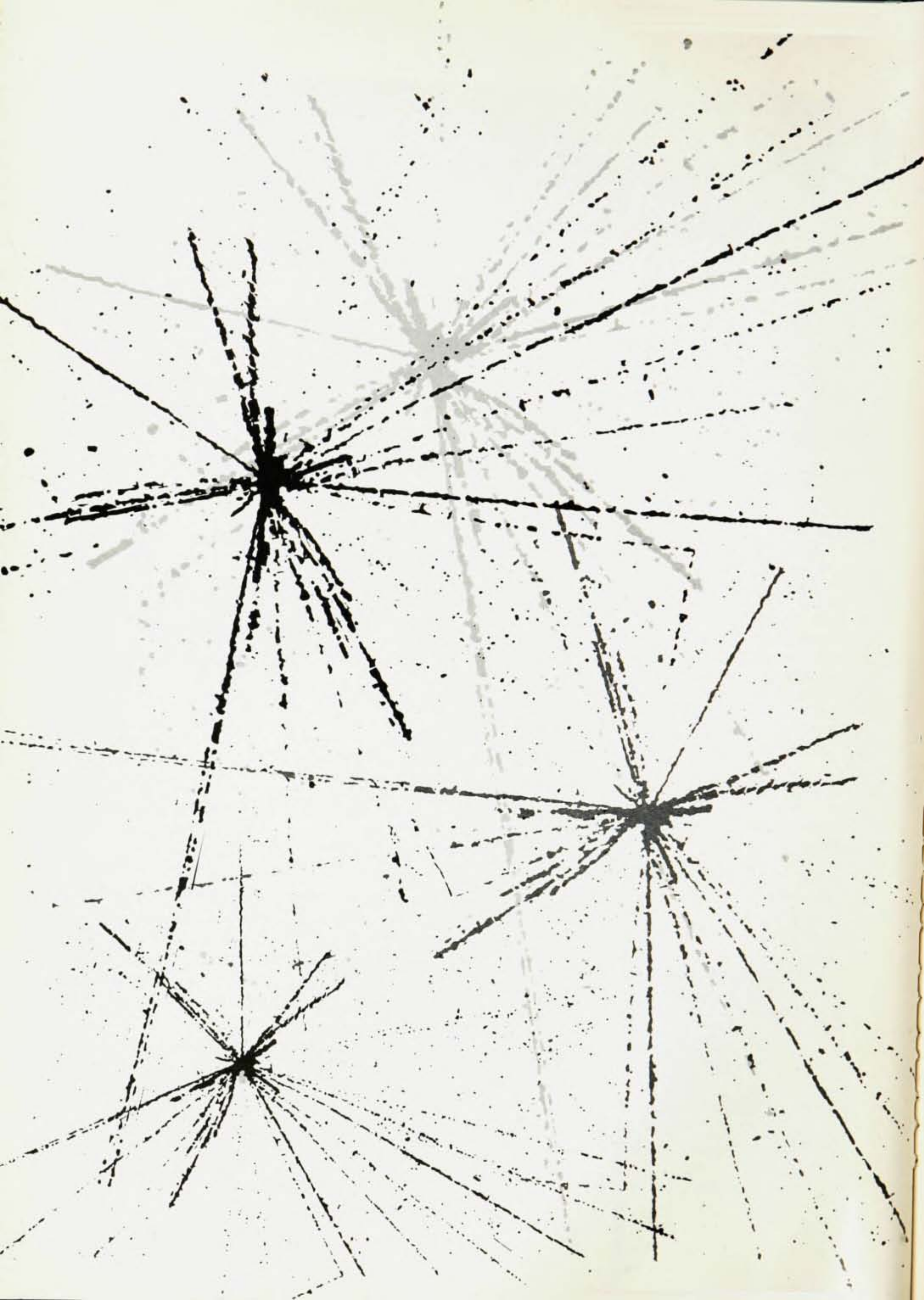

THE GENESIS OF COSMIC RADIATION

Are cosmic rays really cosmic, pervading all space; or are they limited to galaxies such as our Milky Way; or do they originate within the solar system? In the August, 1949 issue of Physics Today, Edward Teller favored the latter theory; the author of the present article surveys the situation and comes to a different conclusion.

by ***Serge A. Korff***

The total energies involved in cosmic radiation are so large, individually and collectively, that however they are generated the process or processes involved certainly are basic to the total structure of the universe. Moreover, since some of the hypotheses suggest experimental tests, the speculation on the origin of cosmic radiation has been extremely beneficial to the progress of physics. The speculations exhibit an exciting variety and give full play to imaginative thinking which, nevertheless, must be limited by experimental facts and by reasonable conjectures based on experimental facts.

The physicists and astronomers both pour their work into a reservoir of pertinent data. On the part of physics, it is today believed that primary cosmic radiation consists mostly of protons and some heavier nuclei, with an energy spectrum lying between 10^9 and 10^{16} electron volts, possibly extending beyond both figures, but mainly concentrated in the region of 10^9 to 10^{11} volts. An energy-distribution of approximately the -1.8 power is thought to apply to practically the entire spectrum, so that the rays carrying extremely high energy are very rare. Furthermore the variations in time are extremely slight, and the radiation seems to have quite uniform directional isotropy. Thus the earth is apparently imbedded in a gas of radiation, with the rays coming to us at all times and from all directions.

While it is true that the earth's magnetic field tends to deflect the less energetic rays and produces a latitude effect, there is no evidence that at distances of a few earth radii there is any inhomogeneity. This uniformity with time and direction, and the absence of significant correlations with solar time, may be regarded as arguing against the sun as a source of any appreciable fraction of the radiation. One may therefore arrive at the conclusion that the rays are indeed cosmic, and that one must seek their origin in distant places.

Comparing Energies

It is important here to review the astronomical picture, which involves some arithmetic at the very least. The purpose of the review is to compare the distribution of energy in the universe as the astronomer conceives it, with the energies of cosmic radiation as the physicist measures it with the aid of rockets, balloons, planes, and mountain laboratories. Our solar system is situated in a galaxy of stars which we see as the Milky Way. This galaxy is shaped more or less like a fried egg, some 5×10^4 light years across (1 light year is 10^{18} cms) with a central condensation and with a less dense dis-

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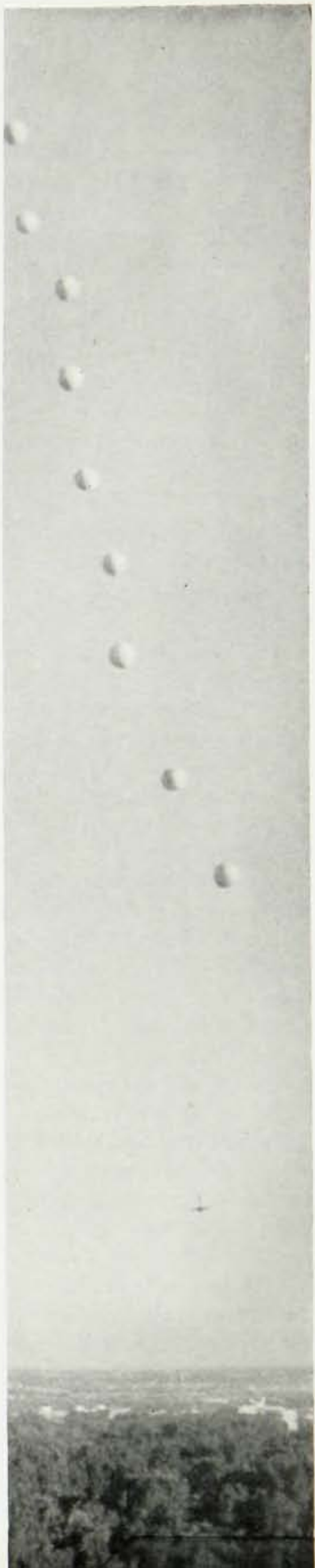
tribution of matter in the plane surrounding it. The solar system is somewhere out in this plane and not in the central condensation. There are many other such galaxies, or spiral nebulae, the nearest being that of Andromeda, which is almost 10^6 light years distant. The distribution of these nebulae appears to be uniform, as far as our telescopes have been able to penetrate. Between the galaxies space is very empty, and contains very few stars or diffuse matter.

In computing the energy of a system, one simply adds all the kinds of energy, including mass-energy of its matter and the kinetic energy of its matter in motion. Our galaxy contains about 30×10^9 stars, with average masses of 2×10^{33} grams each. In addition there is a considerable amount of diffuse matter. Plaskett estimates the total mass of the galaxy at 3.27×10^{44} grams. The total mass-energy in our galaxy is therefore, from $e = mc^2$, this figure times c^2, or 2.95×10^{65} ergs. Its volume is of the order of 10^{68} cc. (This last figure is closer to the cube of the radius than to the spherical volume because of the flattened shape of the galaxy.) The density of matter in the galaxy is therefore, on the average, 10^{-24} grams per cc, and the mass-energy density is 3×10^{-3} erg per cc.

The galaxy is in rotational motion, and all the stars have high average velocities. These velocities average about 10^8 cm per sec., and the kinetic energy of the stars in the galaxy is 1.6×10^{60} ergs. The energy density of the kinetic energy of the galaxy is therefore 1.6×10^{-8} erg per cc.

All the visible stars radiate, by definition. The electromagnetic radiation is about what one would expect from bodies with temperatures between 2,500 and 25,000 degrees K. Most of this radiation lies in the visible region of the spectrum, with a fraction known by appropriate detecting techniques to be in the ultraviolet and infrared. The total radiant energy in the galaxy was estimated some time ago, by multiplying the amount of radiation received from each star by the number of stars known to be in that spectral type. The total radiant energy turns out to be 1.78×10^{-3} erg per sq. cm per sec. received at the earth, or (dividing by c) 5.8×10^{-14} erg per cc. The flux from all known nebulae is two orders of magnitude less, so the density of radiant energy emitted by the entire known universe is roughly 6×10^{-16} erg per cc.

The galaxies are distributed with mean spacings



Cosmic ray balloon flight taking off from Denver, Colorado. Apparatus is the plane-shaped speck some distance below the balloons. The Rockies are in the distance and the University buildings in the foreground. Photo by Korff of 10^{24} cms. They may be considered as being located at about a hundred radii from each other (the radius of our own galaxy is larger than the average). In terms of volume, the dilution factor is thus 10^{-6}. Any figure (except of course the radiation from nebulae) which we have cited as applying to our galaxy may be diluted by this factor when applied to intergalactic space. For example the mass-energy-density of all matter in the universe will be roughly 3×10^{-9} ergs per cc.

We are now ready to fit cosmic radiation into this picture. To compute the total energy in the form of cosmic radiation arriving at the earth, we may either multiply the flux of cosmic ray particles by the average energy of each, or follow the procedure, indicated twenty-five years ago by Millikan, of integrating the total energy under the ionization-vs-depth curve. In either case we arrive at the figure of 3×10^{-3} erg per sq. cm per sec. reaching the surface of the earth, or an energy density of around 10^{-13} erg per cc.

Thus we see that the total energy of cosmic radiation is more than the entire luminous output of all the stars and nebulae in the universe put together. This quite spectacular conclusion was drawn by Millikan in 1925, and was again emphasized by Korff in 1933 when the total radiant energy in the galaxy was computed. Yet it has not, until recently, been seriously considered by many physicists. It was this situation which led Teller to propose the sun as a source of cosmic radiation, suggesting that we have measured cosmic ray energies in a region of high concentration, which would mean the average for the galaxy or for the universe as a whole would be much less.

In view of the great energies, however, it is now most important to consider the possible mechanisms by which cosmic rays may be produced. It is clear that whatever the process, it operates on a grand scale and competes favorably with the luminous energy-generation in stars. Indeed the cosmic ray generator may be capable of producing even greater total energies.

Cosmic Generators

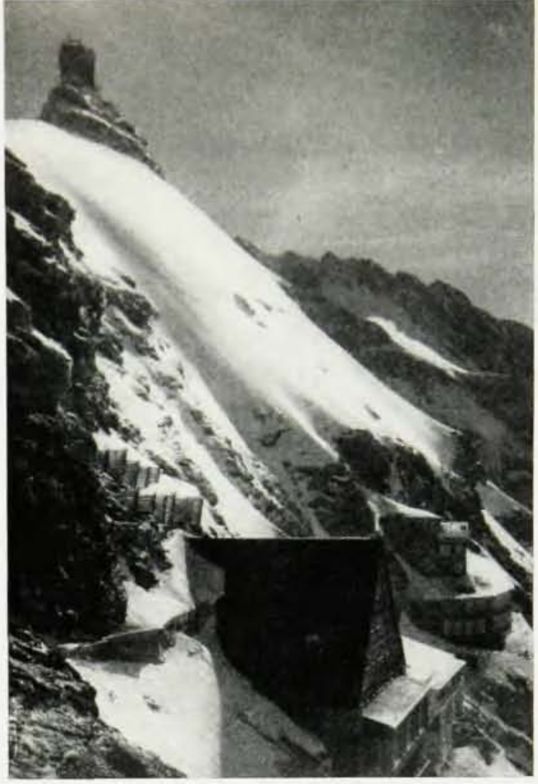
The possible modes of generating particles with cosmic ray energies, may be divided into microscopic and macroscopic processes where, by microscopic, we mean processes connected with individual atoms, and by macroscopic those occurring over appreciable spaces.

The microscopic processes do not appear to offer much hope for an explanation. The annihilation energy of a proton is about 10^{9} electron volts. Whereas no mechanism is today known by which this annihilation may be effected, proton annihilation is a perfectly proper subject for speculation. Heavier nuclei will have proportionally higher annihilation-energies, up to over 2×10^{11} volts for the heaviest. This, however, would set an upper limit to cosmic ray energies which is far too low. It would further require that nuclear annihilation would give rise to fast protons, whereas it is well known that electron annihilation gives rise to gamma rays and symmetry suggests that proton annihilation would do likewise.

In order to obtain still higher energies by microscopic processes, it is necessary to postulate that many nuclei are simultaneously annihilated, and that the entire energy of all these annihilations is somehow transferred to one nucleon. Since such a mechanism is not in accord with our present picture of physics, it is generally conceded that microscopic processes must be abandoned as a possible source of the full range of cosmic ray energies and the explanation sought elsewhere.

Let us now review some macroscopic processes. Acceleration of charged particles by electric and magnetic fields is possible. Because of large distances, only small fields are needed. Thus for example, over 10^{20} cms, an electric field of 10^{-9} volt per cm would suffice to produce the entire low-energy part of the cosmic ray spectrum. However, space is empty, and if such fields existed, charges would very quickly move in such a way as to neutralize them. In other words, space is a good conductor. For long-time stability, space must be essentially neutral. Electric fields must probably be abandoned as possible sources of this great energy.

With a magnetic field, the situation is different. In this case, what is required is a magnetic field which varies with time, and charged particles would be accelerated by the betatron effect. There are two possible places where one may seek such varying fields. The first is in stars, and the second is the galactic field. In stars, there are two known kinds of fields, those associated with sunspots, and secondly, the general field of the star as a whole. It is known that, in the case of the sun, a large sunspot may develop in a day or two and during this time



Jungfraujoch observatory and high altitude laboratory in Switzerland. The meteorological observatory of the Sphinx (upper left) is at 11,700 feet. The cosmic ray laboratory is at 11,400 feet. In the foreground can be seen the Berghaus Hotel. Photo by Korff

may build up a field from a few gauss to perhaps 5,000 gauss. Such a time-rate-of-change of a field will suffice to build up the lower end of the cosmic ray spectrum. As Swann has pointed out some fifteen years ago, it is not unreasonable to suppose that on larger stars, larger spots may exist, and these may produce the higher energy portion of the spectrum.

The general field of the sun itself is small, perhaps only 50 gauss or less, certainly not more, and seems to have no large time-derivative. But recently Babcock has discovered some stars with very large and rapidly varying general fields. Some of these are many thousand gauss, and vary from one sign to the other in a few days. Such variations could certainly produce cosmic ray energies. Further, there are many magnetic binary stars, and if one considers a point in space nearby, the net magnetic vector due to the two stars will show time variations. This mechanism has been invoked by Alfven, who over the past two decades has computed a number of possible arrangements and cases. Thus there appears to be no shortage of possible mechanisms whereby cosmic ray energies can be generated.

When, however, we consider total intensities, we find an embarrassing situation. If we assume that one percent of all the stars are rotating magnetic doubles, one finds that to produce the total of cosmic ray energies one will have to use up all the rotational kinetic energy of these stars very fast indeed. Such a process would obviously be rapidly self-terminating. If one assumes that sunspots or star-spots are very usual, then one is still left with the difficulty that the total energy is so big that the spots would have to emit more energy than the bright radiating surface, a situation which, at least for the sun, is not the case.

One then comes to the galactic magnetic field. Here we are on much less certain ground, for there is a lot about the galaxy that astronomers do not yet know. It seems reasonable to suppose that a portion of the diffuse material in the galaxy is photoionized by the bright stars nearby. Since the entire galaxy is in rotational motion this charged matter revolving in a curved path will set up a galactic magnetic field. Clouds of ionized diffuse matter passing by each other, or occasionally colliding, will certainly set up fields with time-variations which could generate the requisite high energies. Moreover, since this process had the entire rotational kinetic energy of the galaxy to draw upon, it could, without depleting itself too fast, supply the total energy. Galactic fields have been discussed for twenty years. Recently Fermi has calculated one possible situation, on this basis, which is entirely credible and which may indeed be an answer to a part of this problem. However, no experimental test has yet been proposed which is capable of deciding whether any such process exists at all.

Possible Origins

To summarize the situation as regards energy-density, the amount of cosmic ray energy arriving at the earth somewhat exceeds the total luminous energy arriving from all the stars and nebulae in the universe. Now this cosmic ray energy may be local, arising from the sun, as considered by early investigators or more recently by Teller; or it may be galactic, on a scale generated by and trapped in our own galaxy; or it may be truly intergalactic, pervading all space. Each possibility has its enthusiastic champions, but as yet no conclusive experimental test has been proposed.

The trapping mechanism for cosmic rays of local origin would be local magnetic fields; for cosmic rays of galactic origin a galactic field; and for cosmic rays of intergalactic origin, which do not require trapping, an upper limit can be computed for galactic and local fields. For generating processes, local origin represents no especial problem because cosmic radiation is but a tiny fraction of solar radiation; galactic origin would involve a galactic dynamo; and uniform intergalactic distribution implies that cosmic radiation is the preponderant energy of the universe.

About the generators we can say that the sun could, from the known spot fields and other features, supply the low-energy part of the radiation. But in this case we have two difficulties, first the high-energy part of the spectrum, and second the lack of marked solar-time dependence. If the high-energy part of the spectrum is produced elsewhere, is it a coincidence that it fits smoothly on to the local part with no joint detected thus far? The time and directional isotropy is attributed to a local field; but this field must be large enough to scramble the rays thoroughly and not large enough to be detected. Numbers attached to these two possibilities do not yield a picture which anyone other than an enthusiast would believe. For a solar field of 10^{-5} gauss at a distance of the earth's radius could be detected on the earth; yet a field of 10^{-6} gauss would only trap particles of one or two billion electron volts. And since the field of a dipole falls off as the inverse cube of the radius, the sun's general field will be quite negligible at great distances. One must then invoke fields produced by streams of particles, as considered by Alfven, and one must assume that there are enough of these everywhere and at all times to complete the isotropic mixing; yet how can this be done without having much more matter in space than is known to be there?

The galactic generation hypothesis is much more hopeful. It permits a greater range in assumed variables and more reasonable assumptions. If true, it suggests the energy-density of cosmic radiation is characteristic of the galaxy but not of intergalactic space. Therefore it requires a total energy for which known sources will suffice.

The third alternative, that cosmic rays are truly intergalactic, requires very large total energies. These could be generated by intergalactic fields or by the explosion we shall discuss next. Any magnetic field is also a trap for charged particle radiation. If a field with a time-derivative is invoked as a generator, this same field will hold within itself any particles whose radius of curvature in this field is less than the physical dimensions of the field. Thus it might happen that the low-energy part of the radiation, say that below 10^{13} volts, is galactic in origin and is trapped, while the high-energy part is cosmic. In this case again we shall have the uniformity of the energy spectrum to explain. But if all the cosmic radiation arriving at the earth is galactic then we must have a galactic field capable of holding a particle of 10^{16} volts, which again poses a serious difficulty.

Finally, we come to the intriguing hypothesis put forward by Lemaître. He has suggested that the cosmic radiation is radiation left over from the original explosion in which the present universe was formed. There can be no question that during this explosion a fantastically great amount of radiation was formed, with the highest individual energies now known, and possibly much more. Certainly protons and other nuclei were shot out in all directions, with all energies, and in sufficient numbers.

Such protons would then have been circulating in the universe for the requisite time, a few times 10^{9} years. During this time a fraction of the radiation would have disappeared by absorption. But if one takes the mean effective absorbing area of a galaxy as 10^{42} sq. cms, and the mean separation of galaxies as 10^{24} cms, the classical mean free path of a particle in the universe will be many times the probable radius of the universe, and the mean free time before it will collide with a galaxy and be absorbed will be more than the necessary billions of years. In the early days of the universe, when it was much smaller, absorption played an important part; but after the first 10^{8} years, it has been negligible. Thus it could be possible that Lemaître is right, and that cosmic rays are indeed fossil radiation left over from the largest nuclear explosion of all time.

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