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AN HYPOTHESIS ON THE ORIGIN OF THE COSMIC RADIATION


Cosmic rays are more and more being recognised as a phenomenon of cosmic importance. As an introduction I would like to give a few figures that stress this importance. We know the intensity of the cosmic radiation that comes from the outside into the atmosphere. The number of particles with an energy of the order of or greater than four billions of electron volt is about 0.1 particles per square centimetre per steradian per second. From this figure we can estimate the energy present per cm³ in the form of cosmic rays of over 4 Gev. One finds $6 \cdot 10^{-13}$ erg/cm³.

Very probably, particles of lower energy are also present and may be cut of by magnetic field action, perhaps by the magnetic field of the sun. By a rather uncertain estimate one may be led to increase the previous figure by a factor 3. The cosmic rays represent therefore an energy density of $22 \cdot 10^{-13}$ erg/cm³. This energy should be compared with other astronomical or cosmic energies.

If one assumes that radiation with this average density occupies all the interstellar space of the galaxy, one obtains the result that the overall energy of the cosmic radiation is of the same order of magnitude as the kinetic energy of the disordered motions of the stars. The amount of energy is so large that one mightLegimately doubt whether or not it is possible to find a mechanism capable of producing cosmic radiation in such a staggering amount. For this reason Teller has recently proposed a “Non-Cosmic Theory” of the cosmic radiation by assuming that the cosmic radiation instead of extending to the interstellar space is confined to the immediate vicinity of the sun. This hypothesis was later developed by Teller, Richtmyer and Alfvén.

I will not discuss it now because I believe that Prof. Alfvén will do so next, and I will not even discuss the hypothesis considered in Bagge’s report concerning a possible stellar origin of the cosmic radiation. I would like
instead to discuss a different possibility according to which cosmic rays acquire most of their energy while travelling through space.

I want to assume: first, that the cosmic radiation is a galactic phenomenon, whereby I mean that the cosmic radiation fills with more or less uniform energy distribution all the space of our galaxy. This assumption requires a mechanism capable of holding the cosmic ray particles within the galaxy. It has been often assumed that this may be due to a galactic magnetic field with closed in lines of force. Before making further assumptions, I would like to investigate what one can deduce from this hypothesis.

Our galaxy comprises stars and matter. The diffuse matter has an average density of about $10^{-44}$ g/cm$^3$, a figure easy to remember because it corresponds approximately to one hydrogen atom per cm$^3$. A simple calculation shows that the probability of collision of a cosmic ray against a star is extremely small. However, the probability that the cosmic ray particle may have a nuclear collision is not at all negligible. Indeed, we can make a crude estimate of this probability as follows: We know directly from cosmic ray experiments that when cosmic ray particles enter from the outside into the earth's atmosphere they soon collide with air nuclei. The mean free path for this collision is of the order of magnitude of one hundred grams per cm$^3$. Since the density is $10^{-44}$, the corresponding mean free path for a cosmic ray particle travelling through the galaxy will be about $10^{46}$ cm. Since the particle travels with almost the velocity of light, the time taken for traversing this distance will be $10^{46}/3\cdot10^5 = 3\cdot10^{15}$ sec $= 10^8$ years. In the following calculations I have used slightly different figures yielding:

\begin{equation}
T = 7\cdot10^7 \text{ years},
\end{equation}

for the average time that a cosmic ray particle travels before a nuclear collision happens that effectively destroys it.

This time is rather short compared to the age of the universe estimated to be two or three billion years. We are therefore led to the conclusion that only very few of the cosmic ray particles that we now observe can be as old as the galaxy. It seems necessary, therefore, to assume the existence of a mechanism that continuously produces new cosmic ray particles.

Without discussing yet what this mechanism may be, we want to introduce as a second assumption that the production is uniform in time. Since a particle has a mean life of 70 million years, its probability of survival after a time, $t$, will be

\begin{equation}
\exp\left(-\frac{t}{T}\right).
\end{equation}

This expression gives the age distribution law of the particles that are now in existence.

One can now make two alternate assumptions: one is that the cosmic radiation particles are originally produced with a energy equal to or higher than their present energy. The other one is that the cosmic ray particles are originally produced at a relatively low energy and are gradually accelerated. In what follows we shall take this second point of view which has the advan-
tage to require an injection mechanism less powerful than the one that would be required for the first assumption.

We assume, therefore, the existence of an accelerating process whereby the energy of a particle gradually increases as its age increases and is a function of the age. The dependence of the energy upon the age may then be determined from the knowledge of the energy distribution of the cosmic radiation. The experimentally known energy distribution of cosmic ray particles is rather complicated at low energies but takes the form of a simple power law for energies above a few Gev. We will assume this simplified law:

\[ I(E) \, dE = kE^{-\alpha} \, dE. \]

the exponent 2.9 is chosen to fit the observations.

We have assumed that the energy of a particle is a function of its age, \( t \)

\[ E = f(t) \]

From the knowledge of the age distribution (2), and the energy distribution (3), one can determine \( f(t) \). Indeed, the number of particles with age between \( t \) and \( t + dt \) is proportional to \( \exp \left( -\frac{t}{T} \right) \, dt \), and the number of particles with energy between \( E \) and \( E + dE \) is proportional to

\[ \frac{dE}{E^{\alpha}} = \frac{df}{f^{2.9}} \]

we find, therefore,

\[ \frac{df}{f^{2.9}} = a \exp \left( -\frac{t}{T} \right), \]

where \( a \) is a proportional constant. Integration yields

\[ \frac{1}{t^{1.9} f^{2.9}} = \frac{a}{T} \exp \left( -\frac{t}{T} \right), \]

where the integration constant has been set to equal zero because for large \( t \), \( f \) becomes infinite. This equation can be rewritten in the form:

\[ f(t) = E_0 \exp \left( \frac{t}{(1.9 \, T)} \right), \]

where \( E_0 \) is a new constant that represents the initial energy of the particle. From our assumptions follows a very specific law (7) whereby the energy of the cosmic ray particles must increase with time. According to (7), the energy must increase every year by a fraction of about 10^{-8} of its value, so for a proton with energy equal to its rest energy, the energy will increase at the rate of about only 10 eV per year and will increase correspondingly faster for protons of higher energy. It is clear, however, that in any case the rate of increase of the energy will be quite slow since it takes about 100 million years to double the initial value of the energy.

A very simple process that leads to the acceleration law (7), is due to the collision against large moving objects. Without specifying yet what particular objects will be considered as likely obstacles against which the collisions take place, we want to assume that a cosmic ray frequently collides against large moving obstacles. That the energy of the cosmic ray will
on the average increase in such collisions is clear from the fact that ultimately statistical equilibrium would be established with equipartition of energy between the obstacles and the cosmic ray particles. This corresponds, of course, to an extremely high energy very many orders of magnitude beyond the maximum energy observed in cosmic rays. What limits the efficiency of this process in increasing the energy of the cosmic ray particles is, therefore, not the maximum energy attainable which is effectively infinite, but rather the rate at which the energy is transmitted.

Not all collisions will accelerate the particle. Actually, head-on collisions will produce an acceleration and over-taking collisions will produce a deceleration. On the average, there is acceleration primarily because head-on collisions are somewhat more probable than over-taking collisions since the relative velocity is larger in the former case. One can compute in an elementary way the order of magnitude of the average increase, $\delta E$, per collision of a particle of energy $E$ (including rest energy) colliding against objects moving with velocity, $V$. The result is:

$$\delta E \sim \frac{EV^2}{c^2}.$$  

If we assume that the collision cross-section is independent of the energy, the number of collisions per unit time will also be approximately independent of the energy since the velocity of the cosmic ray particles is practically constant and equal to $c$. It follows from (8) that the gain in energy per unit time is proportional to the energy. The energy therefore increases according to an exponential law.

We shall take $V$ of the order of 30 km/sec. This gives (8) $\delta E \sim 10^{-8} E$. That is again an average gain of energy per collision of one part in $10^8$.

After $N$ collisions the energy will be:

$$E = E_0 \exp[NB^*],$$

where

$$B^* = \frac{V^*}{c^2} = 10^{-8}.$$

In order to estimate the number of collisions, we introduce a scattering mean free path $\lambda$. The number of collisions after a time, $t$, since the initiation of the process will be $N = \frac{ct}{\lambda}$, since the particle travels practically at the velocity of light. Consequently we get:

$$E = E_0 \exp\left[\frac{ctB^*}{\lambda}\right].$$

Comparing (10) with (7) one obtains

$$\lambda = 1.9 B^* cT \sim 10^{18} \text{cm} = 1 \text{ light year}.$$  

We will now further specialize our assumptions and introduce the hypothesis that the collisions responsible for the increase in energy are against moving irregularities in a cosmic magnetic field.
The idea of the existence of such a moving magnetic field is due to Dr. Alfvén who has made a thorough magneto hydro-dynamic study of the influence that the extremely tenuous interstellar matter has on the propagation of a magnetic field that penetrates it.

Unfortunately, I do not have the time to explain in detail his very stimulating ideas on this subject. I shall only mention that due to the relatively high electrical conductivity of the interstellar medium, the lines of force are practically attached to the matter so that they are dragged by the turbulent motion of the interstellar matter. A cosmic ray particle will be deflected by the action of the magnetic field and will gain energy in the process as previously discussed. In order to obtain agreement with the experimentally observed spectrum, we must assume that the size of the minimum vortices which drag the lines of force is of the order of one light year, a value which does not appear implausible.

Nothing has been said so far of the injection mechanism of the particles of relatively low energy which will be further accelerated by the proposed method. In order that a particle so injected may eventually become an energetic cosmic ray, it is necessary that its initial energy be above a certain limit which will be called the injection threshold. Indeed, the accelerating mechanism will function only when the energy gained by the accelerating mechanism is greater that the energy lost by ionization. An estimate of the injection threshold yields for various particles the following values:

- Protons \(-100 \text{ Mev}\)
- \(\alpha\) Particles \(-1 \text{ Gev}\)
- Oxygen nuclei \(-1 \text{ Gev per nucleon}\)
- Iron nuclei \(-5 \text{ Gev per nucleon}\)

It is seen that the injection threshold is quite large for heavy nuclei and this represents the most serious difficulty for the proposed theory. Even without special assumption as to the origin of the initial protons and \(\alpha\) particles the injection of these light components of the cosmic radiation may be understood perhaps as due to the collisions of the cosmic radiation itself with the nuclei of the interstellar matter. From this point of view, cosmic radiation would be a self regenerating process.

No such simple explanation, however, seems adequate for the injection of heavier nuclei like, for instance, oxygen or iron, since no known mechanism could yield an iron nucleus with 5 Gev per nucleon without destroying the nucleus itself. One must assume, therefore, a special injection mechanism for these particles, perhaps like the one suggested recently by Spitzer [1].

In conclusion, the proposed theory seems to be quite adequate for understanding the main features of the proton components of the cosmic radiation and perhaps also of the \(\alpha\) particle component. It does not seem adequate to understand the presence in the cosmic radiation of a significant fraction of heavier nuclei. If the general features of the present theory should prove correct, there should be an independent and very powerful injection mechanism, of the heavy component of the cosmic radiation.
BIBLIOGRAPHY.

1] Lyman Spitzer, Jr., *Phys. Rev.*, 76, 583 (1949).


E. Bagge, Hamburg:


E. Fermi, Chicago:

In order to avoid a large loss of particles out of the boundaries of the galaxy it is sufficient to assume that the lines of force are closed or at least that very few of them escape to the outer space.

L. Janossy, Dublin:

The injection process of protons is helped by the circumstance that a nucleon colliding with a nucleus is likely to retain an appreciable fraction of its energy and thus remain very much above the injection energy. The question is raised whether heavy fragments arising out of nuclear collisions can serve to inject heavier nuclei.

E. Fermi, Chicago:

Naturally I hope that you are right. On the other hand it seems to me very difficult to understand the fact from the theoretical point of view. But, of course, if the fact should prove to be true it will have some theoretical explanation.