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## GALACTIC MAGNETIC FIELDS AND THE ORIGIN OF COSMIC RADIATION\*

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I became interested in the possible existence of magnetic fields extending through the volume of the galaxy in connection with a discussion on the origin of the cosmic radiation a few years ago.<sup>1</sup> The hypothesis was discussed then that the acceleration of cosmic-ray particles to extremely high energies was due to their interaction with a galactic magnetic field that was postulated to pervade the galactic space. According to Alfvén's ideas on magnetohydrodynamics, this field would be strongly influenced by the turbulent motions of the diffuse matter within the galaxy. Indeed, the electric conductivity of this matter is so large that any lateral shift of the magnetic lines of force with respect to the matter is effectively prevented. A strong magnetic field quenches the transverse components of the displacement due to the turbulent motion. A weak field yields to the material motions, so that its lines of force are soon bent into a very crooked pattern.

The observation by Hiltner and Hall of an appreciable polarization of the light coming to us from distant stars has been interpreted<sup>2</sup> as due to the orientation of nonspherical dust grains by a magnetic field. If this general type of interpretation is correct, the polarization gives us some information on the strength and the direction of the magnetic field. Hiltner's measurements<sup>3</sup> indicate that in the vicinity of the earth the magnetic field is approximately parallel to the direction of the spiral arm. This fact suggests that we may perhaps think that the spiral arms are magnetic tubes of force. In the following discussion we will assume that this is the case.

The direction of polarization of the stellar light indicates further that in our vicinity the magnetic lines of force show irregular deviations from parallelism of the order of  $10^\circ$ . This fact excludes the hypothesis that the lines of force yield completely to the turbulent motions of interstellar matter, because then they would be rapidly bent into shapes much more irregular than those observed. One is rather led to the conclusion that the field is

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<sup>1</sup> E. Fermi, *Phys. Rev.*, **75**, 1169, 1949; cited hereafter as "r."

<sup>2</sup> Davis and Greenstein, *Ap. J.*, **114**, 206, 1951; Spitzer and Tukey, *Ap. J.*, **114**, 187, 1951.

<sup>3</sup> *Ap. J.*, **114**, 241, 1951.

sufficiently strong to yield only a little to the transverse component of the turbulent motion. Indeed, as was pointed out by Davis, the small deviations from parallelism of the field enable one to estimate that the intensity of the magnetic field must be of the order of  $10^{-5}$  gauss. Recently Chandrasekhar and I<sup>4</sup> have re-examined this problem, considering, in particular, the balance between magnetic and gravitational effects in the spiral arm. Our conclusion is that the field intensity is about  $6 \times 10^{-6}$  gauss. Owing to the turbulence, the lines of force are irregularly pushed sidewise until the magnetic stress increases to the point of forcing a reversal of the material motion and of pushing back the diffuse matter, impressing on it some kind of very irregular oscillatory motion. One expects, therefore, that the lines of force sway back and forth and also that the field intensity will fluctuate along the same line of force.

A cosmic-ray particle spiraling around these moving lines of force is gradually accelerated. The acceleration mechanism was discussed in  $\mathfrak{R}$ , although the shape of the lines of force assumed then was quite different from what we now believe it to be. A cosmic-ray proton of 10 bev energy is bent in a magnetic field of  $6 \times 10^{-6}$  gauss in a spiral having a radius of the order of one-third the radius of the earth's orbit. This is very small on the galactic scale. The motion of a proton with this energy and also of one with much greater energy is, therefore, properly described as a very small radius spiral around a line of force. Apart from the very rapid changes due to the spiraling, the general direction of motion may change for two reasons. One is that the line of force around which the particle spirals may be curved. In  $\mathfrak{R}$  a change of direction of this kind was called a "collision of type *b*." A second type of event, called a "collision of type *a*," takes place when the particle in its spiraling encounters a region of high field strength.

Let  $\vartheta$  be the angle between the direction of the line of force and the direction of motion of the spiraling particle. The angle  $\vartheta$  will be called the "angle of pitch." One can prove that, in a static magnetic field, the quantity

$$q = \frac{\sin^2 \vartheta}{H} \quad (1)$$

is approximately constant with time. For this reason, in a static field, the particle cannot enter a region where

$$H > \frac{1}{q}. \quad (2)$$

When the particle approaches such a region, its pitch decreases until  $\vartheta = 90^\circ$ , at which moment the particle is reflected and spirals backward in the direction whence it came.

In a variable magnetic field both *a*- and *b*-type collisions may cause changes in energy. As a rule, the energy will increase or decrease according to whether the irregularity of the field that causes the collision moves toward the particle (head-on collision) or away from it (overtaking collision). It was shown in  $\mathfrak{R}$  that, on the average, the energy tends to increase primarily because the head-on collisions are more probable than the overtaking collisions. In the present discussion the same general acceleration mechanism will be assumed. The details, however, will be quite different from those previously assumed.

It was shown in  $\mathfrak{R}$  that through this mechanism the energy of the particle increases at a rate that, for extreme relativistic particles, is proportional to their energy. The energy  $E$ , therefore, increases exponentially with time:

$$E(t) = E_0 e^{t/A}. \quad (3)$$

According to this law, the oldest particles should have the highest energy.

The time  $A$  needed for an energy increase by a factor  $e$  was estimated in  $\mathfrak{R}$  to be about 100 million years. If this estimate was correct,  $A$  would be comparable to the time  $B$  for

<sup>4</sup> *Ap. J.*, 118, 113, 1953.

nuclear collisions of the particle. Assuming that a nuclear collision effectively destroys the particle, the probability that a particle has the age  $t$  should be

$$e^{-t/B} \frac{dt}{B}. \quad (4)$$

Combining conditions (3) and (4), one readily finds that the probability that a particle observed now has energy  $E$  should be proportional to

$$\frac{dE}{E^n}, \quad (5)$$

with

$$n = 1 + \frac{A}{B}. \quad (6)$$

An exponent law like (5), with  $n$  of the order of 2 or 3, seems to fit fairly well the observed energy spectrum of the cosmic radiation.

Two main objections can be raised against the theory proposed in R. One is that, according to present evidence, the structure of the galactic magnetic field is much more regular than was assumed in R. We shall try to make plausible the conclusion that, in spite of this fact, the acceleration may still take place at an adequate rate. Indeed, as will be discussed below, it will be necessary to provide an acceleration process five to ten times more efficient than was previously supposed. The second difficulty arises from the fact that the protonic and the nuclear components of the cosmic radiation have very much the same energy spectrum. Heavy nuclei have a larger nuclear collision cross-section than protons. Their mean life  $B$ , therefore, should be shorter, and the exponent  $n$  given by equation (6) should be larger.

This difficulty would be removed if the process that eliminates the particles were equally effective against protons and against larger nuclei, because  $B$  would then be the same for both kinds of particle. For example, collisions against stars or planets do not differentiate between protons and nuclei. On the other hand, a simple estimate shows that the probability of collisions against such massive objects is quite negligible, even in a time equal to the age of the universe. Another means of removing cosmic-ray particles that is equally effective for protons and nuclei is diffusion outside the galaxy. Assume, for example, that the lines of force follow the spiral arms. The stretched-out length of the galactic spiral is about a million light-years, and the particles travel with a velocity very close to that of light. They could, therefore, escape in a time of the order of a million years. The escape time, of course, would be longer if the particle occasionally reversed its direction, owing, for example, to collisions of type  $a$ .

In a theory that yields essentially the same energy spectrum for cosmic-radiation protons and nuclei it will be necessary to assume that the escape time for diffusion outside the galaxy is appreciably shorter than the nuclear collision time. Then escape will be dominant with respect to nuclear collisions. We will assume that this is the case, and we will take, somewhat arbitrarily, in the numerical examples the escape time,

$$B = 10 \text{ million years.} \quad (7)$$

The escape time is then about ten times shorter than the nuclear collision time.

Assuming 2.5 as an average value of the exponent  $n$  in quantity (5), we have, from equation (6),

$$A = 1.5B = 15 \text{ million years,} \quad (8)$$

in which  $A$  is the time through which the energy of the particle increases, on the average, by the factor  $e$ . This time, 15 million years, is appreciably shorter than was estimated in R.

It therefore appears necessary to modify the acceleration mechanism of  $\mathfrak{R}$  in two ways. The mean free path must be much longer, in order to allow the escape of the particles from the galaxy in a relatively short time. And the process of acceleration must be much faster. At first sight, these two requirements seem to be contradictory, and perhaps they are. On the other hand, there is an acceleration mechanism that is potentially much more efficient than the others. This process was discussed in  $\mathfrak{R}$  and was then dismissed as of little importance for certain reasons to be mentioned shortly. I propose to criticize those reasons and to make a case in favor of this acceleration mechanism.

First of all, we observe that the knowledge that we now have of the general shape of the magnetic field makes the collisions of type  $b$  rather unimportant. We shall therefore concentrate our attention on type- $a$  collisions. They take place, as will be remembered, when the particle encounters a region of large field strength, where condition (2) is fulfilled. A particle that finds itself between two such regions will be trapped on the stretch of line of force comprised between them. When this happens, the energy of the particle will change with time at a rate much faster than usual. It will decrease or increase according to whether the jaws of the trap move away from or toward each other.

Let  $H$  be the average value of the magnetic field and  $H_{\max}$  the maximum field along the line of force that may be likely to cause a type- $a$  reflection. If  $\vartheta$  is the angle of pitch of the spiral where the field is average, reflections will occur only for particles having

$$\vartheta > \chi, \quad (9)$$

where

$$\sin \chi = \sqrt{\frac{H}{H_{\max}}}. \quad (10)$$

A simple calculation shows that when a particle with  $\vartheta > \chi$  is caught in a trap, both its energy and its angle of pitch will change with time, but the product,

$$E \sin \vartheta, \quad (11)$$

remains approximately constant. The particle can escape the trap only when  $\vartheta$  has decreased to the point that condition (9) is no longer fulfilled. In this process the energy must increase by a factor

$$\frac{\sin \vartheta}{\sin \chi}. \quad (12)$$

This process may lead to a sizable energy gain in a relatively short time. For example, if the jaws of the trap are 10 light-years apart and move toward each other at 10 km/sec, the time needed for a 10 per cent energy increase is only a few tens of thousands of years.

To be sure, the jaws will occasionally move away from each other, causing a loss instead of a gain of energy. But in this case  $\vartheta$  will increase, making the particle more easily caught in similar traps. The process ends only when the energy has increased to the point that  $\vartheta$  has become less than  $\chi$ , because only then will the particle be capable of passing without reflection through occasional maxima of the field intensity that it may encounter along its path.

When this condition is reached, the process of acceleration becomes exceedingly slow. Indeed, if  $g$  in equation (1) were exactly a constant of motion, the particle would always keep on spiraling in the same direction and would eventually escape from the galaxy. It is for this reason that the process of acceleration in a trap was not considered of major importance in  $\mathfrak{R}$ . The process may become important only if there is machinery whereby the angle of pitch, after having been reduced to a small value in the process of acceleration in a trap, can be increased. If this is the case, the trap mechanism again becomes operative, and the energy may be increased by a further factor.

Now one finds that  $q$  is almost exactly a constant as long as the particle is not caught in a trap and there are no sharp variations in the magnetic field either in time or in space. When I first discussed the acceleration of cosmic rays by magnetic fields, I was not aware of the possibility of sharp discontinuities of the field and for this reason did not think that the traps could be the dominant factor. I propose now to show that discontinuities in the direction of the magnetic field should not be too exceptional in the galaxy.

Recently de Hoffmann and Teller<sup>5</sup> have discussed the features of magnetohydrodynamic shocks. They show, in particular, that at a shock front sudden variations in direction and intensity of the field are likely to occur. One is tempted to identify the boundaries of many clouds of the galactic diffuse matter with shock fronts. If this is correct, we have a source of magnetic discontinuities. Probably many of these discontinuities will be rather small. However, either their cumulative effect or the effect of some occasional major discontinuity will tend to convert the angle of pitch that a previous trap acceleration has reduced to a small value back to a statistical distribution corresponding to isotropy of direction. At this moment the particle is ready for a new trap acceleration.

Probably our knowledge of the galactic magnetic field is still inadequate for a realistic discussion of the process here proposed. I would like, nevertheless, to list here in a purely hypothetical way a set of parameters that may be compatible with our present knowledge. We assume that a particle for part of the time has  $\vartheta < \chi$  and that it spirals in the same direction along the line of force without being caught in traps. Let  $\lambda$  be the average distance of travel while the particle is in this state, measured along the line of force. After the mean path  $\lambda$ , the particle will change  $\vartheta$  back to a high value and for a period of time will be frequently caught in traps, until its energy increases by a factor  $f$  and  $\vartheta$  decreases again to  $\vartheta < \chi$ . After this the process repeats itself. Let  $T$  be the average duration of one such cycle. The time  $A$  for acceleration by a factor  $e$ , then, is

$$A = \frac{T}{\ln f}. \quad (13)$$

The escape time  $B$  can be estimated as follows. Let  $L$  be the stretched-out length of the galaxy. The motion of the particle along  $L$  can be described as a random walk, with steps of duration  $T$ . The mean displacement in a step is given in first approximation by  $\lambda$ , because the particle, during the acceleration phase, changes its direction very frequently and does not move far. Estimating  $B$  with the diffusion theory, one finds

$$B = \frac{T(L/\lambda)^2}{\pi^2}. \quad (14)$$

A set of parameters that yields  $A = 15$  million years and  $B = 10$  million years is the following.

$$\begin{aligned} L &= 1.3 \times 10^{24} \text{ cm}, & \lambda &= 2 \times 10^{23} \text{ cm}; \\ T &= 2.3 \times 10^6 \text{ years}, & f &= 1.17. \end{aligned}$$

Naturally, these values are given here merely as an indication of possible orders of magnitude. Only a much more thorough discussion of the actual conditions in the galaxy may enable one to find reliable values of these quantities.

Two important questions should be discussed further. One is the injection mechanism that should feed into interstellar space an adequate number of particles of energy large enough for the present acceleration mechanism to take over. This problem was discussed in R, but no definite conclusion was reached there. The fact that the acceleration by the galactic magnetic field discussed here is appreciably faster than in R makes the requirements of the injection somewhat less stringent. Nevertheless, one still needs a very

<sup>5</sup> *Phys. Rev.*, **80**, 692, 1950.

powerful injection mechanism. Recent evidence that cosmic-ray-like particles are emitted by the sun indicates the stars, or perhaps stars of special types, as the most likely injectors.

A second question has to do with the energy balance of the turbulence of the interstellar gas. If it is true that the cosmic radiation leaks out of the galaxy in a time of the order of 10 million years, it is necessary that its energy be replenished a few hundred times during a time equal to the age of the universe. A simple estimate shows that the energy present in the galaxy in the form of cosmic rays is comparable to the kinetic energy due to the turbulence of the intergalactic gas. According to the present theory, the cosmic rays are accelerated at the expense of the turbulent energy. This last, therefore, must be continuously renewed by some very abundant source, perhaps like a small fraction of the radiation energy of the stars.

In conclusion, I should like to stress the fact that, regardless of the details of the acceleration mechanism, cosmic radiation and magnetic fields in the galaxy must be counted as very important factors in the equilibrium of interstellar gas.