \tag{7}$$

The number of times N they will reach a solar distance of R during the time T before they are absorbed is

$$N=\pi R^2cTU^{-1}=\pi\cdot 10^{-3}cR^2TH^3p^{-3}. \tag{8}$$

With $T=3\cdot 10^{14}$ sec., $H=10^{-5}$ gauss, $p=10^{11}$ gauss cm, we find $N=3\cdot 10^{-26}R^2$. Even if the acceleration is active at a solar distance of $R=10^{14}$ cm, a particle will not have a chance of being accelerated more than 30 times, each time by the order of 10^8 ev. This is obviously insufficient, so this mechanism does not work, at least not for the high energy range of cosmic radiation.

IX. THE ENERGY SPECTRUM

The other possibility is that the main acceleration occurs for particles in trapped orbits. Consider a particle at the solar distance R. In the dipole field it may go in a circular path around the sun if its energy is $V'=H\cdot R=aR^{-2}$, where $a=4.2\cdot 10^{33}$ gauss cm^3 is the solar dipole moment. The time for a revolution is $T'=2\pi R/c$. The circular orbit is unstable but if the energy is say $V=0.1V'$ it will go in a stable trochoidal path at the same average solar distance. The time T for one revolution around the sun is at the same time increased to the order of $T=10T'$. If the acceleration per turn $\Delta V_t=V_a-V_b$ remains approximately constant during a time τ, the change in energy during this time is

$$\Delta V=(\tau/T)\Delta V_t=c\tau\Delta V_t/20\pi R \tag{9}$$

so that its relative change in energy becomes

$$\frac{\Delta V}{V}=\frac{c\tau}{2\pi a}\Delta V_t\cdot R. \tag{10}$$

Putting $\tau=10^6$ sec., $\Delta V_t=3\cdot 10^5$ gauss cm $(=10^8$ volt) we find $\Delta V/V=0.3\cdot 10^{-12}R$ so that as soon as R is larger than a few solar radii, the relative increase in momentum is very rapid.

As the absorption during the short time $\tau=10^6$ sec. which we have considered is small, particles will change their energy up and down with the same probability. The result is that in the neighborhood of the sun, the particle spectrum will be constant, i.e. the number of particles with energies between V and $V+\Delta V$ will be independent of V up to the vicinity of the maximum energy which the solar field can keep.

The solar dipole field is certainly disturbed very much for example by the storm-producing stream. Hence particles will frequently change from one periodic orbit to another. They will also pass over from periodic orbits in the dipole field into orbits to the surrounding space, in which case they are emitted from the sun. If we change the solar distance R and at the same time change the particle energy V proportionally to R^{-2}, the particle orbits have the same geometrical form. This similarity indicates that the rate of emission f should be a simple power function of the solar distance or of the energy. Hence let us suppose that the emitted spectrum is $f(V)=f_0V^{n_1}$ where f_0 and n_1 are constants. It is possible to determine n_1 only after a detailed analysis of the scattering process.

The emitted cosmic rays fill a volume proportional to V^3. If the intensity of cosmic radiation is given by the equilibrium between emission and absorption, the energy spectrum would be

$$N=N_0V^{n_1-3}.$$

On the other hand, if the main loss is not due to absorption, but to diffusion outwards towards infinity, the loss is proportional to the surface of the volume filled by cosmic radiation, i.e. to V^2 and we would have

$$N=N_0V^{n_1-2}.$$

In order to obtain agreement with the observational curve

$$N=N_0V^{-2.8},$$

we should have $n_1\approx 0$ in the first case, or $n_1\approx -1$ in the second case.