Cosmic radiation striking the earth is thought by some to come from the depths of outer space and by others to originate in the sun. The present article describes a theory in which both ideas may in part prove valid.

NEW LIGHT on

By Arthur Beiser

THE problem of the origin of the cosmic radiation has provoked much controversy in recent years. The proponents of a literally cosmic origin (see, for example, the article by Serge A. Korff in *Physics Today*, January, 1950) survey the properties of this radiation and what is known of the universe and conclude that the cosmic rays must be either the product of some interstellar mechanism or energetic particles "left over" from the creation of the universe itself. Those who favor the hypothesis of the origination of cosmic rays within the solar system (Edward Teller, *Physics Today*, August, 1949), on the basis of much the same empirical information, arrive at a considerably different result. As is frequently the case when two apparently opposing points of view, both expounded with equally convincing logic, are held on a problem, the actual solution as it appears today seems to combine important features of both.

Before the most recent ideas on cosmic-ray origin can be properly discussed, it is necessary that some of the experimental discoveries made since the time the above-mentioned articles were written be considered. The ones most pertinent concern the so-called "heavy primaries", atomic nuclei incident with high energies upon the earth. These particles have been studied mainly by research groups at the Universities of Rochester and Minnesota, using photographic emulsions flown to great altitudes by plastic balloons. The charges of the nuclei, i.e., their atomic numbers, may be evaluated from the tracks they leave in the emulsions, the values being determined from the grain densities of the tracks or, for nuclei of high atomic number, the frequency of occurrence of knock-on electrons. The relative abundances of the elements involved have been found to parallel closely those present in the universe generally, as determined spectroscopically from the sun and stars and by chemical analysis of meteorites. Such elements as hydrogen, helium, carbon, oxygen, etc. predominate in both cases, with the meagre abundances of lithium (atomic no. 3), beryllium (atomic no. 4) and boron (atomic no. 5) in the universe being duplicated by corresponding scarcities in cosmic radiation.

The significance of this latter point, the low abundances of lithium, beryllium, and boron, has been pointed out by Bradt and Peters of the University of Rochester. These elements are known to be very often produced as fragments in energetic collisions between heavy nuclei and other atoms, such as may be expected to occur frequently in the cosmic radiation if it must pass through matter before reaching the earth.

The Origin of the Heavy Primaries

The nuclei, if originating in the sun, will, in covering the comparatively short distance to the earth, not encounter sufficient matter to alter significantly their initial atomic number distribution by means of collision processes. However, in traversing the enormously greater distances encountered in interstellar space, where there is an average density of about one atom per cubic centimeter, an entirely different situation will be present, with the abundance of the lighter elements rivalling if not actually exceeding in magnitude that of the heavier ones. Since this is not observed to occur, it is necessary to conclude that the heavy primaries observed in cosmic rays probably have their origin in some very near source, most likely the sun.

This conclusion is greatly substantiated by the diurnal variation in the intensity of the heavy primaries observed by Lord and Schein. They find that the number of such primaries entering the earth's atmosphere during the day is approximately 2.5 times the number entering at night, a difference explainable only in terms of a solar origin when the particle energies are taken into account. The presence of an appreciable number of the nuclei at night may be interpreted on the basis of the existence of magnetic fields in the solar system sufficient to "scramble" them, while nevertheless too weak to be measured directly by the terrestrial observers. These fields have already been proposed by several

he ORIGIN OF COSMIC RAY

physicists in connection with theories of the solar origin of the entire cosmic radiation. It may be noted that the magnetic intensities required to overcome entirely any diurnal effect in the entire radiation if due to solar origin, which almost certainly must be of such magnitude as to assure detection on the earth, need not be invoked to account for the existence of heavy primaries entering at night.

Do all cosmic rays originate in the sun? What has been said concerning the heavy primaries implies a solar source, but is there any justification for extending this origin to cover all of the incident particles? On the basis of the evidence at hand a negative answer to these questions is indicated.

There are a number of convincing reasons behind this conclusion. Foremost among them are the quite enormous energies associated with the primary cosmic rays, with the known energy spectrum extending up as high as 10^{16} electron volts and perhaps higher still. It must be mentioned that protons make up by far the most numerous component of cosmic rays, their frequency of occurrences being about a thousand times that of the heavy nuclei, and it is with them that the high energies and directional isotropy are associated. If the protons originate in the sun, for them to have the uniform distribution with respect to the earth that they do would require magnetic fields within the solar system more than sufficient to assure a similar distribution for the heavy nuclei, which have a more pronounced interaction with magnetic fields than protons due to their higher charge. The importance of the occurrence of the diurnal effect only in the heavy nuclei is twofold: it confirms a solar origin for these particles while at the same time rendering virtually untenable a similar origin for the remainder of the cosmic radiation. In addition, the existing theories of solar origin require that the particles circulate in the solar system for many thousands of years before collision with the earth in order for the observed energies to be built up. However, times sufficient for this purpose would, as has been indicated above, alter the relative abundances of the nuclei involved while a much smaller transit time would not.

The Origin of the Proton Component

Many possible "cosmic" generation mechanisms have been suggested, none of them as yet adequate to explain completely all aspects of the experimental data. The theory originated by Enrico Fermi seems in a number of ways to be the most plausible yet presented.

Fermi's theory is predicated upon the existence of wandering magnetic clouds in space, as proposed by the Swedish physicist Alfvén. These are thought to be the result of a coupling between the magnetic field carried by interstellar matter and the streaming motion through space of the matter itself. The kinetic energy of this motion will be partially transformed into magnetic energy, this effect being caused by the ordering of the initially random magnetic lines of force and the increasing of their density. When the two energies are of roughly the same magnitude an equilibrium condition will result in which neither can gain any further at the expense of the other. The internal friction in such a moving magnetic cloud of matter, which would ultimately reduce the streaming motion to zero, will be diminished because of the self-perpetuating action of the equilibrium. This will occur since any motion of the particles of the cloud which tends to bring them together would have the effect of constricting the lines of force and so increase the magnetic energy present, this action being counteracted by the opposition of the lines of force to such closer contact. The equilibrium will thus serve to maintain the clouds indefinitely in their motion through interstellar space. The velocities of these clouds are thought to be of the order of 30 kilometers per second, and the intensities of the fields

---

Arthur Beiser is a graduate physicist at the University Heights campus of New York University. A member of the NYU cosmic ray research group, he is currently working on studies of the diurnal effect in various components of the cosmic radiation.

associated with them are estimated to be about 5×10^{-6} gauss for the more dilute clouds and probably higher for the more dense ones.

The existence of these wandering magnetic fields has received considerable support from the discovery that starlight is polarized when it passes through dust clouds in space. The polarization could only occur if the clouds have associated with them magnetic fields, as predicted by Alfven's theory. It is now possible to picture the acceleration of cosmic rays by interaction with these interstellar magnetic fields.

A fast charged particle moving through one of these fields will spiral around the lines of force, continuing along them until it meets with an irregularity in the field. It will thereupon suffer a deflection, either gaining or losing energy in the process depending upon whether the velocities of the irregularity and the particle are directed in the opposite or in similar senses. This effect may be pictured as a collision between the particle and an irregularly moving massive reflecting body, with a head-on collision increasing the energy of the particle and an overtaking collision decreasing this energy. The net energy change over a number of such interactions can be shown to be in the direction of an increase by a very simple argument: since the particles suffer many random encounters with the cloud irregularities, whose energies greatly exceed their own, by the principle of the equipartition of energy the particles will on the average tend to gain at the expense of the cloud energies. The mean gain per collision turns out to be B^2w, where B is the velocity of the cloud divided by the velocity of light and w is the total energy of the particle, including its rest energy mc^2. For a proton the mean increase per collision is about 10 electron volts at first, and, of course, this becomes larger with each succeeding collision.

Particle Injection

It is evident that the initial energies of the particles must exceed a certain minimum, so that they can gain energy after a number of collisions without undergoing too great an ionization loss before the gain mechanism predominates. Such a minimum does not exist for electrons, whose energy loss by ionization of the matter they pass through in space (and, at higher energies, by radiation) will always exceed that which can be imparted by magnetic clouds. The absence of a primary electron component in cosmic radiation is a natural consequence of this fact. For protons the energy gain will exceed the loss above 200 Mev, which is therefore the minimum injection energy for these particles. With heavier nuclei much greater values are required, ranging from about one billion electron volts for helium nuclei (alpha particles) to 300 Bev for iron nuclei.

Not only is a relatively low injection energy needed for protons, but a regeneration process in space is probable, which, according to Fermi, should be responsible for many of the total number of cosmic-ray protons. This would consist of collisions between fast protons and other nuclei, producing as a result more than one proton with the minimum injection energy. Of course, depending upon the energy of the proton and the weight of the nucleus involved, this will not always be the case, but Fermi believes that sufficient new protons will be produced in this way to maintain the amount of cosmic radiation constant in space.

Proton Source

The number of protons in cosmic rays in each energy interval may be found from Fermi's theory to have an exponential form, with the number decreasing with increased energies. This is in agreement with experimental observations on the energy spectrum of incident protons. Chang-Yun Fan (University of Chicago) has found that this spectrum will depend upon the location of the source of the protons, i.e., upon the place of their injection. Hence a comparison of the results of various assumed positions with the observed spectrum will indicate the approximate probable source of the protons. This turns out to be the nucleus of our galaxy, the central concentrated region of stars in the "island universe" in which the sun occupies a place about one-third of the distance to its periphery. This region is not only at the necessary distance from the earth but also approximates the condition of being a point source of particles, rather than an extended one.

It is thought very likely that individual stars can eject protons having sufficient energy for subsequent acceleration by Fermi's mechanism. The presence of heavy nuclei originating in the sun need not require the postulation of a source of the enormous energies necessary for their injection into magnetic clouds. Protons, requiring less initial energy, would then circulate through space acquiring the tremendous energies associated with them in cosmic rays. Since the average rate of energy increase of these protons may be calculated, it is possible to estimate the minimum age of our galaxy from the highest energies that have been discovered. This will be true if, as seems certain, both the magnetic clouds and the protons are confined to our galaxy by magnetic fields associated with the galaxy itself. This minimum age turns out to be roughly two billion years, which is of the same order of magnitude as the most usual figure for the age of the universe, three billion years.

The foregoing covers the salient aspects of what seems to be the most promising recent theory of proton origin and correlates it with the probable origin of the heavy primaries. According to these ideas, both the "cosmic" and solar hypotheses have validity, although they each describe only part of the total picture. While there still remain details which must be clarified, the bulk of experimental evidence is in their favor. It must be remembered, however, that the complete explanation of every feature of cosmic radiation, in the earth's atmosphere as well as in space, is far from realization, and that there is still much room in this field for original and inquiring minds to do creative work.