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The origin and implications of the cosmic radiation

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Cosmic Rays have been known for about half a century [1]. The fact that we are only today beginning to understand some of the problems associated with them indicates the order of magnitude of the complexity of the problem, and the degree to which we were dealing with phenomena with which we had little familiarity. Our opinions have gone through a series of changes as we have slowly realized the true nature of the factors involved. For example, in the early 1920's the general opinion about cosmic rays was that they were of the nature of gamma rays, of some hundreds of Mev's in energy, and that most of the secondary particles at sea level were electrons. Contrast this with the fact that it has been proved that the majority of primary cosmic rays are protons, with energies tens to thousands of times the previous hundreds of Mev's, and that the secondary particles reaching sea level are mostly mesons. We see then just how revolutionary has been the change of view which modern detection techniques have made possible.

It is the purpose of this article to review our present thoughts about the radiation, about the mechanisms operating to produce it, and about the interesting astrophysical implications suggested by its presence. Further, we are today on the threshold of a new era in which we shall see important developments that follow from the use of the radiation as a tool of geophysical investigation. In this discussion we use the word «Geophysical» in its broadest sense, to include not only the science of our earth, but also the many fascinating, important, and complex solarterrestrial relationhips.

Review of Known Facts

Any acceptable theory of the origin of the radiation must explain the main features which characterize the cosmic rays. We shall briefly recapitulate these and indicate how each was determined. In so doing we have the great advantage of hindsight, and need not follow developments chronologically. Briefly, an acceptable theory must provide a mechanism which will generate radiation within the following characteristics.

First, the composition of the radiation. We know today that the primary radiation reaching the earth is, by number, mostly

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protons. A smaller number of alpha particles is also present, and a numerically much smaller number of heavy nuclei. The exact percentages are still being disputed by the experts, and differences of opinion exist. To quote a figure, for the purposes of this article, and with which some experts will disagree, most experts consider that the primary radiation is by number, 70 % to 90 % protons, 29 % to 9 % alpha particles, and somewhat under 1 % heavy nuclei. The primary radiation contains few, if any, electrons or photons. By definition, it cannot contain unstable particles, such as neutrons or mesons, for these would have decayed in flight. Neutrons might reach the earth from the sun, but not from outside the solar system.

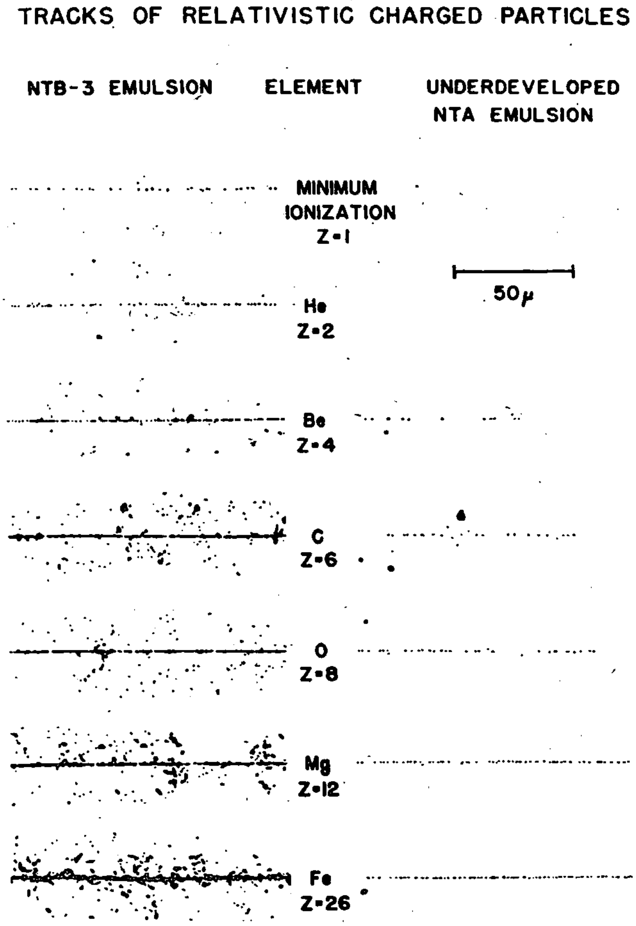


Fig. 1. Typical tracks in photographic emulsions made by protons, alpha particles and heavier nuclei. The photograph shows how the tracks appear, and how the various constituents of the primary radiation may be distinguished from one another. Much of our knowledge of the composition of the primary radiation derives from plates flown at balloon altitudes.
Photo courtesy M. F. Kaplon, University of Rochester. For other photos of heavy primaries and nuclear disintegrations produced by them, see: H. Bradt and B. Peters, *Phys. Rev.*, *76*, 156 (1949); Kaplon, Peters, and Bradt, *Phys Rev.*, *76*, 1735 (1949); Bradt and Peters, *P. R.*, *75*, 1779 (1949) and *74*, 1828 (1948).

The data cited above on the identity of the primaries are secured principally through the use of photographic emulsions. These emulsions are flown to great heights in balloons, and, when recovered and, developed, show tracks which can be identified and counted. The presence of heavy nuclei in the primary radiation was discovered by those emulsions. Figure 1 shows a typical emulsion track of a heavy cosmic ray primary.

Second, the energy of the radiation.

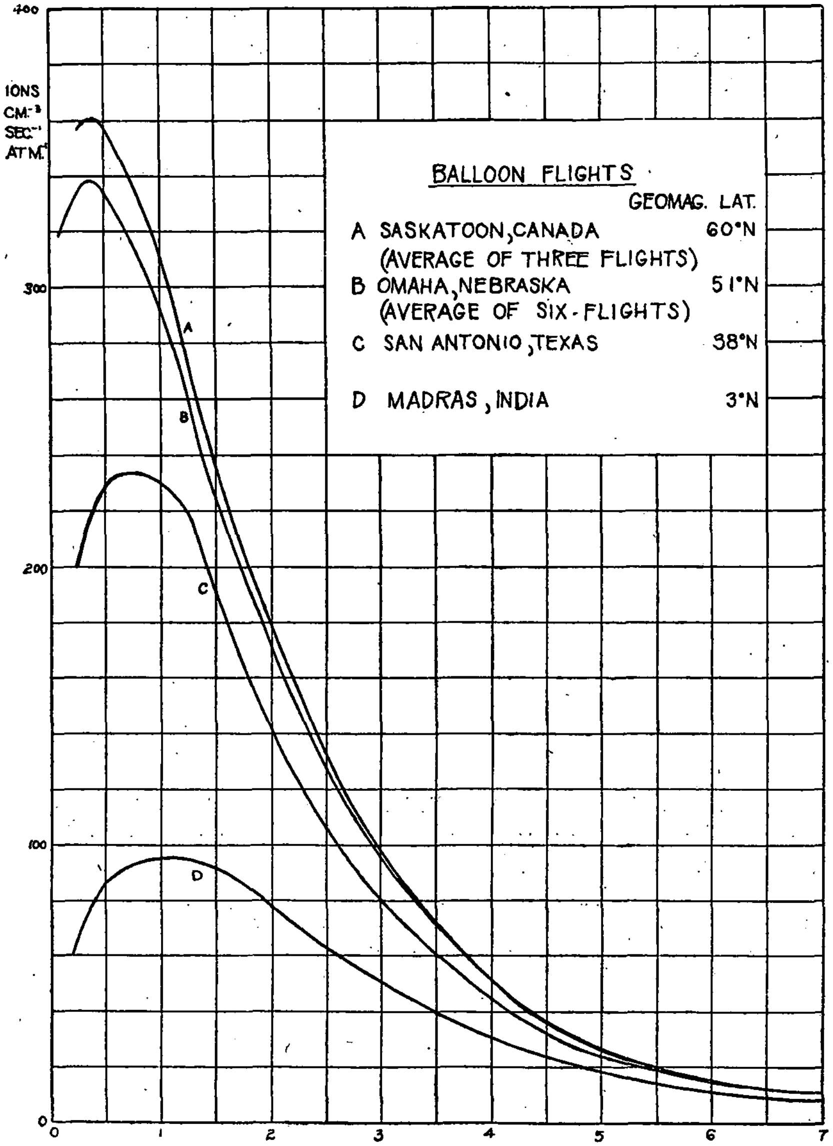
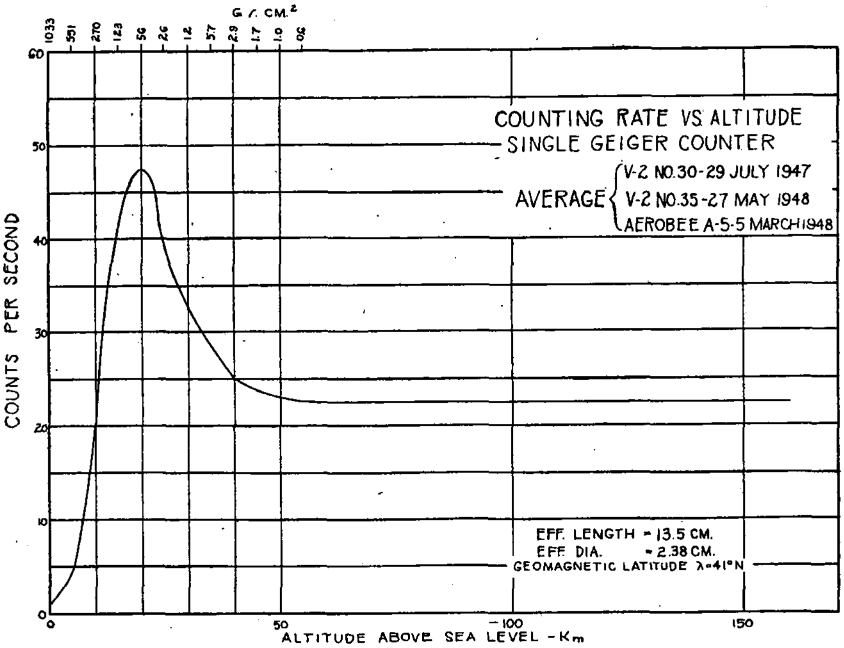


Fig. 2. Cosmic Ray Intensities at four different latitudes, plotted throughout most of the atmosphere, from data obtained by balloons carrying couters. On the depth scale, zero (at the left) represents the top of the atmosphere, and sea level is about 10.3. The half point, 5 meters of water equivalent, is at around 18,600 feet altitude. The maxima of these curves wil lie at about 50,000 to 60,000 feet, altitude above sea level. Note that the latitude effect is larger at high altitudes than lower down. These curves plus the magnetic analysis give the energy and energy-spectrum of the radiation in the range between about 10^9 and 10^{11} electron-volts. From: Bowen, *et. al.*, *Phys. Rev.*, *53*, 855-861 (1938)

The energy of the primary radiation lies mostly between 10^9 and 10^{18} electron volts (e. v.) per particle. Neither the upper nor the lower limit is exactly established. There may be some lower energy particles with energies of 10^8 e. v. or even less. and the upper limit is hard to determine exactly. Today, experimenters consider that 10^{18} e. v. is a proved value, and this author has even heard the figure 10^{20} e. v. seriously discussed. Such an energy is indeed huge for a nuclear particle. It would enable a single proton to lift a mass of one kilogram a meter against gravity.

The energy of the cosmic ray particles is measured, in the interval between 10^8 or 10^9 e. v. and 10^{12} e. v., by their deflection in the earth's magnetic field. The theory of the deflection was worked out by LeMaitre and Vallarta [2]. The energy distribution manifests itself as the latitude effect in the radiation. The latitude effect has been well measured in a series of world surveys by Millikan's and Compton's groups and by others [3]. Figure 2 shows the latitude effect at various altitudes. At energies in excess of 10^{12} e. v., the deflection produced by the earth's field becomes immeasurably small, and another method is required. This method is the study of «extensive showers». A high energy primary particle produces an extensive shower of secondary particles. Fortunately, cascade theory enables the distribution of particles in such a shower to be calculated. Careful experiments have substantiated the correctness of the theory. From the couting rates of counters wich are separated by considerable distances, the primary energies can be in-



Smoothed composite curve of Applied Physics Laboratory single-counter counting rates above White Sandes, geomagnetic latitud 41 N.

Fig. 3. Cosmic ray intensity above the atmosphere. Similar to Fig. 2 but horizontal scale turned right-for-left. Simple linear scale of altitudes. Note that above about 60 kms altitude there is no further change in cosmic ray intensity. The value here is a measure of the true primary intensity, after correction is made for secondaries generated in the instrument and particles scattered back out by the «albedo» effect. From Gagnes, *et al.*, *Phys.Rev.*, 77, 57-69 (1949).

fer. Counter separations of 100 meters or more have been used for high energies with success, and a few experiments have been made at considerably greater separations . At large separation, the experimental dificulties become great since the travel times of the pulse form widely separated counters become comparable with the resolving time of the electronic components. However, as techniques improve, it seems reasonable to predict that before long we shall be able to prove conclusively whether particles in the very high energy brackets do or do not exist, and if so how many there are. In the lower energy brackets we are on safe ground and have quite accurate figures.

Recently wiith the aid of the rockets [4] it has been possible to obtain measurements of the primary cosmic ray intensities. Rockets can go up to a sufficient altitude so that the magnitude of the hump produced by secondary particles can be evaluated. Figure 3 shows such a curve

The third feature of the radiation which a theory must explain is its remarkable constancy with time. A cosmic ray meter at any place on the earth's surface shows a radiation which has fluctuations of only a few per cent, after the usual meteorological effects have been allowed for. The diurnal wave is less than two tenths of a per cent in amplitude, and some observers consider that it has never been proved conclusively to exist at all. Similarly, no appreciable variation with sidereal time has been found except perhaps for a small effect in the extensive showers which again some observers find but others claim is still within the error of the measurement. Long period changes over several years have been found to exist, in the excellent series of measurements made by Forbush [5] with the Carnegie meters distributed at many different places all over the world. However, these changes are of the order of two or three per cent,, and seem to show a connection with the 11-year sunspot cycle.

Figure 4 shows such a part of the long-term record. Clearly the absence of a marked 24-hour wave imposes on any theory the requirement that (*a*) the source schall be far away and preferably distributed about in many places, or (*b*) if the source is near, that a scrambling mechanism must be invoked which will be capable of completely scrambling the directions of even the most energetic components. A possible scrambling mechanism would be an interplanetary magnetic field. Yet such a field would have to satisfy two apparently mutually exclusive criteria. The field would have to be strong enough to bend the high energy particles but it must also be small enough so that we do

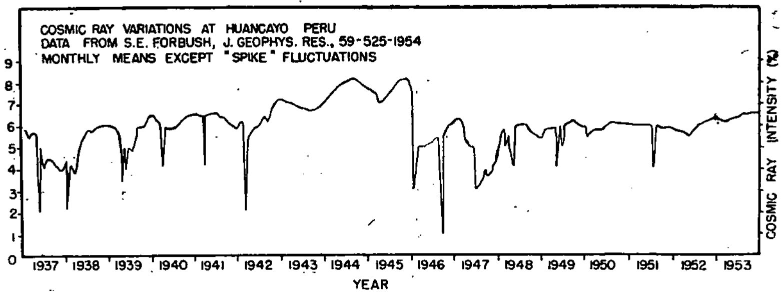


Fig. 4. Long-time constancy of cosmic radiation. Monthly means of cosmic ray intensities except for the «spike» fluctuations which are daily means. These represent cases in which changes in earth's field have modulated incoming cosmic ray beam. Vertical scale is per cent change in intensity. Long term fluctuations do not exceed a few per cent over this observed interval.

not measure it here on earth with our best magnetometers. We measure no such field. It is today thought that an interplanetary field of the order of a few microgauss may exist, so small as to be impossible to measure directly. Such a field would not be sufficient to scramble the directions of the high energy part of the cosmic ray spectrum.

The radiation does show flutuations, and the study of those changes is most interesting. We shall discuss these in detail later. But the fluctuations have a known cause, and the theories of origin must explain the non-varying part.

The fourth feature which characterizes the radiation and which presents a unique problem to the theories of origin is that of the total intensity. The total energy which arrives at the earth in the form of cosmic radiation is about the same as that of starlight [6]. This amount is either very large or very small, depending on how it is considered. If one compares this radiation to the amount of energy arriving in the form of sunlight, it is very small. The reason is that we are near a source of energy, the sun. However, if we consider that starlight is the sum total of the output of all the luminous bodies in the universe put together, then the total is seen to be vast indeed. The problem of whether the total amount should be regarded as large or small therefore depends on whether the earth, as far as the cosmic rays are concerned, may be thought of as occupying a unique place near a source, or whether it occupies an average, typical place in a widely distributed system. If the earth is near a source of radiation, then the total amount of the cosmic radiation is quite unimportant. But if the earth occupies a representative typical place, such that if it were at some other place quite far from here it would receive approximately the same amount of energy, then we have a very difficult problem. In this case, we must look for a source of cosmic rays which must be able to produce as much energy as all the luminous surfaces of all the stars combined.

Further, our sun is in a part of a vast aggregation of stars, a galaxy (see Figure 5) (1). There are many millions of other galaxies at various distances from ours. The amount of starlight we receive is typical of what one receives inside a galactic system, and far greater than one would receive at an average point out in intergalactic space. Cosmic rays may also be characteristic of this place inside a galaxy. If cosmic rays should turn out to pervade all space, the problem will be more difficult by six orders of magnitude. Since galaxies have an average separation of about a hundred times their diameters, the total volume which they occupy is one millionth of all space. If cosmic rays were truly intergalactic, then we should be forced to conclude that there is a million times as much energy in this form as in all other forms put together. As we shall see, present evidence suggests that this is not so, and that cosmic rays are galactic phenomena, typical as also is our light radiation, of a place in an arm of a galaxy

A Review of Possible Mechanisms of Origin

We pass next to considering what possible mechanisms could have given rise to radiation having the characteristics which we have cited above. Many years ago it was suggested that the radiation might have its origin in microscopic, atomic, or nuclear processes. Today we know that this solution is out the question, for the most energetic possible nuclear process would be the complete annihilation of a heavy nucleus, and the annihilation of heaviest we know would produce only of the order of 2.5×10^{11} e v. This energy is

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(1) A figura 5 a que se refere o texto é a que ilustra a capa do presente fascículo.

far too small to account for the observed cosmic ray energies, which may go up to amounts of a million or more times this. Therefore we can consider nuclear energy as infinitesimal in the scale which we have to explain.

Since the above argument excludes all microscopic processes as totally insufficient we must next consider macroscopic processes. Charged particles can be accelerated in fields. Of these, there are both electric and magnetic. The electric case is quickly also ruled out. Space is too good a condútor, and if large potential differences existed between parts of space, such as would give rise to large electric fields, currents would flow and charged particles would move so as to restore electrical neutrality. To maintain the radiation we should then have to introduce a vast mechanism which would be required to bring about a separation of charges, and which would have to continue to do so. No one has seriously suggested any mechanism of this type. We turn for consideration then to magnetic fields.

In the case of magnetic fields, the situation is totally different. In the first place, for a charged particle to gain energy in a magnetic field, it must move through a field which is not constant. A simple illustration is the field in a betatron which varies with time. If we seek, we find such varying fields in a number of different forms and places. Not all af them will do the trick, however. Let us consider a few cases.

There are large magnetic fieds in sunspots. We can measure the fields, and their rate of growth, by the Zeeman effect in sunspot spectra. We find spots which in some cases grow up to as much as 5000 Gauss in a single day. Both the magnitude of the field and its rate of growth are sufficient for accelerating cosmic ray particles up to energies of 10^{11} or 10^{12} e. v. Since our sun is not a particularly large star, it may be, as Swann has suggested, that on super-stars there are super-spots, and that these could produce energies which might account for the upper parts of the energy spectrum also. However, the sunspot solution as a source for all cosmic rays immediately runs into two difficulties. First, as far as our own sun is concerned, since our sun is near, the absence of any 24-hour wave in the radiation makes it improbable that our own sun is the source. It is true that certain large fluctuations can be traced to solar origins, but it is unlikely that the sun would send radiation around to the dark side of the earth with exalctly the same intensity as on the sunlit face. Further, to assume that cosmic rays originate in distant sunspots on super-stars is to assume that the output of the disturbed spot areas is as great as that of all the luminous non-disturbed spot areas put together, which is certainly untrue for our own sun and scarcely believable for other stars.

Recently Babcock [7] has discovered some very amazing stars, which are called the magnetic Babcock-type stars. In these, the whole star shows a strong magnetic field, which quite rapidly changes to an equally strong field in the opposite direction. No explanation of these curious properties has yet met with wide acceptance, but it is clear that such stars also could serve as cosmic ray accelerators. Again, however, the total energy argument is against these, for there are very few such stars, and it seems impossible to ascribe all the cosmic ray energy to a few stars.

Similarly there are the rotating magnetic double-star systems. The Swedish astrophysicist Alfven has calculated that double-star systems, if both stars have even small magnetic movements, could accelerate charged particles. However, in this case the acceleration would be at the expense of the angular momentum of the system, and if one were to ascribe all the cosmic rays to such systems, then all such systems would long since have exhausted their rotary kinetic energy and run down.

We come finally to one other magnetic field, which has several advantages. That is the galactic field. It is easy to show that there should be a weak field throughout most of the galaxy. There is a great deal of matter, dust, and gas atoms spread throughout the galaxy. An appreciable part of this matter is photoionized by being near hot stars which emit quanta of the requisite energy. Figure 6 shows a typical cloud near some hot stars. Moreover, we also know that the various clouds of dust and other matter are in motion, both in random motion with respect to one another and in a general rotary motion with respect to the center of the galaxy. Such motion of charged particles will set up the necessary magnetic fields, and easy calculations show the magnitude of such fields to be of the order of a few microgauss. The field will vary from place to place, both in magnitude, in direction and in time rate of change. Let us examine how such a galactic field would affect charged particles. Figure 5 shows a typical spiral nebula or galaxy.

Fig. 6. A gas-cloud within our own galaxy. There are several very hot stars imbedded in this enormous mass of gas which cause it to glow, to move and which photoionize it. In consequence gas -clouds such as this have magnetic fields associated with them, which are capable of accelerating particles to cosmic ray energies. These clouds may be thought of as the real seat of the Fermi mechanism.

The original calculations of this effect were made by Fermi [8], who showed that the fields were sufficient to accelerate particles to cosmic ray energies. But two more, extremely important features followed. The first is that galactic fields can account not only for cosmic ray energies but for the shape of the spectrum.

The energy spectrum of the cosmic radiation is described by an empirical power law formula which a negative exponent (approximately varying as E^{-2}) which may vary somewhat as one passes through various energy intervals. Its general form can be understood by saying that there are progressively fewer cosmic ray particles in each energy interval as one goes to progressively higher energies.

Cosmic ray particles in space will of course from time to time make collisions on atoms of gas, or on dust particles or on stars in space. Such collisions will result in loss of energy by the cosmic ray particle, the amount ranging from a small loss of energy for a «near miss» on the nucleus of a free gas atom, to complete absorption on colliding with a star. The amount of energy lost depends on *(a)* the projectile, *(b)* the target, and *(c)* the energy of the particle. The amount of matter in space is known, and the mean free paths can be calculated for each type of collision. It will here suffice to say that collisions with stars are rare events; and that the mean free time between nuclear collisions with atoms is on the average a milion years. In the galactic field theory the actual spectrum is a survival spectrum, characterized by those particles which by chance have not lost energy through collisions staying around longer and getting progressively more and more energy from the field. Another way of looking at this model is to consider that particles are making inelastic collisions with fields, and that in some of these collisions the particles gain energy. Naturally there will also be collisions in which the particles lose energy, but these particles disappear from the system and are of progressively less importance.

The second important feature of the galactic origin is that this time we have the entire rotational kinetic energy of the galaxy to draw upon, and therefore for the first time we have a source which has enough energy to supply the observed total. Actually it is not necessary to draw upon this vast supply and, in fact, the excellent organization of the galaxy shows that not much energy has been withdrawn from its supply of angular momentum. The clouds of dust and gas near hot stars are often in rapid turbulent motion, the turbulence being produced by the tremendous outpouring of energy from these hot stars. Some of these stars are radiating at such rates that they cannot be very old. This large radiative output is presumably the result of previous gravitational accumulation of dust and gas by the star. The expansional energy of the ionized luminous cloud is itself quite sufficient both to provide the necessary varying fields and the total energy.

Some other interesting consequences follow from this view. If cosmic rays are of galactic origin, we do not face the insuperable problems which we cited earlier for an intergalactic radiation, namely a total energy a million times greater than that of the luminous thermal radiation. Further, the composition of the radiation makes sense, for we should expect the radiation to be composed of the same material which we know to be abundant in the universe, namely, mostly hydrogen (protons), substantially less helium (alpha particles), and a small amount of the heavier elements. This is the normal qualitative statement of the cosmic abundances although quantitatively there are somewhat more of the heavy nuclei than normal cosmic abundance would suggest. Further heavy nuclei cannot have made any collisions at all, for they would have been fragmentized, since cosmic ray energies are far greater than nuclear binding energies. Protons on the other hand could have survived collisions.

The galactic field mechanism requires some sort of «injection». Particles can be accelerated by galactic fields if they start out with appreciable energies. The energies they must have are of the order of their «rest energies» M_0c^2. At such energies the energy-loss per collision is a minimum. For a pront this is about 10^9 e. v., which is just about the bottom of the observed cosmic ray spectrum. The injection is necessary because of the collisions mentioned above. At lower energies, a particle will lose energy by ionizing collisions faster than it gains energy from the field. The galactic process therefore has a definite starting potential. Fermi's latest mechanism requires somewhat less injection energy than does his first model, because of the greater rate of gain of energy. As it happens there are many injectors. All the mechanisms we have cited above, sunspots, superspots, magnetic stars, and possibly also super novae, will inject particles at the requisite energy into the galaxy, whereupon the galactic field takes over, and provides the acceleration to the really large energies. All particles, and there will be many, with less than this minimum of energy will simply not be accelerated and will form a part of the low energy debris in space. The composition of the material injected will be that which is cosmically available. If supernovae are injectors, and if the suggestions made by some students of the subject about the «cooking» of heavy nuclei in supernovae are correct, then we may in fact find somewhat more heavy nuclei in the cosmic ray mass spectrum than in the standard galactic abundance tables. Incidentally it is not the supernova explosion in itself which would bring particles up even to injection energies. A supernova, spectacular though it is, still a low-energy process. But the act of blowing out a huge cloud of material, much of which is ionized, will set up strong but local electric fields since the ions and the electrons will presumably not all move at the same speed. It is these electric and the consequent magnetic fields which can in certains circumstances accelerate particles. The processes involve that super-complex subject, magneto-hydrodynamics of heavily ionized gases.

If the galactic magnetic field is a gigantic betatron, then in all probability the various mechanisms we have cited, such as the Babcock stars and the sunspots will be the ion-sources, and will inject into the field these particles which the field will then accelerate. Further, the absence of electrons and photons from the primary radiation is explained, for photons are lost by being able to escape from the galaxy and electrons do not survive owing to their high rate of energy loss upon making radiative as well as ionizing collisions with the matter in space. In the language of nuclear physics, electrons have a large cross section for energy-dissipating collisions.

Consider next the curvature of the particle orbits and the problem of the entrapment of the radiation in the galaxy. The theory of relativity gives a relationship, between the energy for «relativistic» particles, that is for particles whose energy is very large compared to their rest-energy, M_0c^2, and their curvature in a magnetic field.

$$HR = 3 \times 10^{-3} \, E \qquad (1)$$

where H is the magnitude of the field in Gauss, R is the radius of curvature in cms, and E the energy in electron volts. Note that this is a relativistic formula and will give quite wrong results if applied to a «classical» particle at slow speeds. For fields of a microgauss, i. e., for an H of 10^{-6} Gauss, and an energy of say 10^{12} e. v., the formula gives a radius of 3×10^{15} cm. The sun is about 1.5×10^{13} cms from the earth, so the curvature is quite small on the cosmic scale, being only 200 times the earth sun distance. A particle of energy 10^{18} e. v. has a curvature in such a field of 3×10^{21} cms. Now a light year is about 10^{18} cms. Hence such a particle has a radius of curvature of about 3000 light years. This figure is of the order of the thickness of the spiral arm of the galaxy, and suggests that particles of this energy would still be confined to the galaxy. An interesting effect occurs at the higher energy, say 10^{20} e. v., where the radious becomes larger than the thickness of the galaxy. At these energies we should expect some change in the cosmic ray distribution, and in the observed spectrum, for such rays would be able to escape from the galaxy if the plane of their orbit was at right angles to the plane of the galaxy. Further, we should expect some time-variations, for a given point on the earth's surface will at times be directly in the galactic plane, and at other times the galaxi may be on the horizon. This situation would introduce some of the directional effects known to be absent in the lower energy part of the radiation. These high energies are today just on the edge of what can be observed, and it will be most interesting and extremely revealing to see whether the spectrum changes as one goes to these energies and whether the particles show a variation with time which is not present in the lower brackets. This experiment is therefore one of the most promising cosmic ray experiments, and one which could tell us much about all the various factors. With present techniques it is extremely difficult, but it represents a most challenging new observation, and the one from which the most important new directions can be gained. Indeed it would seem at present that this study would provide for us one of the really vital keys to the structure of the universe.

Astrophysical Implications

Steady-state solutions or alternative long term implications. We may also say a word about the astrophysical implications contained in the galactic accelaration picture of cosmic rays. There are two quite different possibilities, first that cosmic rays are in equilibrium today, being produced, accelerated, and absorbed, so that we are measuring a part of a long-term equilibrium process, and the second that cosmic rays are residual from an original catastrophic explosion. The latter possibility has been considered at length by LeMaitre [9]. Today's opinion strongly leans in favor of the first of these alternatives. The Fermi picture of injection by such events supernovae super-sunspots, magnetic stars, and other mechanisms at moderate energies, followed by an acceleration to cosmic ray energies by the galactic fields, and eventual disappearance by absorption due to collisions with matter, either diffuse or in stars, is a «steady state» type of solution. The amount of the galactic field needed for the acceleration is sufficient to cause the rays to be trapped in the galaxy, and suggests that if we measured cosmic rays in intergalactic space, we should find that its intensity there was much less than within the galaxy.

If alternatively it should turn out that cosmic rays were residual from an explosion which took place perhaps when the universe in its present form came into being, then certain other consequences might be expected to follow. Since there is enough matter in the galaxy so that cosmic rays would perhaps survive for a million years or so at present densities, we must have the bulk of the radiation outside the galaxy, or it could not have survived for the approximateley five billion years which have passed since the original explosion. In this event, the total amount of energy in the form of cosmic rays as we have mentioned earlier is a million times greater than the energy being emitted by the thermally hot luminous surfaces of all the stars in the universe. This would in turn impose old properties upon the original explosion. We should have to have an explosion in which the radiation was generated in enormous amounts at a time after the matter had already separated appreciably, for while today in intergalactic space the mean free time of a cosmic ray particle is longer than the five billion years since the explosion, during the dense phase the free times were shorter. The curves cross at about one per cent of the present age of the universe, i.e., at perhaps fifty million years, and at time previous to this, the free time between collisions is smaller than the total time elapsed since the initial instant. In other words, it is hard to see how the radiation could have survived the first fifty million years, and easy to see how it could have survived in the later periods

Geophysical Aspects of the Cosmic Radiation

A. Solar flare effects. We may next consider the geophysical aspects of cosmic radiation, a subject which will undoubtedly see great development during the next decade. In this first case we shall be dealing with the fluctuations in the cosmic radiation and not with the constant portion. We know that large fluctuations occasionally occur, a spectacular recent one being that which took place on February 23, 1956, when the neutron intensity at and near sea level abruptly rose by 600 per cent, and then returned to normal in about 4 hours. The fluctuation was reported by observers all over the world, and while the amplitude varied with latitude and altitude, the thime and general form of the increase is generally agreed upon. Figure 7 showes a curve of this effect. It is quite clear that, on this occasion, superposed on the normal pattern, some additional radiation reached the earth from the sun, and that this radiation included some particles with energy enough to penetrate the earth's field at the equator, and produce a large number of neutrons as secondaries.

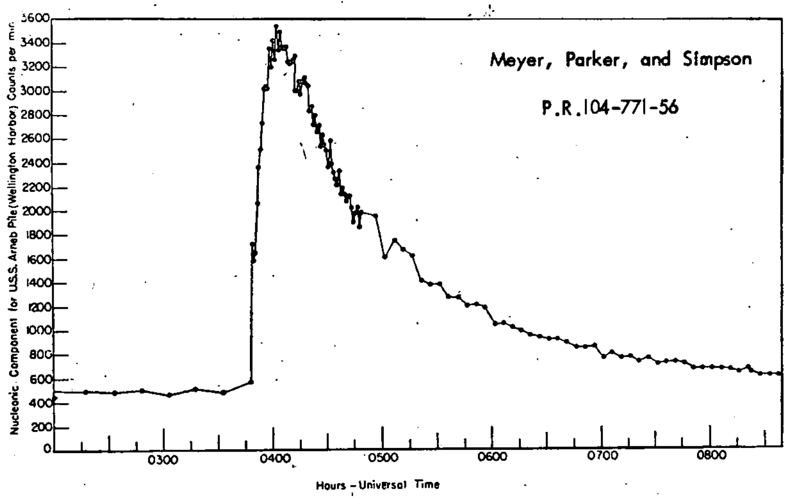
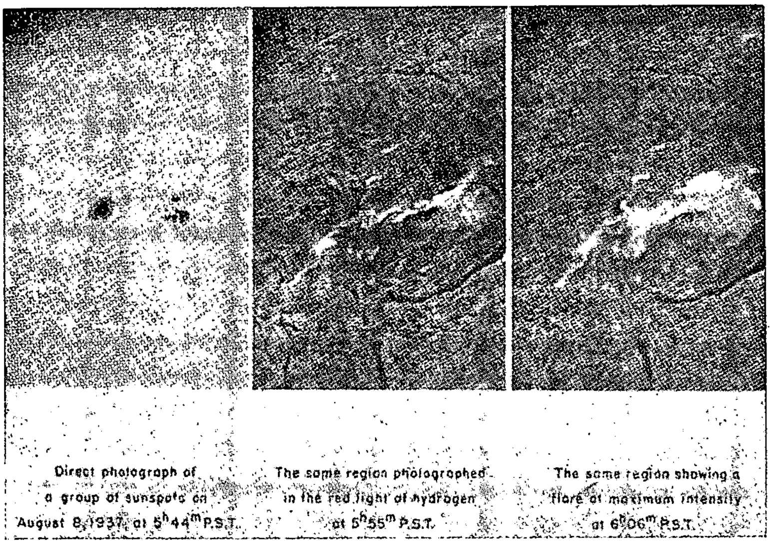


Fig. 7. Abrupt increase in neutron counting rate coincident with solar disturbance, the so-called «flare effect». The large increase indicates the arrival of o swarm of particles from the sun with energy sufficient penetrate the earth's magnetic field and atmosphere and to generate at sea level the observed number of additional neutrons.

This increase in cosmic ray intensity took place at the same time as the appearance of a solar flare, and was also accompanied by notable disturbances in the ionosphere and in a normal auroral activity. While it has not been established that it is actually radiation from the flare itself that produces the effect, the name «flare effect» has ben used to identify the type of disturbance. It is of course possible that the radiation originates in disturbed regions on the sun adjacent to the flare itself, and that the flare is merely another manifestation in a certain frequency interval of a disturbed condition and an abrupt emission maximum. Flares are generally associated whith sunspots, although not coextensive with them, but, rather, both are indicators of non-equilibrium disturbed areas on the sun. Figure 8 shows a photograph of a solar flare. It is clear that the increases in cosmic ray intensity are manifestations of an intermittent and occasional charged-particle emission from the sun. The charged particles have energy enough to penetrate to sea level and to produce the large observed number of secondary neutrons. It is known that these occasional bursts of charged particle radiation produce brilliant auroral displays and show effects in geomagnetism. They undoubtedly produce other geophysical effects and a study of them promises much new information.

B. Magnetic storm effects. There is also a different kind of fluctuation which occurs from time to time. This is a decrease in the observed radiation instead of an increase, which decrease takes place simultaneously with a magnetic storm.

The intensity curves look very much like the inverse of the «flare effects» mentioned already, except that they persist for a day or two instead of an hour or two. The intensity drops abruptly several per cent, then slowly recovers to its original value. The curves of the earth's magnetic field do likewise. Figure 9 shows a typical storm decrease. Actually, it is the fact that both the radiation and the field show a decrease which is the clue to what is happening. In this case we have a change in the cutoff produced by the earth's field. If the limiting energy admitted by the field changes, then a differing amount of radiation will enter. These decreases are known as the «Forbush type decreases» after the investigator who has observed more of them than anyone else and who has done much to explain their nature. In this case the effect is again due to charged particle radiation which arrives from the sun, particles with comparatively low energy. These particles are trapped in the earth's filed and form a «ring current» around the earth, moving in almost stable orbits. Owing to their motion they set up a field of their own and this field when added to the earth's field determines the limiting cutoff energy of radiation entering from outside. We may thus say that the charged particle radiation alters the earth's field and this in turn modulates the incoming radiation which originated far away. Eventually the particles dissipate and move off into space, and the situation returns to normal.



Direct photograph of a group of sunspots on August 8, 1937, at $5^h 44^m$ P.S.T.

The same region photographed in the red light of hydrogen at $5^h 55^m$ P.S.T.

The same region showing a flare of maximum intensity at $6^h 06^m$ P.S.T.

Photo Mt. Wilson and Palomar Observatories

Fig. 8. Sunspot and flare, of Aug. 8, 1937. The two pictures at the right are spectroheliograms, and show a disturbed area on the sun. The flare right emitted a very large amount of ultraviolet. Disturbances of this sort produce the large fluctuations in radiation observed here at the earth, and may also serve as possible «injectors» of particles into the Fermi accelerating mechanism.

C. Effects of the cosmic radiation on terrestrial isotope distribution.

Another interesting effect is that of the changes which the cosmic rays produce upon the isotopes in the atmosphere, the oceans, and the crust of the earth. The first of these to be discovered was the formation of radiocarbon, predicted in 1940 in the paper by Bethe, Korff, and Placzek [10]. Cosmic ray neutrons, produced as secondary particles in the atmosphere by the original radiation, are captured by nitrogen nuclei to form the radiactive isotope of carbon, the isotope of mass 14. This isotope has a long half life, something over 5500 years. By the application of some very well thought-out thecniques, Libby [11] and his colleagues have actually not only identified the radiocarbon in nature, but also have made quantitative estimates thereof. Since this carbon in the atmosphere mostly becomes attached to oxygen to form carbon dioxide, and since

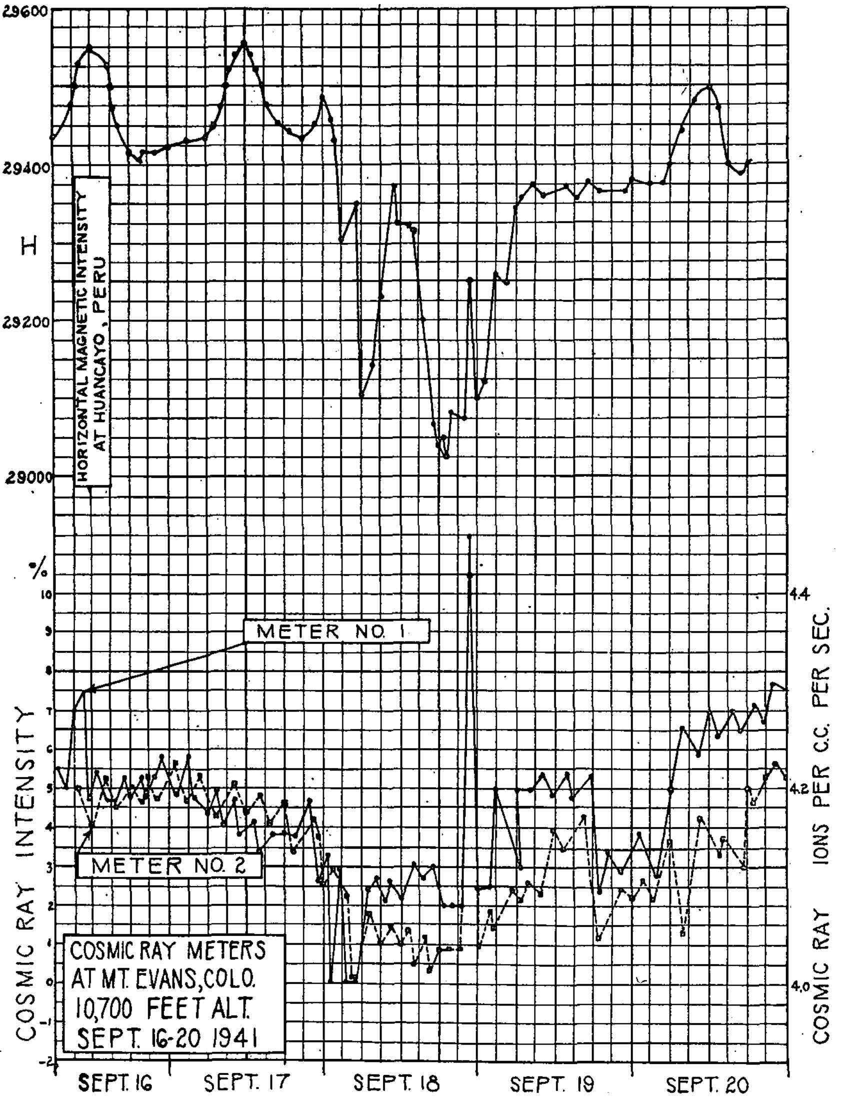


Fig. 9. Cosmic ray fluctuations. Top curve horizontal component of earth's magnetic field, units in gammas (one gamma is 10^{-5} Gauss) showing normal diurnal variations until about 1 A.. M. on Sept. 18, when abrupt magnetic storm started, and lasted until about noon of the following day. Two cosmic ray meters of the Millikan-Neher electroscope type, measuring total intensities, inside 10-cm lead shields, operating at Echo Lake, on Mt. Evans, Colorado, show Forbush-type decrease associated with the storm, and also a spectacular spike at about 11 P. M. on Sept. 18 signaling the arrival of a swarm of charged particles from the sun, which not only increased the ionization but made a disturbance in the geomagnetic field. Top curve coutesy Carnegie Institution of Washington; bottom from Korff, *J. Terr. Magg.*, *48*, 217 (1943).

the carbon dioxide is ingested by plants and animals and is incorporated in their biological structures, and further, since this process stops at the time of the death of the specimen, the percentage of radiocarbon among the normal carbon atoms in its system can be used to establish the date at which the specimen stopped metabolizind. The use of this important dating tool by archaeolists is too well known today to need further elaboration. It has been used for dating wood from Egyptian tombs, charcoal from old kitchen middens and for finding the dates at which trees are pushed over by glaciers, to mention but a few. This use is an interesting illustration of the normal function of pure research and of how such pure research leads into unexpected applications. Who would have imagined, had he started out to find a better method of dating wood in ancient tombs, that the thing he should do was to study the absorption properties of cosmic ray secondaries high in the atmosphere with the aid of neutron counters flown in free balloons from sites thousands of miles away from his specimens ?

Another isotope produced by cosmic rays in the atmosphere is that of radioactive hydrogen, tritium. This substance also is produced by the cosmic ray neutrons. Since it has a much shorter half life, a bit over twelve years, and since it enters inanimate as well as the life cycle of living matter in a different manner from carbon, it too can be used as a dating tool, with quite differing characteristics and limitations. It may help us, for example, to date ice in glaciers, or to study the speed with which water moves at great depths in the ocean. Further, since tritium decays into helium three, and helium three is easily detected in and distinguished from normal helium four, we now have still another dating tool. It is probable that all the helium three in the atmosphere is of cosmic ray origin, and its rate of escape from the atmosphere and total accumulation may tell us something about the average temperature which has existed in the atmosphere at remote times in the past. Helium three may also be identified in solid object. It is possible that a study of the distribution of helium three inside meteors will tell us about the origin of these objects, or perhaps about how long they have been circulating, or alternatively, about the intensity which cosmic rays have had at times in the distant past.

Further study by the author [12] and by others has shown that there are many other isotopes also produced by the cosmic rays. The point is that the primary radiation has more than enough energy to break up the nuclei which it hits in the atmosphere, and that therefore we should expect to find spallation products of all masses less than those of the normal constituents of the atmosphere. Since argon 40 is present in air to the amount of the amount of about a per cent, we shall find quite a collection of different fragments of mass 40 or less. The first of these, phosphorus 32, has already been identified by a group of Brazilian investigators [13]. Beryllium 7, a spallation product of the lighter but more abundant nitrogen and oxygen nuclei, has also been reported [14]. It may confidently be anticipated that many new isotopes will be found in the years to come and these will each open up new and interesting vistas in research.

In addition to effects in the atmosphere, some cosmic ray neutrons reach sea level. The fraction near the surface of the earth is much smaller than the number in the high atmosphere, but all the neutrons produced are eventually captured by nuclei, and the process has been going on for a long time. While one can compute that the deuterons in sea water cannot be of cosmic ray origin at present cosmic ray intensities, it is clear that a study of the isotopes in the earth's crust and oceans will shed light upon many in-