

On the Origin of the Cosmic Radiation

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A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller¹ has advocated the view that cosmic rays are of solar origin and are kept relatively near the sun by the action of magnetic fields. These views are amplified by Alfvén, Richtmyer, and Teller.² The argument against the conventional view that cosmic radiation may extend at least to all the galactic space is the very large amount of energy that should be present in form of cosmic radiation if it were to extend to such a huge space. Indeed, if this were the case, the mechanism of acceleration of the cosmic radiation should be extremely efficient.

I propose in the present note to discuss a hypothesis on the origin of cosmic rays which attempts to meet in part this objection, and according to which cosmic rays originate and are accelerated primarily in the interstellar space, although they are assumed to be prevented by magnetic fields from leaving the boundaries of the galaxy. The main process of acceleration is due to the interaction of cosmic particles with wandering magnetic fields which, according to Alfvén, occupy the interstellar spaces.

Such fields have a remarkably great stability because of their large dimensions (of the order of magnitude of light years), and of the relatively high electrical conductivity of the interstellar space. Indeed, the conductivity is so high that one might describe the magnetic lines of force as attached to the matter and partaking in its streaming motions. On the other hand, the magnetic field itself reacts on the hydrodynamics³ of the interstellar matter giving it properties which, according to Alfvén, can pictorially be described by saying that to each line of force one should attach a material density due to the mass of the matter to which the line of force is linked. Developing this point of view, Alfvén is able to calculate a simple formula for the velocity V of propagation of magneto-elastic waves:

$$V = H / (4\pi\rho)^{1/2}, \quad (1)$$

¹ Nuclear Physics Conference, Birmingham, 1948.

² Alfvén, Richtmyer, and Teller, *Phys. Rev.*, to be published.

³ H. Alfvén, *Arkiv Mat. f. Astr., o. Fys.* 29B, 2 (1943).

where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar medium with energy above a certain injection threshold gains energy by collisions against the moving irregularities of the interstellar magnetic field. The rate of gain is very slow but appears capable of building up the energy to the maximum values observed. Indeed one finds quite naturally an inverse power law for the energy spectrum of the protons. The experimentally observed exponent of this law appears to be well within the range of the possibilities.

The present theory is incomplete because no satisfactory injection mechanism is proposed except for protons which apparently can be regenerated at least in part in the collision processes of the cosmic radiation itself with the diffuse interstellar matter. The most serious difficulty is in the injection process for the heavy nuclear component of the radiation. For these particles the injection energy is very high and the injection mechanism must be correspondingly efficient.

II. THE MOTIONS OF THE INTERSTELLAR MEDIUM

It is currently assumed that the interstellar space of the galaxy is occupied by matter at extremely low density, corresponding to about one atom of hydrogen per cc, or to a density of about 10^{-24} g/cc. The evidence indicates, however, that this matter is not uniformly spread, but that there are condensations where the density may be as much as ten or a hundred times as large and which extend to average dimensions of the order of 10 parsec. (1 parsec. = 3.1×10^{18} cm = 3.3 light years.) From the measurements of Adams⁴ on the Doppler effect of the interstellar absorption lines one knows the radial velocity with respect to the sun of a sample of such clouds located at not too great distance from us. The root mean square of the radial velocity, corrected for the proper motion of the sun with respect to the neighboring stars, is about 15 km/sec. We may assume that the root-mean-square velocity

⁴ W. S. Adams, *A.p.J.* 97, 105 (1943).

is obtained by multiplying this figure by the square root of 3, and is therefore about 26 km/sec. Such relatively dense clouds occupy approximately 5 percent of the interstellar space.⁵

Much less is known of the much more dilute matter between such clouds. For the sake of definiteness in what follows, the assumption will be made that this matter has a density of the order of 10^{-25} , or about 0.1 hydrogen atoms per cc. Even fairly extensive variations on this figure would not very drastically alter the qualitative conclusions. If the assumption is made that most of this material consists of hydrogen atoms, it is to be expected that most of the hydrogen will be ionized by the photoelectric effect of the stellar light. Indeed, one can estimate that some kind of dissociation equilibrium is established under average interstellar conditions, outside the relatively dense clouds, for which

$$n_+^2/n_0 \approx (T_1)^{\frac{1}{2}}, \quad (2)$$

where n_+ and n_0 are the concentrations of ions and neutral atoms per cc, and T_1 is the absolute kinetic temperature in degrees K. Putting in this formula $n_+ = 0.1$, one finds that the fraction of undissociated atoms is of the order of 1 percent, even assuming a rather low kinetic temperature of the order of 100°K.

It is reasonable to assume that this very low density medium will have considerable streaming motions, since it will be kept stirred by the moving heavier clouds passing through it. In what follows, a root-mean-square velocity of the order of 30 km/sec. will be assumed. According to Alfvén's picture, we must assume that the kinetic energy of these streams will be partially converted into magnetic energy, that indeed, the magnetic field will build up to such a strength that the velocity of propagation of the magneto-elastic waves becomes of the same order of magnitude as the velocity of the streaming motions. From (1) it follows then that the magnetic field in the dilute matter is of the order of magnitude of 5×10^{-6} gauss, while its intensity is probably greater in the heavier clouds. The lines of force of this field will form a very crooked pattern, since they will be dragged in all directions by the streaming motions of the matter to which they are attached. They will, on the other hand, tend to oppose motions where two portions of the interstellar matter try to flow into each other, because this would lead to a strengthening of the magnetic field and a considerable increase of magnetic energy. Indeed, this magnetic effect will have the result to minimize what otherwise would be extremely large friction losses which would damp the streaming motions and reduce them to disordered thermal motions in a relatively short time.

⁵ B. Stromgren, A.p.J. **108**, 242 (1948).

III. ACCELERATION OF THE COSMIC RAYS

We now consider a fast particle moving among such wandering magnetic fields. If the particle is a proton having a few Bev energy, it will spiral around the lines of force with a radius of the order of 10^{12} cm until it "collides" against an irregularity in the cosmic field and so is reflected, undergoing some kind of irregular motion. On a collision both a gain or a loss of energy may take place. Gain of energy, however, will be more probable than loss. This can be understood most easily by observing that ultimately statistical equilibrium should be established between the degrees of freedom of the wandering fields and the degrees of freedom of the particle. Equipartition evidently corresponds to an unbelievably high energy. The essential limitation, therefore, is not the ceiling of energy that can be attained, but rather the rate at which energy is acquired. A detailed discussion of this process of acceleration will be given in Section VI. An elementary estimate can be obtained by picturing the "collisions" of the particles against the magnetic irregularities as if they were collisions against reflecting obstacles of very large mass, moving with disordered velocities averaging to $V = 30$ km/sec. Assuming this picture, one finds easily that the average gain in energy per collision is given as order of magnitude by

$$\delta w = B^2 w, \quad (3)$$

where w represents the energy of the particle inclusive of rest energy, and $B = V/c \approx 10^{-4}$. This corresponds, therefore, for a proton to an average gain of 10 volts per collision in the non-relativistic region, and higher as the energy increases. It follows that except for losses the energy will increase by a factor e every 10^8 collisions. In particular, a particle starting with non-relativistic energy will attain, after N collisions, an energy

$$w = Mc^2 \exp(B^2 N). \quad (4)$$

Naturally, the energy can increase only if the losses are less than the gain in energy. An estimate to be given later (see Section VII) indicates that the ionization loss becomes smaller than the energy gain for protons having energy of about 200 Mev. For higher energy the ionization loss practically becomes negligible. We shall discuss later the injection mechanism.

IV. SPECTRUM OF THE COSMIC RADIATION

During the process of acceleration a proton may lose most of its energy by a nuclear collision. This process is observed as absorption of primary cosmic radiation in the high atmosphere and occurs with a mean free path of the order of magnitude of 70

g/cm², corresponding to a cross section of about

$$\sigma_{\text{abs}} \approx 2.5 \times 10^{-26} \text{ cm}^2 \quad (5)$$

per nucleon.

In a collision of this type most of the kinetic energy of the colliding nucleons is probably converted into energy of a spray of several mesons.

It is reasonable to assume that the cosmic rays will occupy with approximately equal density all the interstellar space of the galaxy. They will be exposed, therefore, to the collisions with matter of an average density of 10^{-24} , leading to an absorption mean free path

$$\Lambda = 7 \times 10^{25} \text{ cm.} \quad (6)$$

A particle traveling with the velocity of light will traverse this distance in a time

$$T = \Lambda/c = 2 \times 10^{18} \text{ sec.} \quad (7)$$

or about 60 million years.

The cosmic-ray particles now present will therefore, in the average, have this age. Some of them will have accidentally escaped destruction and be considerably older. Indeed, the absorption process can be considered to proceed according to an exponential law. If we assume that original particles at all times have been supplied at the same rate, we expect the age distribution now to be

$$\exp(-t/T) dt/T. \quad (8)$$

During its age t , the particle has been gaining energy. If we call τ the time between scattering collisions, the energy acquired by a particle of age t will be

$$w(t) = Mc^2 \exp(B^2 t/\tau). \quad (9)$$

Combining this relationship between age and energy with the probability distribution of age given previously, one finds the probability distribution of the energy. An elementary calculation shows that the probability for a particle to have energy between w and $w+dw$ is given by

$$\pi(w)dw = (\tau/B^2 T)(Mc^2)^{\tau/B^2 T} dw/w^{1+\tau/B^2 T}. \quad (10)$$

It is gratifying to find that the theory leads naturally to the conclusion that the spectrum of the cosmic radiation obeys an inverse power law. By comparison of the exponent of this law with the one known from cosmic-ray observations, that is, about 2.9, one finds a relationship which permits one to determine the interval of time τ between collisions. Precisely, one finds: $2.9 = 1 + \tau/B^2 T$, from which follows

$$\tau = 1.9B^2 T. \quad (11)$$

Using the previous values of B and T , one finds $\tau = 4 \times 10^7 \approx 1.3$ years. Since the particles travel with approximately the velocity of light, this corresponds to a mean distance between collisions

of the order of a light year, or about 10^{18} cm. Such a collision mean free path seems to be quite reasonable.

The theory explains quite naturally why no electrons are found in the primary cosmic radiation. This is due to the fact that at all energies the rate of loss of energy by an electron exceeds the gain. At low energies, up to about 300 Mev, the loss is mainly due to ionization. Above this energy radiative losses due to the acceleration of the electrons in the interstellar magnetic field play the dominant role. This last energy loss is instead quite negligible for protons. Also, the inverse Compton effect discussed by Feenberg and Primakoff⁶ will contribute to eliminate high energy electrons.

V. THE INJECTION MECHANISM. DIFFICULTIES WITH THE INJECTION OF HEAVY NUCLEI

In order to complete the present theory, the injection mechanism should be discussed.

In order to keep the cosmic radiation at the present level it is necessary to inject a number of protons of at least 200 Mev, to compensate for those that are lost by the absorption process. According to recent evidence,⁷ the primary cosmic radiation contains not only protons but also some relatively heavy nuclei. Their injection energy is much higher than that of protons, primarily on account of their large ionization loss. (See further Section VII.) Such high energy protons and heavier nuclei conceivably could be produced in the vicinity of some magnetically very active star.⁸ To state this, however, merely means to shift the difficulty from the problem of accelerating the particles to that of injecting them unless a more precise estimate can be given for the efficiency of this or of some equivalent mechanism. With respect to the injection of heavy nuclei I do not know a plausible answer to this point.

For the production of protons, however, one might consider also a simple mechanism which, if the present theory is at all correct in its general features, should be responsible for at least a large fraction of the total number of protons injected. According to this mechanism the cosmic radiation regenerates itself as follows. When a fast cosmic-ray proton collides in the interstellar space against a proton nearly at rest, a good share of the energy will be lost in the form of a spray of mesons, and two nucleons will be left over with energy much less than that of the original cosmic ray. Estimates indicate that in some cases both particles may have an energy left over above the injection threshold of

⁶ E. Feenberg and H. Primakoff, Phys. Rev. **73**, 449 (1948).

⁷ Freier, Lofgren, Ney, and Oppenheimer, Phys. Rev. **74**, 1818 (1948); H. L. Bradt and B. Peters, Phys. Rev. **74**, 1828 (1948).

⁸ See for example W. F. G. Swann, Phys. Rev. **43**, 217 (1933) and Horace W. Babcock, Phys. Rev. **74**, 489 (1948).

200 Mev, in some cases one and in some cases none. We can introduce a reproduction factor k , defined as the average number of new protons above the injection energy arising in a collision of an original cosmic-ray particle. As in a chain reaction, if k is greater than one the over-all number of cosmic rays will increase; if k is less than one it will decrease; if k is equal to one it will stay level.

Apparently the reproduction factor under interstellar conditions is rather close to one. This is perhaps not a chance, but may be due in part to the following self-stabilizing mechanism. The motions of the interstellar matter are not quite conservative, in spite of the reduced friction, caused by the magnetic fields. One should assume, therefore, that some source is present which steadily delivers kinetic energy into the streaming motions of the interstellar matter. Probably such a source of energy ultimately involves conversion of energy from the large supplies in the interior of the stars. The motions of the interstellar medium are in a dynamic equilibrium between the energy delivered by this source and the energy losses caused by friction and other causes. In this balance the amount of energy transferred by the interstellar medium to cosmic radiation is by no means irrelevant, since the total cosmic ray energy is comparable to the kinetic energy of the streaming, irregular motions of the galaxy. One should expect, therefore, that if the general level of the cosmic radiation should increase, the kinetic energy of the interstellar motion would decrease, and vice versa. The reproduction factor depends upon the density. As the density increases, the ionization losses will increase proportionally to it. This tends to increase the injection energy and consequently to decrease the reproduction factor. On the other hand, also, the rate of energy gained will change by an amount which is hard to define unambiguously. One might perhaps assume, however, that the velocity of the wandering magnetic fields increases with the $\frac{1}{3}$ power of the density, as would correspond to the virial theorem, and that the collision mean free path is inversely proportional to the $\frac{1}{3}$ power of the density, as one might get from geometrical similitude. One would find that the rate of energy increase is proportional only to the $\frac{2}{3}$ power of the density. The net effect is an increase of the injection energy and a decrease of the reproduction factor with increasing density. If the reproduction factor had been initially somewhat larger than one, the general level of the cosmic radiation would increase, draining energy out of the kinetic energy of the galaxy. This would determine a gravitational contraction which would increase the density and decrease k until the stable value of one is reached. The opposite would take place if k initially had been considerably less than one.

But even if this stabilizing mechanism is not adequate to keep the reproduction factor at the value one, and therefore an appreciable change in the general level of the cosmic radiation occurs over periods of hundreds of millions of years, the general conclusions reached in Section IV would not be qualitatively changed. Indeed, if k were somewhat different from one, the general level of the cosmic radiation would increase or decrease exponentially, depending on whether k is larger than or less than one. Consequently the number of cosmic particles injected according to the mechanism that has been discussed will not be constant in time but will vary exponentially. Combining this exponential variation with the exponential absorption (8), one still finds an exponential law for the age distribution of the cosmic particles at the present time, the only difference being that the period of this exponential will be changed by a small numerical factor.

The injection mechanism here proposed appears to be quite straightforward for protons, but utterly inadequate to explain the abundance of the heavy nuclei in the primary cosmic radiation. The injection energy of these particles is of several Bev, and it is difficult to imagine a secondary effect of the cosmic radiation on the diffuse interstellar matter which might produce this type of secondary with any appreciable probability. One might perhaps assume that the heavy particles originate at the fringes of the galaxy where the density is probably lower and the injection energy is therefore probably smaller. This, however, would require extreme conditions of density which are not easily justifiable. It seems more probable that heavy particles are injected by a totally different mechanism, perhaps as a consequence of the stellar magnetism.⁸

If such a mechanism exists one would naturally expect that it would inject protons together with heavier nuclei. The protons and perhaps to a somewhat lesser extent the α -particles would be further increased in numbers by the "chain reaction" which in this case should have $k < 1$. Indeed their number would be equal to the number injected during the lifetime T increased by the factor $1/(1-k)$. Heavy particles instead would slowly gain or slowly lose energy according to whether their initial energy is above or below the injection threshold. They would, however, have a shorter lifetime than protons because of the presumably larger destruction cross section. Their number should be approximately equal to the number injected during their lifetime.

One should remark in this connection that a consequence of the present theory is that the energy spectrum of the heavy nuclei of the cosmic radiation should be quite different from the spectrum of the protons, since the absorption cross section for a

heavy particle is presumably several times larger than that of a proton. One would expect, therefore, that the average age of a heavy particle is shorter than the age of a proton, which leads to an energy spectrum decreasing much more rapidly with energy for a heavy particle than it does for protons. An experimental check on this point should be possible.

VI. FURTHER DISCUSSION OF THE MAGNETIC ACCELERATION

In this section the process of acceleration of the cosmic-ray protons by collision against irregularities of the magnetic field will be discussed in somewhat more detail than has been done in Section III.

The path of a fast proton in an irregular magnetic field of the type that we have assumed will be represented very closely by a spiraling motion around a line of force. Since the radius of this spiral may be of the order of 10^{12} cm, and the irregularities in the field have dimensions of the order of 10^{18} cm, the cosmic ray will perform many turns on its spiraling path before encountering an appreciably different field intensity. One finds by an elementary discussion that as the particle approaches a region where the field intensity increases, the pitch of the spiral will decrease. One finds precisely that

$$\sin^2\vartheta/H \approx \text{constant}, \quad (12)$$

where ϑ is the angle between the direction of the line of force and the direction of the velocity of the particle, and H is the local field intensity. As the particle approaches a region where the field intensity is larger, one will expect, therefore, that the angle ϑ increases until $\sin\vartheta$ attains the maximum possible value of one. At this point the particle is reflected back along the same line of force and spirals backwards until the next region of high field intensity is encountered. This process will be called a "Type A" reflection. If the magnetic field were static, such a reflection would not produce any change in the kinetic energy of the particle. This is not so, however, if the magnetic field is slowly variable. It may happen that a region of high field intensity moves toward the cosmic-ray particle which collides against it. In this case, the particle will gain energy in the collision. Conversely, it may happen that the region of high field intensity moves away from the particle. Since the particle is much faster, it will overtake the irregularity of the field and be reflected backwards, in this case with loss of energy. The net result will be an average gain, primarily for the reason that head-on collisions are more frequent than overtaking collisions because the relative velocity is larger in the former case.

Somewhat similar processes take place when the cosmic-ray particle spirals around a curve of the line of force as outlined in Fig. 1 ("Type B"

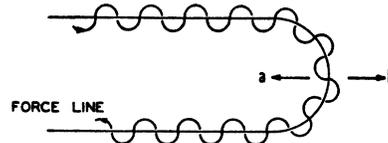


FIG. 1. Type B reflection of a cosmic-ray particle.

reflection). Here again, the energy of the particle would not change if the magnetic field were static. On the other hand, the lines of force partake of the streaming motions of the matter, and it may happen that the line of force at the bottom of the curve moves in the direction indicated by the arrow *a*, or that it moves in the direction indicated by the arrow *b*. In the former case there will be an energy gain (head-on collision) while in case *b* (overtaking collision) there will be an energy loss. Gain and loss, however, do not average out completely, because also in this case a head-on collision is slightly more probable than an overtaking collision due to the greater relative velocity.

The amount of energy gained or lost in a collision of the two types described can be estimated with a simple argument of special relativity, without any reference to the detailed mechanism of the collision. In the frame of reference in which the perturbation of the field against which the collision takes place is at rest, there is no change of energy of the particle. The change of energy in the rest frame of reference is obtained, therefore, by first transforming initial energy and momentum from the rest frame to the frame of the moving perturbation. In this frame an elastic collision takes place whereby the momentum changes direction and the energy remains unchanged. Transforming back to the frame of reference at rest, one obtains the final values of energy and momentum. This procedure applied to a head-on collision, gives the following result,

$$\frac{w'}{w} = \frac{1 + 2B\beta \cos\vartheta + B^2}{1 - B^2}, \quad (13)$$

where βc is the velocity of the particle, ϑ is the angle of inclination of the spiral, and Bc is the velocity of the perturbation. It is assumed that the collision is such as to produce a complete reversal of the spiraling direction by either of the two mechanisms outlined previously. For an overtaking collision, one finds a similar formula except that the sign of B must be changed. We now average the results of head-on and overtaking collisions, taking into account that the probabilities of these two types of events are proportional to the relative velocities and are given therefore by $(\beta \cos\vartheta + B/2\beta \cos\vartheta)$ for a head-on collision and $(\beta \cos\vartheta - B/2\beta \cos\vartheta)$ for an overtaking collision. The result for

TABLE I. Energy loss per g/cm² of material traversed.

Energy	Loss/g/cm ²	Gain/g/cm ²
10 ⁷ ev	94 × 10 ⁶ ev	7.8 × 10 ⁶ ev
10 ⁸	15 × 10 ⁶	8.6 × 10 ⁶
10 ⁹	4.6 × 10 ⁶	16.1 × 10 ⁶
10 ¹⁰	4.6 × 10 ⁶	91 × 10 ⁶

the average of $\ln(w'/w)$ up to terms of the order of B^2 is:

$$\langle \ln(w'/w) \rangle_{av} = 4B^2 - 2B^2\beta^2 \cos^2\vartheta \quad (14)$$

which confirms the order of magnitude for the average gain of energy adopted in Section III.

As a result of the extreme complication of the magnetic field and of its motion, it does not appear practical to attempt an estimate by more than the order of magnitude.

One might expect that after a relatively short time the angle ϑ will be reduced to a fairly low value so that Type *A* reflections will become infrequent. This is due to the fact that when ϑ is large, fairly large increases in energy and decreases of ϑ may occur, if the particle should be caught between two regions of high field moving against each other along a force line. One can prove that Type *B* reflections change gradually and rather slowly the average pitch of the spiral. It appears, therefore, that except for the beginning of the acceleration processes the Type *A* will not give as large a contribution as one otherwise might expect.

VII. ESTIMATE OF THE INJECTION ENERGY

Acceleration of a cosmic-ray particle will not be possible unless the energy gain is greater than the ionization loss. Since this last is very large for protons of low velocity, only protons above a certain energy threshold will be accelerated. In

Section III a value of 200 Mev for this "injection energy" has been given; a justification for this assumed value will be given now. In estimating the injection energy we will assume that the particle, during its acceleration, finds itself both inside relatively dense clouds and in the more dilute material outside of the clouds for lengths of time proportional to the volumes of these two regions. The ionization loss will be due, therefore, to a material of an average density equal to the average density of the interstellar matter, which has been assumed to be 10^{-24} g/cm², consisting mostly of hydrogen. In Table I the energy loss per g/cm² of material traversed is given as a function of the energy of the proton. In the third column of the table the corresponding energy gain is given. It is seen that the loss exceeds the gain for particles of energy less than about 200 Mev, as has been stated.

A similar estimate yields for the acceleration of α -particles an injection energy of about 1 Bev, for the acceleration of oxygen nuclei the initial energy required is about 20 Bev, and for an iron nucleus it would amount to about 300 Bev. As already stated, it does not appear probable that the heavy nuclei found in the cosmic radiation are accelerated by the process here described, unless they should originate at some place in the galaxy where the interstellar material is extremely dilute.

I would like to acknowledge the help that I had from several discussions with E. Teller on the relative merits of the two opposing views that we are presenting. I learned many facts on cosmic magnetism from a discussion with H. Alfvén, on the occasion of his recent visit to Chicago. The views that he expressed then were quite material in influencing my own ideas on the subject.