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Intergalactic Space and Cosmic Rays.

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Summary. — Arguments are presented suggesting that the most energetic particles observed in the Cosmic Radiation are accelerated outside the galaxy, in the intergalactic space. The problem of the Cosmic Ray acceleration in the intergalactic space is discussed and some possible models are presented.

Introduction.

The problem of the origin of the Cosmic Radiation (C.R.) can be subdivided into two parts.

One deals with the problem of the acceleration of ions from rest to, say, 10^{10} eV; the second with the subsequent acceleration of a small percentage of C.R. from 10^{10} eV to the maxima energies observed, i.e. $> 10^{18}$ eV.

It is probable that the first acceleration takes place in the neighborhood of stars, though the actual mechanism is still quite controversial. We are not going to discuss this topic here.

The opinions about the subsequent acceleration are also divided; however, there is a quite universal agreement that the highest energies cannot be reached through mechanisms operating in the neighborhood of the stars, but that the acceleration takes place in the interstellar space, through interaction of the already accelerated ions emitted by the stars with the turbulent conducting galactic gas.

The fundamental work on this subject is by FERMI (1); modifications to

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(1) E. FERMI: *Phys. Rev.*, **75**, 1169 (1949).

the first model have been later proposed by FERMI himself [2] and by others [3-5], but the assumption has always been made that the acceleration takes place within the galaxy, be it the flat disk determined by the population I stars, or the spheric object determined by the population II stars and the gas [6].

However, the experimental evidence gained in the last years seems to suggest that at least the most energetic particles cannot be accelerated inside the galaxy, and that in a complete picture of the origin of C.R. a chapter must be added, dealing with the acceleration of C.R. in the Inter-Galactic Space (I.G.S.).

The present note is dedicated to this problem. In Sect. 1 the arguments will be presented that suggest the necessity of an inter-galactic acceleration. In Sect. 2 some considerations about the I.G.S. acceleration are presented.

1. – Arguments Against a Purely Galactic Origin of the Cosmic Radiation.

The experimental information most directly related to the origin of C.R. is the following:

a) The analysis of the Extensive Air Showers by means of several hundreds detectors spread over surfaces of the order of one square kilometer gives conclusive evidence that primary C.R. with energies up to $10^{18} \div 10^{19}$ eV exist, and that their frequency corresponds to a power spectrum (integral) with exponent $1.8 \div 2.0$ (CLARK, KRANSHAW, VERNOV) [7]. This is the same law that holds for lower energies. Hence, a single spectrum describes the frequency of the primary C.R. for energies from 10^{11} to $10^{18} \div 10^{19}$ eV.

b) All the systematic measurements thus far made on Extensive Air Showers produced by primaries of $\sim 10^{17}$ eV (KRANSHAW, CLARK [7] and KRANSHAW [8]) suggest that the distribution in space of these particles is isotropic. If a sidereal anisotropy exists, the amplitude, δ, of the first armonic is probably not larger than 0.10 times the average intensity. For primaries of 10^{10} to 10^{15} eV the measurements done thus far give $\delta < 10^{-3}$ (DAUDIN [9]).

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(2) E. FERMI: *Ap. Journ.*, **119**, 1 (1954).
(3) P. MORRISON, S. OLBERT and B. ROSSI: *Phys. Rev.*, **94**, 440 (1954).
(4) C. Y. FAN: *Phys. Rev.*, **101**, 314 (1956).
(5) L. DAVIS: *Phys. Rev.*, **101**, 351 (1956).
(6) S. B. PIKELVER: *Dokl. Akad. Nauk SSSR*, **88**, 229 (1953); G. R. BURBIDGE: *Phys. Rev.*, **101**, 906 (1956).
(7) *Communications at the Guanajuato (Mexico) Meeting* (September 1955).
(8) J. K. KRAWSHAW and H. ELLIOT: *Proc. Phys. Soc.*, **A 69**, 102 (1956).
(9) J. DAUDIN, P. AUGER, A. CACHON and A. DAUDIN: *Nuovo Cimento*, **3**, 1017 (1956).

c) Up to energies per nucleon of $\sim 10^{14}$ eV the mass spectrum of the primary C.R. seems to remain unchanged, i.e., preponderantly composed of protons. Various arguments, in part based on experimental evidence, in part speculative, make it plausible that even at the highest energies ($10^{18} \div 10^{19}$ eV) the protons still are the most abundant particles in the primary C.R. ([10]).

In the models proposed thus far, where the acceleration of C.R. takes place inside the galaxy, the three requirements listed above are met as follows:

1) By limiting the average life spent by C.R. in the galaxy to a time that corresponds to the crossing of no more than $\sim 1\ \text{g}\cdot\text{cm}^{-2}$ of interstellar matter. This assures that the particles do not suffer nuclear collisions during their stay in the galaxy, an essential condition for explaining the existence of heavy ions in the primary C.R. with the abundances observed.

2) By diffusing the C.R. in the turbulent magnetic fields of the galaxy, fields with average magnitude of the order of $10^{-6} \div 10^{-5}$ gauss. This insures both the acceleration of the particles up to the highest energies with a power spectrum, and their isotropic distribution.

In order to see how the models so far proposed fit the experimental evidence, let us consider first the model in which the galaxy is a sphere of radius $R = 5\cdot 10^{22}$ cm filled with gas of density $\sim 10^{-25}\ \text{g}\cdot\text{cm}^{-3}$, in which C.R. diffuse at random ([6]). In this case the anisotropy, δ, can be easily correlated to the total path of the particles in the galaxy, L.

Following the method of MORRISON *et* al. ([3]), the anisotropy is given by:

$$\delta = \frac{2(\psi_2 - \psi_1)}{\psi_1 + \psi_2}\,,$$

where ψ_1 and ψ_2 are the fluxes of C.R. at the earth, going towards and away respectively from the centre of the galaxy. If S is the strength of the C.R. source, and ϱ_0 the C.R. density in the galaxy, then:

$$4\pi R_s^2(\psi_2 - \psi_1) = \int_0^{R_s} S\,\mathrm{d}V \qquad \text{and} \qquad \psi_1 + \psi_2 = \tfrac{1}{2}\varrho_0 v\,,$$

where R_s is the distance of the sun from the center of the galaxy ($R_s \approx 3\cdot 10^{22}$ cm),

([10]) Actually the last point of *c*) is not of fundamental importance for the evaluation of the magnetic rigidity. If the primaries of the most energetic Extensive Air Showers are heavy nuclei, then the estimate of their energy from the secondaries observed at sea-level must be increased and their magnetic rigidity would not change substantially. Besides, a factor of 2 would come from the mass to charge ratio of stable nuclei. More important is the fact that at $10^{13} \div 10^{14}$ eV/nucleon heavy nuclei have been observed roughly in the same proportion as observed at the lowest energies.

and v the velocity of C.R.; ϱ_0 can be eliminated by observing that the ratio

$$\frac{L}{v} = T_0 = \text{average time spent by C.R. in the galaxy}\,,$$

is equal to the ratio between the total number of C.R. present in the galaxy and the total source output per unit time:

$$\frac{L}{v} = \frac{\int_0^R \varrho_0 \, \mathrm{d}V}{\int_0^R S \, \mathrm{d}V} \approx \frac{\frac{4}{3}\pi R^3 \varrho_0}{\int_0^R S \, \mathrm{d}V}\,.$$

This gives:

$$\delta = \frac{4R}{3L}\left(\frac{R}{R_s}\right)^2 \frac{\int_0^{R_s} S \, \mathrm{d}V}{\int_0^R S \, \mathrm{d}V} \approx \frac{4}{3}\frac{R_s}{L}\,.$$

Utilizing this relation one obtains the lower limits for L as given in Table I.

TABLE I.

Average energy (eV)	δ observed	
$U_1 = 10^{10}$	$< 10^{-3}$	$L_1 > 4 \cdot 10^{25}$ cm $= 4$ $\text{g} \cdot \text{cm}^{-2}$
$U_2 = 10^{15}$	$< 10^{-3}$	$L_2 > 4 \cdot 10^{25}$ cm $= 4$ $\text{g} \cdot \text{cm}^{-2}$
$U_3 = 10^{17}$	$< 10^{-1}$	$L_3 > 4 \cdot 10^{23}$ cm $= 0.04$ $\text{g} \cdot \text{cm}^{-2}$

The fact that L remains as large as at least several $\text{g} \cdot \text{cm}^{-2}$ up to 10^{15} eV means that, in this model, the particles of 10^{15} eV from the moment of their injection to the final energy must cross a total thickness equivalent to

$$L_{\text{tot}} > L_1 \ln \frac{U_2}{U_1} \approx 10 L_1 = 40 \ \text{g} \cdot \text{cm}^{-2}\,.$$

This is incompatible with the observed existence of heavy ions ([11]). It is worth

([11]) It seems that this point has been missed in the previous literature. What is usually quoted is L_1 the average path length of *all* C.R. in the galaxy, i.e., of the particles with average energy $\sim U_1$. When particles of energy U_2 are actually observed, their average path length is $\ln (U_2/U_1)$ times larger than the average path length of all particles.

noticing that we are evaluating lower limits, since no sidereal anisotropy has been actually observed thus far.

The evaluation of L_{tot} is based only on the asymmetry; actually it must be proved that the particles in question can cover that length while diffusing inside the galaxy.

If the average magnetic field in the turbulent elements of the galaxy is H gauss, and U (eV) is the (relativistic) energy of the particles, the radius of curvature in such a field for a particle of charge e is $r = U/300H$ cm. This is also the lower limit for the dimensions of the diffusing elements. The m.f.p. between collisions must be somewhat larger, say:

$$\lambda \approx 2\pi U/300H \,.$$

The particles being accelerated over the whole volume, the average displacement before leaving the galaxy will be $\approx aR$, with $a \approx \frac{1}{3}$, and the average number of collisions in the galaxy will be:

$$N = \left(\frac{aR}{\lambda}\right)^2 .$$

This corresponds to a total length:

$$L_{tot} = N\lambda = \frac{6 \cdot 10^{40}}{U} \text{ cm} \,,$$

if $H = 5 \cdot 10^{-6}$ gauss is used. For $U = 10^{15}$ eV and $U = 10^{17}$ eV the values of L given by this equation barely stay within the limits given in Table I. This means that the spherical galaxy, even if evenly packed with diffusing elements is barely able to hold the most energetic C.R. for the time required to mask, at the earth, the effect of the empty space.

The same arguments are even more radically against any model in which it is assumed that the random diffusion takes place in a disk-shaped galaxy or in the spiral arms.

In more recent models, however, the acceleration is not attributed to random collisions, but to series of coherent collisions against pairs of moving shock waves ([2-4]), or to « betatron » collisions ([5]). In these cases an overall magnetic field along the spiral arms of $\sim 5 \cdot 10^{-6}$ gauss prevents the escaping of C.R. from the sides, and allows it only at the end of the spiral arms. The evaluation of the anisotropy expected depends then essentially on the detailed features of the magnetic field ([12]). Probably it would be possible to imagine

([12]) L. Davis: *Phys. Rev.*, **96**, 743 (1954).

a situation such that the experimental data known thus far can be satisfied. However, we want to remark that in a field of $5 \cdot 10^{-6}$ gauss a proton of $10^{18} \div 10^{19}$ eV has a radius of curvature of $10^{21} \div 10^{22}$ cm, even larger than the cross dimensions of the spiral arm. How can a particle not only be confined, but also be accelerated in the spiral arms at these energies?

Another argument that applies to all galactic models is the following. The exponent γ of the integral spectrum of C.R. remains practically the same (~ 1.8) from 10^{11} eV to 10^{19} eV.

In all galactic theories this is considered as due to the fact that the energy of each C.R. in the galaxy increases exponentially with the number N of collisions between the particle and the accelerating turbulences:

$$U = U_0 \exp [\beta^2 N] ,$$

while the probability P of staying inside the galaxy decreases exponentially with N,

$$P = P_0 \exp [- N/N_1] ,$$

where β is proportional to the velocity of the accelerating turbulence and N_1 is the average number of collisions before escaping from the galaxy. Combining the two expressions, one gets:

$$P = P_0 \left(\frac{U_0}{U}\right)^{1/\beta^2 N_1} , \qquad \text{so that} \qquad \gamma = \frac{1}{\beta^2 N_1} .$$

The constancy of γ means that the product $\beta^2 N_1$ is independent of energy for $10^{11}\text{ eV} < U < 10^{18}$ eV. If both β and N_1 remain constant, then the difficulties discussed before become worse, because the smallest maximum anisotropy ($\delta < 10^{-3}$) would apply also to the highest energies.

It is more plausible to assume that at small energies the C.R. are scattered more, i.e., that the turbulent fields are not all of the same strength; this would mean that N_1 decreases when the energy increases. and β correspondingly increases. But this is just the opposite of what is expected of any of the proposed accelerating mechanisms; i.e., that in a collision the percent gain of the C.R. energy should increase as the energy of the C.R. increases.

We can conclude that all the arguments presented strongly suggest that at least part of the cosmic radiation comes from outside the galaxy.

We want to emphasize that the strength of these arguments is limited only by the inadequacy of the observational material and that any reasonable extrapolation would make them even more compelling.

For instance, it is quite sensible to expect that the energy spectrum extends well beyond the $10^{18} \div 10^{19}$ eV to which the present experimental possibilities limit our knowledge. In such a case, the mechanisms « ad hoc » barely able to justify the existence of the maxima energies observed thus far will become totally inadequate, and more general properties of the Universe will have to be investigated.

2. – Some Consequences of the Intergalactic Acceleration.

a) Let us first consider the problem of the amount of matter crossed by C.R. moving in the Inter-Galactic Space.

The value of the density of matter in I.G.S. is still in question. However, it is admitted that it must be several orders of magnitude smaller than that in the galaxy. The values most frequently quoted range between 10^{-27} and 10^{-30} g·cm^{-3}.

The upper limit to the total thickness of matter crossed by C.R. being ~ 1 g·cm^{-2}, these densities correspond to path lengths of $10^{27} \div 10^{30}$ cm, and for relativistic particles to times of $10^{9} \div 10^{12}$ years.

The first of these figures is smaller than the so called age of the Universe ($\sim 10^{10}$ years), but the second is quite larger, so we can conclude that likely the movement of C.R. in the intergalactic spaces is not limited by time.

b) Let us now assume that the I.G.S. is empty, and that each galaxy is emitting a flux, φ (erg s^{-1}), of C.R. equal to that emitted by our own galaxy. Then,

$$\varphi = \frac{\varrho_0 \omega}{T_0},$$

where: ϱ_0 = average energy density of C.R. in the galaxy,

ω = volume of the galaxy,

T_0 = average life of C.R. in the galaxy $= \sim 10^7$ years.

What is then the average energy density of C.R., ϱ, in the intergalactic space?

If T is the average life of the particles in the Universe, and Ω the average volume of I.G.S. surrounding each galaxy ($\Omega \approx 10^7 \, \omega$):

$$\varrho \approx \frac{\varphi T}{\Omega} = \varrho_0 \frac{\omega}{\Omega} \frac{T}{T_0} \approx 10^{-7} \, \varrho_0 \frac{T}{T_0}.$$

The value of T depends on the model chosen for the Universe. An infinite static Universe gives $T=\infty$ and $\varrho \to \varrho_0$; this is the Cosmic Ray analogue of the Olbers' paradoxe for the visible light ([13]).

For an Universe expanding with the recession constant

$$h \approx \frac{1}{10^{10}\ \text{years}}, \qquad \text{one has} \qquad T = \approx \frac{1}{h} = 10^{10}\ \text{years}.$$

For a steady state Universe, with the same recession constant ([13]), again $T \approx 10^{10}$ years.

The most accepted models of the Universe being of these last kinds, we conclude that, if there is no acceleration in the I.G.S.:

$$\varrho \approx 10^{-4}\, \varrho_0 .$$

Thus any mechanism capable of accelerating C.R. in the I.G.S. has, to start with, a flux of C.R. up to the highest galactic energies, 10^4 times smaller than that in the galaxies themselves, or larger.

This can be of help in providing a mechanism of acceleration with the injection of particles of high energy ([14]).

c) If the acceleration takes place through interaction of the C.R. with moving magnetic fields (Fermi-like mechanism), the strength of the fields must satisfy the condition:

$$Hd \geqslant 10^{17}\ \text{gauss}\cdot\text{cm}, \tag{1}$$

where H is the average value of the field, and d its dimension.

The overall field of our galaxy has $Hd \approx 5\cdot 10^{16}$ gauss·cm, and if this value is representative for all galaxies, the galaxies themselves are barely able to partecipate in this kind of acceleration. In fact, the transparency of our galaxy to the most energetic C.R. constitutes the main argument against these particles being of galactic origin.

A mechanism of acceleration by means of the interaction of C.R. with the magnetic fields of two galaxies, (our own and the Magellanic clouds) has been proposed by HEIDMAN ([15]). In the specific case, HEIDMAN does not try to explain the highest energies we are considering here, but it is conceivable that in other systems of galaxies, e.g., the colliding galaxies responsible for the strongest source of radio emission, conditions can arise where the highest energies can be achieved.

([13]) See e.g., H. BONDI: *Cosmology* (Cambridge, 1952).

([14]) Actually it is likely that T_0, the average life of C.R. in the galaxy, decreases as the energy of the particles increases; for very energetic particles, therefore, ϱ is probably larger than $10^{-4}\varrho_0$; for the extreme energies, in fact, $\varrho \approx \varrho_0$.

([15]) J. HEIDMAN: Private communication.

The lack of anisotropy observed for C.R. requires however that these sources are numerous and quite uniformely distributed in the Universe. Besides, if the volume of the accelerating region is limited to a small fraction of the space, the efficiency of production of C.R. must correspondingly increase.

A mechanism operating throughout the volume of the I.G.S. would be more appealing. Let us suggest two models of this kind.

Model one is based on the assumption that in the I.G.S. « clouds » of ionized gas exist with random velocities and dimensions such as to create magnetic fields satisfying condition (1). These clouds would then be capable of accelerating C.R. as in the Fermi model. Condition (1) is demanding; e.g., it requires clouds of $\sim 10^{23}$ cm diameter moving with random velocities of $3000\ \mathrm{km\ s^{-1}}$, assuming equipartition between kinetic and magnetic energy (density of intergalactic matter $10^{-28}\ \mathrm{g \cdot cm^{-3}}$).

How well these conditions are met by the intergalactic gas is difficult to say. It seems likely that the gas is weakly ionized and that turbulences exist in it, because the galaxies with their magnetic fields move in it with random velocities not much smaller than the value quoted above. More experimental evidence is of course necessary.

The second model postulates the emission by the galaxies of electromagnetic waves of very low frequency, say 1 cycle per second, and high amplitude, say $10\ \mathrm{V \cdot cm^{-1}}$.

The density of the intergalactic free electrons is low enough to allow the propagation of these waves, and any C.R. injected with the right phase could have its energy increased by the factor [16]

$$g = 1 + \left(\frac{eE\lambda}{\pi mc^2}\right)^2 ,$$

where: E = max. electric field,

λ = wave length,

m = mass of the accelerated particle.

With the field and the frequency quoted, $g \approx 30$ for protons. Of course, when the injection occurs with the wrong phase the energy of the C.R. is decreased by the same factor, but what matters is that some of the galactic C.R. can gain energy.

There is no experimental evidence for the existence in the I.G.S. of such electromagnetic waves. An extrapolation of many orders of magnitude of the spectra observed for the radio-waves emitted by the galaxies could give

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([16]) E. McMillan: *Phys. Rev.*, **79**, 498 (1950).

numbers not in disagreement with those quoted, but of course such extrapolation is completely arbitrary.

What we want to point out in presenting these models is that, it is possible to think of mechanisms by which C.R. can be further accelerated in the I.G.S. without invoking very unusual phenomena.

A serious difficulty in envisaging an intergalactic acceleration of C.R. stays, in our opinion, in the time scale. It seems that the statistical mechanisms, as, e.g., those described before, are too slow to give an average gain in energy of the many orders of magnitude required in a time as *small* as the age of the Universe ($\sim 10^{10}$ years).

However, our ignorance of both the properties of the I.G.S. and of the structure of the Universe are such that these difficulties cannot be considered unsurmountable.

As a conclusion, we think that problems of this kinds are now ripe for discussion and that, from the experimental point of view, researches that could give more information about the properties of C.R. particles of energies of 10^{18} eV and greater are worth pursuing.

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RIASSUNTO

Vari risultati sperimentali suggeriscono che almeno la parte più energica della radiazione cosmica non sia tutta contenuta ed accelerata nella galassia, ma sia invece comune a tutto l'universo e probabilmente accelerata negli spazi intergalattici. L'evidenza sperimentale è presentata nella prima parte, mentre nella seconda vengono discusse alcune conseguenze della presenza negli spazi intergalattici della radiazione cosmica ed esaminati alcuni meccanismi che potrebbero essere responsabili della sua accelerazione.