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On the Origin of Cosmic Rays

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The presence of heavy particles in cosmic rays makes it plausible that cosmic radiation is generated by the acceleration of charged particles in extended electromagnetic fields. The energy density of cosmic rays (3×10^{-10} Mc^2/cm^3) would lead to very great total amounts of energy if one assumes that cosmic radiation extends throughout intergalactic or throughout interstellar space. This would require very efficient methods of cosmic-ray production. It is therefore of interest to investigate the possibility that cosmic rays are generated in the vicinity of the sun and are confined to the solar system by extended magnetic fields. The strength of these fields is estimated to be 10^{-5} gauss. According to this picture, cosmic rays circulate in the neighborhood of the planetary system for thousands of years, during which time the radiation becomes isotropic. The electron component of the radiation is eliminated by collisions with solar light quanta.

DISCUSSIONS of the origin of cosmic rays have led so far to quite inconclusive results. The following note presents some considerations which may prove helpful in the search for an adequate explanation. Theories presented so far can be divided into three classes: First, the theories which explain cosmic radiation by acceleration of particles in extended electromagnetic fields; second, theories which postulate that great energies are acquired by a cosmic-ray particle in an elementary act; and third, the theories which assume that cosmic rays have been generated at the time of the origin of the universe. We shall show that of these alternatives the first one seems to be most promising, and in addition, we shall give arguments in favor of a more specific hypothesis: The origin of the cosmic rays may lie in the solar system itself.

It seems at present practically impossible definitely to disprove the theory that cosmic rays were generated at the time of the origin of the universe. Physical conditions at that time have certainly been very different from those prevailing at present. Such an explanation would probably be accepted only if good reasons were given that, under present conditions, cosmic rays cannot be produced.

The possibility that cosmic rays are produced in elementary acts has been practically disproved by the discovery[1] that among the cosmic rays there are found heavily charged nuclei. One might imagine elementary acts in which very energetic protons are produced, but it seems highly improbable that all the neutrons and protons of, for instance, a neon nucleus, should be produced or accelerated in an elementary act to an energy of two billion volts per nucleon without giving to the nucleus more than sufficient internal energy to break it up into its constituent particles.

It has been pointed out frequently[2] that electromagnetic fields on the stars, near stars, or in interstellar space may have sufficient strength and extension to accelerate individual particles to the energies observed in cosmic-ray experiments. In fact, it might seem that this process could occur so frequently and easily in the universe that there might arise some embarrassment as to what choice to make among these possibilities. There is, however, another requirement which a theory of cosmic rays must fulfill. It must explain the total energy present in cosmic radiation. This requirement indeed is quite restrictive. The cosmic rays impinging upon the earth indicate an energy density of approximately 3×10^{-10} Mc^2/cm^3, where M is the mass of the proton.[3] If we assume that cosmic rays are evenly distributed throughout all space, including intergalactic space, then the total energy in cosmic rays would be greater than any other energy known to us with the exception of the rest energy of matter.[4] Indeed, the energy represented by the cosmic rays would be approximately 10^{-4} of this rest energy. In order to account for the cosmic rays, one would then have to assume the presence of electromagnetic fields containing as much or more energy than the cosmic rays themselves. This is by no means impossible, but it is clear that such fields could not be due to any mechanism in which other known energies are transformed into electromagnetic fields, since these other energies are quantitatively insufficient for the purpose. The assumption that galaxies carry great charges, or

[1] Freier, Lofgren, Ney, Oppenheimer, Bradt, and Peters, Phys. Rev. **74**, 213 (1948); Freier, Lofgren, Ney, and Oppenheimer, Phys. Rev. **74**, 1818 (1948); H. L. Bradt and B. Peters, Phys. Rev. **74**, 1828 (1948).

[2] See for instance, W. F. Swann, Phys. Rev. **43**, 217 (1933); H. Alfvén, Zeits. f. Physik, **105**, 319 (1937).

[3] Estimated from review article by B. Rossi, Rev. Mod. Phys. **20**, 537 (1948).

[4] F. Hoyle (M. N. R. A. S. **106**, 384 (1946)) proposes that cosmic rays are produced by stars in which densities of 10^{14} g/cm^3 occur. At such a density energies comparable to the rest energy may be released. It seems remarkable, however, that this process gives rise to no other observable energies that are as great or greater than the energies contained in cosmic rays.

that electrically charged particles are accelerated by some fields due to a new type of coupling between gravitation and electricity, would hardly give an acceptable explanation. Even if one made such an assumption, the effective charge of the galaxies would have long since been neutralized.

It has been proposed[5] that the cosmic rays which are observed on the earth are confined by weak magnetic fields to the interior of galaxies. If this idea is accepted one finds that cosmic rays will be absorbed in a time short compared to the age of the universe. The main component which we observe in cosmic rays consists of protons. If the cosmic rays circulate within the galaxy then they will, from time to time, collide with other protons. These collisions lead to meson production accompanied by considerable decrease of the energy of the protons. Since the cross section of a meson production is approximately 0.02 barn, and since there is approximately one proton per cm^3 in the galaxy, the cosmic rays will have a mean free path for meson-producing collisions of about 5×10^{25} cm, or 5×10^{7} light years. This distance is of course great compared to the dimensions of the galaxy, but the cosmic rays will stay inside the galactic system, being guided by magnetic fields. The mesons produced by the cosmic rays decay into electrons and into neutral particles. There is no effective way to return the energy of these particles to the protons. Since protons constitute the main component of cosmic rays, the energy given to mesons must be considered as lost to the cosmic radiation. In order to establish an unchanging level, the energy of these cosmic rays must be renewed every 50 million years. Estimates on stellar radiation intensity inside the galaxy show[6] that approximately 10^{-4} of the energy produced in stars would suffice to compensate the energy lost by cosmic rays in meson production. It is difficult to find a mechanism by which so great a fraction of the star light is converted into energy of protons carrying more than 10^9 ev.

One may assume that the galactic magnetic field does not constrain the cosmic-ray particles to move strictly inside the galaxy, but allows the cosmic-ray orbits to extend over a volume which is a few times greater than the volume of the galaxy. In this case each cosmic-ray particle would lose energy more slowly, but a greater number of particles would be present at any given time, and the energy that has to be fed into cosmic radiation remains the same.

We have considered so far only the observed cosmic-ray spectrum which extends from 2.5×10^{9} ev toward higher energies. Cosmic rays below this lower limit may have escaped observation. In this case a great additional amount of energy may be present in the low regions of the cosmic-ray spectrum, and the energy needed for maintaining cosmic radiation would be increased.

The energy of cosmic rays may be derived from the kinetic energy of interstellar matter or of the stars. Assuming an average density of one hydrogen atom per cm^3, with an average velocity of 3×10^{6} cm/sec., one finds that approximately 10 percent of the kinetic energy is used up by keeping the cosmic rays going for 2×10^{9} years. Added low energy cosmic radiation would raise this estimate. It would seem difficult to explain such an efficient conversion of kinetic energy into high energy radiation.[7]

The difficulties mentioned above can be avoided if one assumes that cosmic rays originate in the neighborhood of the sun[8] and are kept for a protracted period within or near the solar system by an appropriate magnetic field. If one may apply Liouville's theorem and the ergodic hypothesis one would expect that an isotropic distribution of cosmic rays will be established within the region in which the radiation circulates. Deviations from an isotropic distribution would be expected (a) near the fringes of the region to which the cosmic rays are confined, or (b) if the cosmic radiation diffuses away rapidly from the neighborhood of the sun, or (c) if there exists an integral of the orbital motion of the cosmic-ray particles.

Because of (a), we have to assume that the earth lies well within the interior of the region accessible to cosmic radiation.

The point raised under (b) will be valid for most shapes of the magnetic field. We have to assume an appropriate shape of the magnetic field to prevent rapid loss of the cosmic radiation from the planetary system. A field of an appropriate shape would be, for instance, one caused by currents in the ecliptic circulating around the sun and extending throughout the planetary system. Even if such an appropriate magnetic field were established, cosmic rays could still diffuse out due to deflections by perturbing fields. This, however, need not give rise to any difficulty as long as such perturbing fields are confined to the part of the field which is closer to the sun. As long as a time-independent exterior field of appropriate shape exists, cosmic rays can

[5] H. Alfvén, Zeits. f. Physik **107**, 579 (1937).

[6] T. Dunham, Proc. Am. Phil. Soc. **81**, 277 (1939).

[7] E. Fermi (Phys. Rev. **75**, 1169 (1949)) has recently proposed a most ingenious mechanism which may furnish the required energy to the cosmic radiation. According to this proposal, cosmic radiation constitutes an essential component in the energy distribution within the galaxy, and the mechanism regulating the intensity of cosmic rays is based upon the balancing of the various forms of energy. Difficulties connected with the presence in cosmic radiation of nuclei carrying more than one charge give rise to some doubt whether or not Fermi's proposal is the correct explanation of cosmic rays. We are indebted to Professor Fermi for discussions of his paper and of the present note.

[8] The solar origin of cosmic rays has been proposed by M. A. Dauvillier, J. de phys. et rad. **5**, 640 (1934); and by D. H. Menzel and W. W. Salisbury, Nucleonics **2**, 67 (1948).

be confined for long periods of time. Such an effective confinement of the cosmic rays is necessary, not only to explain the isotropy, but also in order to explain the intensity of the radiation.

An integral of motion, as mentioned in (c), will exist if the magnetic field in which the cosmic rays circulate has strict axial symmetry. In this case an axially symmetrical vector-potential $\mathbf{A}$ may be introduced, and the vector $\mathbf{r}\times(m\mathbf{v}+(e/c)\mathbf{A})$, has a constant component along the axis of symmetry. This component, which is known as the Störmer integral, is the appropriate generalization of the angular momentum. It seems likely that axial symmetry is not fulfilled so rigorously as to insure the constancy of this integral for a protracted time. Thus we find no conclusive argument against an isotropic distribution of cosmic rays.

The intensity of the magnetic field which keeps the cosmic rays within or near to the planetary system can be estimated as follows: The most energetic singly charged particles observed in the cosmic rays have an energy of 10^{14} ev. (The Auger showers may be caused by heavier nuclei.) If we want to confine these particles to a region of the dimensions 3×10^{17} cm we need a field of 10^{-6} gauss. This distance is equal to a third of a light-year. Thus fields weaker than 10^{-6} gauss could hardly confine all cosmic rays to the neighborhood of the sun. On the other hand, a field of more than 10^{-4} gauss would have been discovered in the investigations of geomagnetism. Thus we are forced to introduce a field approximately equal to 10^{-5} gauss.

If we assume that all cosmic rays produced near the sun will eventually impinge upon the earth, one finds that less than 10^{-17} of the solar radiation will suffice to maintain the cosmic radiation. It is clear that other planets will serve as sinks of the cosmic rays. Meson-producing collisions could consume some of the energy of the cosmic rays. Collision of cosmic rays with the sun may be prevented or greatly reduced by the solar magnetic field. In any case it will be unnecessary to convert a considerable fraction of the solar energy into cosmic rays. Thus it will be less difficult to find an appropriate mechanism for producing cosmic rays.

The lifetime of a cosmic ray will vary according to the extension of its orbit. If the orbit is comparable to the distance from the sun to the earth, the cosmic ray is likely to collide with the earth in a time somewhat longer than a thousand years. In orbits of greater extension, cosmic rays may circulate for a longer time. In no case can we expect them to live much longer than about 5×10^{7} years, which is the lifetime of fast protons circulating in the galaxy.

According to the calculations of Feenberg and Primakoff,[9] electrons of cosmic-ray energies circulating near the earth's orbit will lose their energy in less than 100 years due to Compton collisions with solar light quanta. We should, therefore, not expect a strong electron component in cosmic rays. Protons and heavier nuclei will be unaffected by sunlight. Indeed, the upper limit of the proton energies is probably given by the escape from the solar system rather than by the results of Compton collisions.

The assumption that cosmic rays are essentially confined to our planetary system leads to a few conclusions which can be checked by cosmic-ray experiments. Among these are:

(1) No protons greatly in excess of 10^{14} ev and no particles greatly in excess of 10^{16} ev are to be expected. Such particles cannot be confined to the neighborhood of the planetary system.

(2) It is likely that particles of lower energy than 2.5×10^{9} ev will be found. To confine cosmic rays to the planetary system, but not to allow them to approach the sun closer than the earth's orbit, would indeed require rather artificial assumptions about the shape of the magnetic lines of force. It should be noted that the sun's dipole gives rise to a field of less than 10^{-5} gauss near the earth.

(3) The cosmic-ray intensity should not depend on the angle included by the cosmic ray and the velocity vector of the solar system with respect to the galaxy. Thus there should be no Compton-Getting effect.[10]

(4) There is no striking reason for different laws of acceleration of protons and heavier nuclei. These particles may be found in cosmic rays with approximately the same abundance ratio as they are found elsewhere in the planetary system. The spectra of the protons and of the heavy nuclei may be similar.

Summarizing the above discussion, we suggest that the energy of cosmic rays is derived from the most plentiful energy source in our neighborhood, the sun. We introduce a magnetic field of about 10^{-5} gauss which extends throughout and beyond the planetary system. This field serves to convert the cosmic rays into isotropic radiation. The long circulation periods in this field (10^{3}–10^{8} years) also explain why the cosmic-ray intensity does not show long-period fluctuations connected, for instance, with the sun-spot cycle. Finally, the magnetic field helps to keep the cosmic-ray intensity at a high level. In the following paper, H. Alfvén presents a plausible explanation of this magnetic field. He also describes a possible mechanism for the acceleration of charged particles near the sun.

If our ideas are correct, the expression "cosmic rays" is a misnomer. We wonder to what extent this name has hindered discussion of the solar origin of this radiation.

We are indebted to Professor Fermi for discussions and criticism. The value of these is the greater because of the necessarily speculative character of the views presented here.

[9] E. Feenberg and H. Primakoff, Phys. Rev. **73**, 449 (1948).

[10] A. H. Compton and J. A. Getting, Phys. Rev. **47**, 817 (1935). The effect is small and is hard to establish. Evidence in favor of the effect (and therefore in contradiction to our views) was given by J. Barnóthy and M. Forró, Nature **193**, 1064 (1937).