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## Cosmic rays and particles of negative mass

by

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**SUMMARY.** — The possible mechanism of acceleration of cosmic ray particles effected by their interaction with a hypothetical heat reservoir of negative temperature is discussed. This heat reservoir is considered as consisting of negative mass particles. The observed energy spectrum of the primary cosmic ray component can be explained if the following three assumptions are made: 1° the mean metagalactic densities of the negative mass particles and positive mass particles are of the same order of magnitude, 2° the constants of interaction between negative mass and positive mass particles, and the constants of interaction between positive mass and positive mass particles, are of the same order of magnitude, 3° the primary component has a metagalactic origin.

The proposed mechanism in general, may account for the acceleration of relativistic particles in regions of their higher density. It is possible that a new energetic cosmic source may operate according to this mechanism.

**SOMMAIRE.** — On discute la possibilité d'une accélération des rayons cosmiques par leur interaction avec un hypothétique réservoir de chaleur à température négative. On admet que ce réservoir serait constitué de particules de masse négative. On peut expliquer le spectre d'énergie des rayons cosmiques primaires en faisant les trois hypothèses suivantes : 1° Les densités métagalactiques moyennes des particules de masses négatives et positives sont du même ordre de grandeur. 2° Les constantes d'interaction entre particules à masse négative et particules à masse positive sont du même ordre

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de grandeur qu'entre particules à masses positives. 3° La composante primaire est d'origine métagalactique.

Le mécanisme proposé peut en général rendre compte de l'accélération des particules relativistes dans les régions où leur densité est la plus forte. Il est possible qu'une nouvelle source énergétique cosmique puisse fonctionner suivant ce mécanisme.

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Let us suppose that in the universe there exist not only particles of positive mass (plus-particles), but also particles of negative mass (minus-particles). If the law of conservation of energy and momentum and Einstein's equivalence principle are not to be violated, the minus-particles must not only possess a negative energy and non-positive rest mass, i. e.,

$$E < 0, \quad M = \frac{1}{c} \sqrt{\left(\frac{E}{c}\right)^2 - \vec{P}^2} \leq 0 \quad (1)$$

but must also have a negative gravitational mass.

If the existence of minus-particles is admitted, it is necessary to radically revise the thermodynamic laws of the Universe. Indeed, if a heat reservoir consisting of minus-particles can be realized, a thermodynamic machine of the second kind is possible, i. e., a machine which produces unlimited work at the expense of some heat reservoir which is cooled indefinitely.

Such a change in the thermodynamic laws is not entirely unexpected. In contemporary thermodynamics systems with negative temperatures are not unknown (for example spin systems in a magnetic field). Using such heat sources, devices such as the laser which can be considered a thermodynamic machine of the second kind (after its population has been inverted) has been realized in practice. In any case, the proposed violation of the second law is not as radical as the non-conservation of energy proposed by Hoyle. According to Hoyle, the first law of thermodynamics, i. e., the most fundamental law of physics can be violated. Our proposal is only a violation of the statistical law <sup>(2)</sup>.

Minus-particles must have some unusual physical properties <sup>(3)</sup>. They must repulse each other gravitationally and be attracted by large positive masses. Therefore, minus-particles tend to fill the entire cosmic space

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<sup>(2)</sup> A more detailed consideration of the possibility of macroscopic violations of thermodynamics was discussed at a theoretical seminar at New York University [1].

<sup>(3)</sup> The possible physical properties of minus-particles has been considered [2].

with approximately homogeneous density. Higher densities of minus-particles can appear only in localities where there is a large accumulation of positive mass. Minus-particles can exist in thermodynamic equilibrium only at negative absolute temperature, since the statistical integral (or the statistical sum) diverges at positive temperatures for systems of unlimited negative energy.

If the minus-particles are distributed throughout space in the above manner, they can act as heat reservoirs with negative temperature for plus-particles if there is an interaction between the two types of particles. However, according to classical thermodynamics, a thermodynamic machine perpetually producing work at the expense of such reservoirs which can undergo infinite cooling, can be realized. Consequently, the usual plus-particles will undergo an increase in mean kinetic energy as a result of collisions with minus-particles. Thus a new mechanism for the acceleration of cosmic ray particles is proposed. Let us consider this mechanism in greater detail.

Let  $f(E, \vec{r}, t)$  be the distribution function in terms of energy, space and time coordinates,  $\rho_0^+$  space density of non-relativistic plus-particles, i. e., the density of normal matter (the density of stars, planets, interstellar gas, etc),  $\rho^-$  the space density of minus-particles. A relativistic particle with energy  $E$ , will gain an amount of energy per unit time which is proportional to some fraction  $\alpha$  of its own energy, when it collides with minus-particles. Thus the mean energy will increase according to the equation

$$\frac{d\bar{E}}{dt} = \alpha\bar{E}. \tag{2}$$

It is evident that the coefficient  $\alpha$  is proportional to the density of minus-particles, the velocity of cosmic ray particles and the effective elastic collision cross-section between plus-particles and minus-particles, i. e.,

$$\alpha = C\rho^-\delta_{+-}. \tag{3}$$

On the other hand, as a result of collisions of cosmic ray particles with usual matter, their energy-space-density  $f$  function will decrease by a factor of  $\frac{1}{T}$  per unit time, where  $T$  is the mean free path time of a cosmic ray particle. It is evident that

$$T = \frac{1}{C\rho_0^+\delta_{+0}} \tag{4}$$

where  $\delta_{+0}$  is the full effective collisional cross-section of cosmic ray particles with non-relativistic particles.

The space-energetic density function  $f$  may also change as a result of ordinary diffusion of cosmic ray particles in interstellar magnetic fields.

If the three above interaction processes occur, the space-energetic diffusional equation of cosmic ray particles can be written as follows:

$$\frac{\partial f}{\partial t} - D \nabla^2 f + \frac{\partial}{\partial E} (\alpha E f) + \frac{f}{T} = Q \quad (5)$$

where  $Q$ —density of injection sources of cosmic rays and  $D$ —the coefficient of space diffusion of cosmic ray particles.

In accordance with [3-6] this equation is simplified, i. e., fluctuations in energies are neglected. However, it is sufficient to describe the acceleration mechanism which is similar to Fermi's mechanism [7].

The simplest solution of this equation is the steady-state solution, which is homogeneous in space. This solution must satisfy the equation

$$\frac{\partial}{\partial E} (\alpha E f) + \frac{f}{T} = 0, \quad (6)$$

which applies for energies higher than that of the injector. This solution has the form

$$f \sim E^{-\gamma} \quad (7)$$

where

$$\gamma = 1 + \frac{1}{\alpha T} = 1 + \frac{\delta_{+0} \rho_0^+}{\delta_{+-} \rho^-}. \quad (8)$$

It is apparent that minus-particles exist at a high mean negative temperature since the negative kinetic energy increases continually as a result of their collisions with cosmic ray particles and they cannot aggregate to form regions of high density as does usual matter. Therefore  $\rho^-$  can be considered as approximately constant for all metagalaxies <sup>(4)</sup>.

Thus, the coefficient  $\gamma$  must be minimal in intergalaxial space and must increase inside nebulae and in the vicinity of stars.

The hypothesis of the metagalactic origin of cosmic radiation, which is probable because of their isotropy, agrees with the supposition

$$\frac{\delta_{+0} \rho_0^+}{\delta_{+-} \rho^-} \cong 2, \quad (9)$$

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<sup>(4)</sup> The density of minus-particles can increase within stars, since at negative temperatures according to the Boltzmann distribution

$$\rho^- \sim \exp \left\{ -\frac{m\varphi}{kT} \right\} = \exp \left\{ -\frac{|m| \varphi}{k|T|} \right\},$$

where  $\varphi$  is the Newtonian gravitational potential.

since for the primary component of cosmic rays  $\gamma \cong 3$ . The relation (9) appears to be reasonable if it is assumed that the mean metagalactic density of plus-particles and minus-particles is about the same, and their effective cross-section  $\delta_{+0}$  and  $\delta_{-}$  are of the same order of magnitude.

If the electron and neutrino components of the primary cosmic rays have the same index  $\gamma$  as the proton components, then it is necessary to assume that minus-particles are capable of interacting with plus-particles with either strong or weak interaction. This indicates that either minus-baryons or minus-leptons exist.

In the vicinity of stars the density  $\rho_0^+$  increases and correspondingly (at a constant density  $\rho^-$ ) the index  $\gamma$  increases. In this manner, cosmic rays must be formed in the vicinity of the sun; however, their energy spectrum must decrease more rapidly than is the case for cosmic rays which are of metagalaxial origin.

The intensity of energy emission, i. e., the energy obtained by cosmic ray particles per unit time in unit volume, evidently is proportional to the density of cosmic ray particles and the coefficient  $\alpha$  multiplied by  $E$ , that is

$$\frac{\partial w}{\partial t} + \text{div } \vec{S} = \int \alpha E f dE, \quad (10)$$

where  $w$  and  $\vec{S}$  are the energy density and energy flow density of cosmic ray particles respectively.

Thus, at an approximately constant  $\alpha$  for all space region, the intensity of energy emission is proportional to the density of cosmic ray particles. Consequently, if in some region of space, for example, near supernovae, an accumulation of relativistic particles occurred, an increased emission of energy from this region will take place. It may be even greater, if minus-particles aggregate in the vicinity of high gravitational masses.

The general problem of the space distribution of cosmic ray particles and intensity of energy emission can be investigated by means of solution of the general equation (5) of the diffusion of cosmic ray particles. Magnetic fields, whose existence is necessary for the occurrence of mixing and space diffusion of cosmic ray particles, can be considered to originate as a result of energy transfer between cosmic ray particles and turbulent hydromagnetic plasma.

It is evident that the hypothesis of minus-particles also supposes the existence of additional energetic sources for non-relativistic particles; the intensity of energy emission from such sources must also increase with increasing density of the matter.

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