gation (C). Energy and momentum seem to be conserved in the weak interactions. The analysis of the conservation of angular momentum in weak interactions is more complex than the corresponding analysis of parity conservation, because parity conservation can be violated in only one way, whereas angular momentum conservation can be violated in a large number of ways. To my knowledge this analysis has not been carried out. Let us now consider T and C. A closer look at these conservation laws shows that there is no proof that these are conserved in weak interactions. One might at first think that the equality of the lifetimes of the π^+ and π^-, or the μ^+ and μ^-, which are charge conjugate particles, says something about this matter. But an examination of this problem shows that the lifetimes will be equal to the lowest order in the weak coupling constant (which is to an order of accuracy of 10^{-12}, and therefore essentially infinite accuracy) merely on the assumption of invariance under orthochronous Lorentz transformations (i.e., Lorentz transformations in which there are neither space nor time inversions). Because of this, the absolute invariance under C must be regarded as experimentally not proved.

Let me conclude with the point that if parity is indeed not strictly conserved, there would be a preference for either right handedness or left handedness in the universe, and this would appear to be unaesthetic. One may however observe that if one's definition of invariance is generalized, the question may appear in a quite different light. Let me give a simple example which T. D. Lee and I have speculated about: suppose that parity is not conserved, i.e., that there is a difference on going from a left-handed to a right-handed coordinate system. It may turn out, however, that by simultaneously going from one coordinate system to the other *and* switching to the anti-world, i.e., replacing π^+ by π^-, protons by antiprotons, etc., symmetry is regained. This merely shows that there is a richness in the structure of these symmetry laws which we are quite far from comprehending.

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On the Origins of Cosmic Rays

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IN 1954, Professor Einstein once remarked that there were two easily observable phenomena that, in his opinion, showed a deep fundamental lack in our knowledge of the physical world. These, he said, were the cosmic rays, and the terrestrial magnetic field. We can be all but sure today that he was wrong in that intuition, but he was expressing exactly that feeling which theoretical physicists have had for many decades, which somehow justifies the inclusion of topics like this one in a program on theoretical physics.

It is my opinion that they no longer quite belong in such a discussion. They have to do neither with the fundamental laws of physics nor with the difficult problems of applying the fundamental laws to relatively simple systems. On the contrary, both of these phenomena (which turn out to have the same fundamental origin) are examples of application of good old classical physics to a world of atomic materials, using nothing but the still unknown solutions to the nonlinear equations of magnetohydrodynamics.

The beginning of the path toward an explanation was shown to us perhaps 20 years ago when Fermi, Vallarta, and others began their series of investigations into the effect of the earth's field upon the cosmic rays which has led us now into a nearly complete understanding of, say, the latitude effect. The idea was gained, and given quantitative support, that the cosmic rays were not given and immutable, something whose origin could not be approached because they were so far beyond ordinary experience. This idea was aided by that kind of theoretical result, but most especially by the facility with which experimental physicists have *made* cosmic rays. For they have the same problems and the same difficulties that are encountered in nature in the large.

The study of the origin of cosmic rays (while we do not yet have a fully understandable, and certainly not a quantitative model) is no longer devoted mainly to the interpretation of empirical evidence obtained from properties of the cosmic rays themselves, but must draw as well from general astrophysical means of observation. These wider results are for the first time sharply relevant this year, and therefore it is perhaps appropriate to summarize very briefly what sort of path one can take for a tentative understanding of this extraordinary and interesting phenomenon. I intend to describe just one path; I know that there are many; I know that there are even people in the audience who have produced other paths for the explanation. The one I shall point out is the most coherent we have today. It is still a model;

it depends upon fitting together loosely many ill-defined parts, and naturally the change of any one of those parts can seriously affect the coherence of the model. Nevertheless, I think it is the best we have at present. As far as I can see, it has no clear inconsistency with anything we know, and it unites a great many phenomena which otherwise would have to stand as separated.

The path which I shall outline is associated with the names of Alfvén, Fermi, Cocconi, the Moscow group (Shklovski and Ginzburg), and Hoyle and Burbidge. I shall try to describe very briefly the logical structure of the ideas, the elements of the theory, but only some of the numbers and the specific mechanisms which bear on it.

The principal facts with which one begins are like many facts we have heard about in recent sessions. They are not at all facts, but only approximately true and simplifying statements. The two first principles are the isotropy and the time independence of the cosmic radiation. It is grossly isotropic, and grossly time independent. That both the isotropy and the time independence fail in detail is clear. Indeed their very failure has given us perhaps the clearest clues to the mechanism which may account for the over-all isotropy and constancy.

The most spectacular failure of both of these principles occurred on February 22, 1956, when the cosmic-ray intensity shot up by a factor of 2 or 3 even for hard mesons at sea level and by a factor of 100 for the neutron component. An analysis of this event and of a few others like it has given a pretty clear understanding that the cosmic rays do not come to us through empty space. They may originate, as these extra particles do in this particular case, on the sun, where the event can be seen to be in sharp time coincidence with extraordinary events on the surface of the sun. But whether or not they originate there, they pass to us through space which is by no means empty. It is the discovery of the population of this "vacuum" with physical, not simply virtual particles, which was the real progress of the past few years, and which has made possible an understanding of the cosmic rays.

The precession radius of curvature is given in familiar units by $R=E/300B$, the radius R in centimeters, the energy E in ev and B in gauss.

Observations have shown directly that the geomagnetic field affecting cosmic rays incident on the earth is skew from the dipole field evaluated on the surface of the earth, by about a tenth of a radian. It seems hard to doubt that this can only be due to the summing of the earth's field with some external fields out in space, not produced by the internal currents which make the dipole field of the earth. Since the deflection of a tenth of a radian comes in at about ten earth radii, what sort of field might be effective still in bending cosmic rays, that is, in producing cosmic-ray deflections with R above ten earth radii for a typical cosmic ray of 10 Bev energy? This turns out to be about one milligauss or a little less.

From this it is pretty clear that in the region around the earth, say ten radii away, there is a field (which may be transient, but which is there sometimes) of the order of a milligauss, perhaps. In this field the radius of curvature of a cosmic ray amounts to one light second. The light transit time from the sun, from which the special pulse of cosmic rays originated on February 22, 1956, is eight minutes, so you see that such a field would mean that the path from sun to earth could by no means be a straight line. Indeed, independent analyses of such flare events have given fair confirmation to the idea that, at least under these peculiar circumstances, the earth-sun region is by no means empty for the cosmic rays, but rather the cosmic-ray path must be some more or less chaotic random walk in this region, the diffusion being caused by scattering, not from nuclear collisions, but from collisions with more or less coherent magnetic fields extensive enough and strong enough (from 10^{-5} up to 10^{-3} gauss) to induce radii of curvature of magnitude small compared to the earth-sun distance. Then a diffusion-theoretic treatment, using elementary ideas of diffusion theories and not implausible ideas of the geometry of such transient clouds of scattering magnetic centers that might come from the sun, gives a semi-quantitative fit to the decay time of a solar flare, to the spectral changes, and to a number of other features.

I take this, not as a demonstration of the origin of the cosmic rays at all, but as an example of the fact that there can exist, in more or less empty space, (to be sure, this is space very near a star of the main sequence, and not typical galactic space) a kind of magnetic material that prevents cosmic rays from traveling in straight lines. It is exactly this which is the key to the whole phenomenon. Astronomers have independently obtained other evidence for fields in galactic space.

The gross cosmic-ray isotropy and time constancy define our first major point; the second major point, the flare events and the skew field, argues for the modification of cosmic-ray direction when they propagate in "empty" space. The third main property derived from the rays themselves is their distribution in energy and charge. There is a paucity of cosmic rays below a couple of Bev, a low-energy "cutoff" which varies with the solar activity cycle of 11 years, and is one more sign of the influence of the magnetic regime around the sun upon our cosmic-ray flux. From some 10 Bev all the way to 10^4 Bev, and with less sureness but still quite plausibly up to 10^7 or even 10^8 Bev, the cosmic-ray integral energy spectrum follows a simple power law at least in rough approximation, with

$$N(>E)=\text{const}/E^{\alpha}, \quad \text{with} \quad 1.3<\alpha<1.8, \qquad (1)$$

where $N(>E)$ is the flux of primary rays with total energies greater than E. The exponent changes slowly over the energy range, not going beyond the limits shown over pretty much the whole range. Besides this over-all energy spectrum, we have some information, though much less, about the charge distribution among the primaries. Not only protons enter the atmosphere, but helium, elements of the CNO group, and some nuclei as heavy as that of iron. Protons predominate, the others being present in amounts very roughly like those anticipated for the mean gas sample of the universe, with maybe a tenth of all the flux being in alpha particles. The energy spectrum of these heavy primaries is poorly known, but for energies up to some 20 Bev per nucleon, it is like that of the protons, at least roughly, and there is some sign that this similarity extends to much higher energies. One must be prepared for departures from the power law of energy distribution, want of close parallelism between the heavies and the proton spectrum, and all sorts of other complications. But the general picture here appears to apply up to about 10^8 Bev or beyond.

About the only additional fact one needs to know for a discussion on this level of accuracy is the total energy density for various kinds of energy in space. The mean energy densities are for various forms, in a typical galactic region not near a star, in units of ev/cc as shown in Table I. This sets the level of the energy to be accounted for, and provides a few comparisons. A typical observer somewhere in a galactic spiral arm would presumably see such values whose variability is indicated by the roundness of the figures.

TABLE I. Energy densities in space.

Type	ev/cm^3
Cosmic rays	1
Starlight	1
Turbulent gas motion	1–10
Kinetic energy of rotation for galaxy as a whole	1000

We see the striking fact that the cosmic ray energy density is like that of starlight. Yet starlight pours out of every star, thermodynamically guaranteed as the degradation product of thermonuclear reactions, and cosmic rays do not as far as we know pour out of any ordinary stars at all. It is true that some do come from the sun, but the rate at which they are made, if extrapolated to all the stars of the system, would amount to a tiny fraction of this energy density (10^{-8} perhaps). Even if there are some unusual stars which flare up all the time, they cannot make up this enormous discrepancy. Moreover, the sun makes very few cosmic ray particles above 10 Bev in its most violent spasms, and stars not very different from the sun are not likely to make some rays 10^7 times as energetic. The turbulent energy looked for a while like a hopeful source, but if it did supply the cosmic rays, they would be the heaviest drag on the turbulence, and the hydrodynamics of the galactic gas would be determined by the cosmic-ray flux. This now seems unlikely, for various reasons. The rotation energy looks like a nice hope. There's plenty of energy there, but it is not easy to convert the kinetic energy of stellar systems whirling about the galaxy in circles of 10 000-light-year radius into kinetic energy of single protons moving in a chaotic motion; everyone has stopped trying to derive any comfort from that big number. Therefore, I will maintain now, and in the sequel will try to demonstrate, that the origin of much of the cosmic-ray energy is, like that of starlight, nuclear in character. This is agreeable, because nuclear energy provides a source of energy that we know how to calculate, and maybe it is true.

What are the processes? This is a kind of analysis or summary of the processes which people have used to describe the mechanisms. I am going to list a few rather formal points and then try to describe them in turn, to show what kind of model can be built up: stirring, storage and loss, acceleration, injection, and cutoff.

Stirring is that process which makes the cosmic rays isotropic, and which arranges them to be time-constant as far as possible. These must be extrasolar processes; it is very hard to doubt that the stirring is caused by a chaotic magnetic field, extending through some or all of the galaxy. Just where it resides I will try to make a little clearer by some photographs, but its presence, I think, we will take as given; nearly all theories join there. The only way in which theories differ is in how these stirring fields are constructed: tight enough to prevent leakage out of the ends, or chaotic; flat or round or what they may be; but everybody has a stirring field. Otherwise, one ought to see where the sources are, for it is not plausible that the sources are isotropically distributed about the earth. This is the Copernican assumption of the cosmic-ray theory.

Next consider storage and loss: this is the root idea in a way. It goes with the stirring. If there is stirring, then the path length of a cosmic ray particle is much longer than a straight line from its source. That implies the energy density may be high without the rate of energy production being very high, because there is a pool of cosmic rays formed by storage. No such pool is formed for light photons; they must move in straight lines, since the galaxy is thin to them. The apparent equality of cosmic-ray and starlight energy then does not mean that one must look for a cosmic-ray source as intense as the light source. This cosmic-ray source, it turns out, needs to be only about 10^{-4} or 10^{-5} as intense, which is already hard, but at least is not so impossible as if it were one to one. The numbers 10^4 to 10^5 come from a comparison of the successfulness of the stirring, that is, the degree of isotropy, with the loss processes which must limit the storage eventually. The storage must be limited. The cosmic rays cannot be arbitrarily old in the galaxy: (a), because they would make nuclear collisions; and (b), because if they escape nuclear collisions, it is extremely hard to define a trapping magnetic field that will hold particles in indefinitely (as all designers of particle accelerators will

FIG. 1. A spiral nebula seen edge on. A galaxy of the Coma Berenices cluster, photographed at Mt. Wilson, NGC 4565.

agree), and certainly with turbulent and chaotic fields it must be even harder. So the rays are going to leak out —that means moving from a region where the energy density of cosmic rays is the tabulated value to an (assumed) region where it is smaller. What that region is we discuss later.

On the other hand, the rays might be destroyed by nuclear collision. One knows that they are not destroyed overwhelmingly by collision because we do see heavy primaries, which means that even if the particles started out all iron (not at all impossible, but not plausible) still they could have reasonably traversed not more than a few tens of grams per square centimeter, a few mean free paths. And they may have moved through much less than one gram per square centimeter. (The argument to be settled by the presence or absence of Li, Be, B, elements which are missing in the chemical abundance of the universe as a whole, is an argument which bears on this question less sharply than it once did. It bears rather on a distinction between less than half a gram and more than a couple of grams.) I think everyone will agree that the cosmic-ray beam does not come through more than five or ten grams/cm^2 anyhow.

The mass of a one cm^2 column of matter along the galactic diameter is a couple of grams. The cosmic rays have not gone through such gas for a distance more than 10 or 20 times that, certainly not any enormously greater distance. Of course, such storage paths guarantee long life, and guarantee that rapid changes of source strength are not likely to be reflected in a change of the intensity observed where we sit, because the pool has stored up rays over a long time. Only if we are so lucky as to live near an actively-generating source of cosmic rays will we see a little fresh injection, as we do. That little contribution is from the sun.

Where is the storage? This is the first and the hardest question to answer. The erroneous answer which we once gave is notorious. I am now giving you another answer. I hope it is not as bad.

Figure 1 shows what led us into giving the wrong answer. This is a photo of a typical spiral galaxy. It is not our own, but it is a spiral of similar class to ours. This thing is characteristically a disk. It is very easy to say, "The cosmic rays are stored in that flat disk, and therefore they are going to be lost wholly by leaking out of the flat faces." This gives rise to a serious problem, because then the storage time is small, and you are forced to accelerate the cosmic rays very quickly, since this disk is so extraordinarily thin.

Figure 2 is M31 in Andromeda which is a sister galaxy, just like ours, seen a little edgewise. Here there is a tilted-disk effect. It is also quite a flat structure. This is a typical picture on a Palomar photographic plate.

In Fig. 3 various distributions through the Andromeda nebula are plotted against angular distance from the center, looking only more or less perpendicular, not correcting for our oblique viewpoint. The lower curve is a curve of the mass distribution, as calculated from the distribution of stars. It is quite a thin disk. The higher broad curve on the other hand shows no sign of a core plus a cloud; it is now just a big near-sphere. This is the picture that radioastronomers see at a frequency of a couple of hundred megacycles. So there is something,

FIG. 2. Our neighbor galaxy, the spiral NGC 224, the Great Andromeda Nebula. In the optical telescope it appears as a tilted flat disk of stars.

invisible to the eye but a good source of radio radiation, making a spiral galaxy nearly spherical.

The proposal that we do away with disk storage and store the cosmic rays in the sphere is extremely likely to be true; but I would like to defer the argument as to why the presence of a radio signal from the whole sphere of Andromeda is a strong argument in favor of storage of cosmic rays in that spherical volume. To have thus increased the storage volume from that of a disk to that of a sphere is very agreeable. It gives a hundred times larger storage volume which means that, since the radio source density does not change much with radius it is fair to take roughly a hundred times the total cosmic-ray energy. Fortunately the lifetime goes up also by a hundred times or two, because there is so much more space in which the rays can make the random path. This means the rate of production is about the same, perhaps a little bit less. But the time rate of acceleration, the rate of storing energy in the particles, does not need to be sizeable. There is plenty of time. Particles can come back and forth many times; or can be accelerated in quite a different way. The difficulty of doing all this in a flat and leaky disk, is gone. Generally speaking, everyone is happy with the astronomical evidence that the cosmic-ray galaxy is not (as it looked to the eye) flat, but as it looks to the radio antenna, spherical. The gas is so tenuous that nuclear collision remains a minor cause of loss.

Next, consider acceleration. This is the process about which we know the least. It was originally proposed, I think by Fermi, that this very chaotic scattering would add energy to the cosmic-ray particle as it changed its direction in collisions. This is a process strictly analogous to the moderation of neutrons as they scatter elastically in a low-temperature moderator. In this case, however, the scattered particles gain energy at the expense of the energy of the large magnetic clouds which cause the scattering. One may say that these large clouds moving at velocities of some tens of kilometers per second and possessing masses of stellar size have

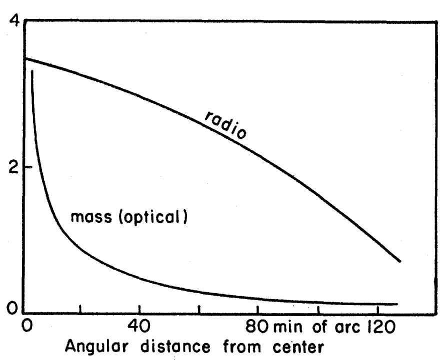


FIG. 3. Distributions seen in the Andromeda galaxy, NGC 224. The upper curve shows the radio source intensity at 200 Mc, plotted on an arbitrary scale, as a function of angular distance from the center of the galaxy. The lower curve shows the mass density calculated from the optical observations on stars, in a similar graph [after J. E. Baldwin, Nature **174**, 320 (1954)].

enormous "temperature:" i.e., large kinetic energies per translational degree of freedom. The cosmic-ray particles try to moderate against such clouds, but in moderating, they must of course rise in energy rather than decline as the neutrons do against cold moderator. It is clear from the magnitudes involved that equilibrium can never be reached, and that the highest energies attained by cosmic-ray particles will be limited by the time available for the process of inverse moderation. Fermi originally suggested that nuclear collisions would limit the process. This would strongly discriminate against heavy primaries in the beam, and seems to be excluded. This is perhaps the major consequence of the measurements on heavy primaries. The similarity in energy spectrum between hydrogen and the heavy primaries seems to imply that the process is limited, not by nuclear collisions which vary strongly as the mass of the nucleus varies, but by leakage out of the magnetic region responsible. This would be nearly independent of the type of particle involved.

The beauty of the Fermi mechanism in general is that it leads to a power-law energy spectrum in the simplest and most natural way. We may formulate the Fermi theory in the most naive form by writing the simple relations

$$dE/dn=\alpha E;\quad E=E_0e^{\alpha n};\quad \text{and}\quad dN/dn=-N/\bar{n},\qquad (2)$$

where α measures the relative energy gain in each collision with a scattering center, n is the number of collisions a given particle has made since its injection into the process, E is its total energy, and $\bar{n}$ the mean number of collisions before loss occurs. $N(n)$ is the flux of particles having made n collisions. With the simplifying assumption that both α and $\bar{n}$ are constants, independent of n, we obtain the spectrum by eliminating n:

$$N(>E)=\int_{n(E)}^{\infty}N(n)dn=\text{const}/E^{1/\alpha\bar{n}},\qquad (3)$$

where $N(>E)$ is the integral flux as in (1). Several detailed models have been proposed for particle motion in a magnetic region, all of which retain the feature that the energy goes up exponentially with collision number. This feature is pretty well maintained even when the mean energy gain is negligible, and only fluctuations can be counted upon. The combination of such an energy gain with the exponential number loss rate characteristic of a particle beam in almost any diffusion process gives a natural power law.

In (3), the exponent $1/\alpha\bar{n}$, which empirically is close to unity, is the combination of two numbers, one depending on the motion of magnetic clouds, the other on their mean field strengths and spatial extent. It is not obvious that these should be related, and if they were really independent (as they would be if loss arose from nuclear collisions) it would be a miracle that the ratio should come out near unity. It will appear immediately that we cannot interpret the full extent of the energy

FIG. 4. The Crab nebula, Messier 1, NGC 1952. Photographed at Mt. Wilson in the light of $H\alpha$ (6300–6700 A filter)

FIG. 5. The Crab nebula viewed in a portion of the spectrum without emission lines, seen in the light of its continuum only. (7200–8400 A filter.)

spectrum as being due to a single simple Fermi mechanism, but rather as the result of the superposition of many such processes, each arising out of a different physical situation. This suggests that perhaps some deeper dynamical connection exists between the extent of the magnetic region and its local properties. It is for the future to uncover such a relation if it is present.

The low-energy spectrum with its tailing-off fits fairly well even with the elementary theory. But we are sure from the year-by-year change of the cutoff (which all but disappeared in 1954) that the residual magnetic fields within the solar system play a major role.

All this looks pretty good, and one would be led to say that the Fermi theory in a sphere, with the loss by leakage and not by collision, would more or less handle everything, if there had not been some very unpleasant observations, some hard facts, to cope with. The hard fact is this: synchrotron radiation by electrons in a magnetic field has many characteristic properties. One of the properties is, of course, its continuum—a continuum which has a peak at a characteristic frequency depending upon the strength of the field, and the energy of a radiating electron. If the electrons have a wide range of energies, there will be a wide continuous range of radiation given off from any source of such synchrotron radiation. This radiation is completely plane polarized, electric vector in a direction normal to the lines of force of the magnetic field, especially for relativistic electrons. The characteristic frequency ν_c is given approximately by

$$\nu_c \cong 1.4\gamma^2 B \text{ Mc/sec} \tag{4}$$

for B in gauss; here γ is the relativistic energy-to-rest-mass ratio for electrons. It is also quite easy to calculate what the loss rate in energy is; it is rather a heavy space rate of loss.

Shklovski in Moscow about three years ago, and after him, a couple of Russian astronomers, and then Oort and now Baade have produced a whole series of predictions and, finally, observational confirmation which demonstrates that synchrotron radiation in enormous amounts is indeed emitted by one very conspicuous and very interesting object. That object is the Crab Nebula, Messier 1 or NGC 1952.

Figure 4 displays the Crab nebula as seen in the Hale telescope on Mt. Palomar, revealing a complex filamentary structure, shining mainly in the emission line H_α. This cloud measures about six light years across its long axis.

In Fig. 5 the same object is viewed through optical filters which pass no important emission line. There is still plenty of light, for remarkably enough what we see here is a hazy amorphous mass shining with a continuous spectrum, a continuum responsible for about nine-tenths of all the light from this object in the visible. It is a bluish continuum; almost nothing like it had ever been seen before. The spectroscopists who tried to analyze it in terms of free-free transitions in hydrogen reached absurd results (which everyone believed for a decade). They had to impute to the structure a mass much greater than anyone had ever seen for any star. Now, we know that this object is the radioactive and exploding debris of a supernova explosion in the year AD 1054. It was an unusual and unstable star, but its mass is not more than several sun's masses.

The Crab nebula is a very strong radio source. At 200 Mc it is the third brightest discrete source in the sky. Shklovski first made the bold assertion that the anomalous radio emission and the optical continuum were part of the same continuous spectrum, stretching from below 100 Mc to beyond 10^8 Mc. The intensity spectrum—two points, essentially—determines a power-law fit with an exponent similar to that for cosmic rays, somewhat steeper. If this is synchrotron radiation there is present either a high field or very high electron energies, or some product of the two. If the field were as small as 10^{-4} gauss, the optical light would imply electrons of 10^{15} or 10^{16} ev; if the field were stronger than say 10^{-2} gauss, the rate of radiation would be so great that the original supernova explosion could not have maintained the structure more than a decade or two. It seems plausible then that the magnetic field is near a milligauss. But the convincing evidence that this brilliant source of light, a thousand times more luminous than the sun, is really shining by synchrotron radiation, is given by the photographs of Fig. 6 (kindly supplied by Professor Baade).

Figure 6 shows the Crab nebula through the Hale telescope, exposed behind filters which exclude the emission lines of the filamentary structure. The arrows on the photographs show the direction of the electric vector passed by the Polaroid filter through which Professor Baade last year took this remarkable pair of pictures. Choose any feature which is prominent in one picture, and you will notice a difference in the intensity of the feature on the other picture which is quite marked. What we are seeing here is the local direction of the electric vector; that is the direction of the normal to the magnetic field producing synchrotron radiation. If you map out the successive directions of polarization of these wispy structures of continuum you are thereby mapping out the magnetic field in this object. No one, as far as I know, has suggested any conceivable way by which you can get 100% polarized light in an object of this kind anywhere except by synchrotron radiation, and I take this as the strongest demonstration: (a) that there are strong magnetic fields in some parts of the universe, and (b) that when there are strong magnetic fields, there may be relativistic electrons moving in them. Next, one can ask where these relativistic electrons come from, and what bearing this has on the cosmic rays.

Professor Oort has drawn the directions of the lines of force to see the shape of the magnetic field; it is a sort of turbulent field, but has no visible fine structure. That may be deceiving, but I don't think it likely, since at any point one looked one could see many directions of polarization if the field were chaotic on small scale, and this would wash the effect out. The presence of 100% polarization means that, at least in the outer portions of the nebula the lines of force are not very chaotic. That is, they are uniform on a scale of a tenth of a light year, or a few tenths of a light year, and a strength of the order of a milligauss. This is something prodigious from the point of view of magnetic fields. It is impossible to doubt that here too are many fast electrons; the total energy content that can be computed for them is quite high. If there are fast electrons, it seems now extremely hard to doubt that there are also fast protons, or heavy particles, made by the same processes. Since the electrons feel the drag of radiating this very synchrotron radiation, it is hard for them to gain energy, moving in paths of short radius. It is relatively easier to accelerate protons in such paths of short radius.

This certainly implies that the heavy-particle spectrum would be even less steep in energy than is the electron spectrum, and that would very well fit, roughly speaking, a mean energy of at least 10^{11} or 10^{12} ev for protons; it may very well be higher by 10^{2-3}. It is even plausible that the source of the fast electrons is simply the collisions of the heavy particles, protons and heavier, with matter in the interior of this object, so that the secondary electrons finally coming from decay of μ mesons are what actually radiate. On this basis these objects are the sources of very large amounts of cosmic rays. I think it cannot be doubted that here is one such source (but one may always doubt that this provides a major class of cosmic-ray sources).

We lose by this means, it seems, Fermi's natural explanation of the energy spectrum. If there are many such supernovae, one per century in our galaxy, the sum of these supernovae is what feeds the pool of cosmic rays, to fill the whole sphere of the galaxy. It seems rather hard to believe that their spectra would all be the same. There is no serious difficulty, if supernovae produce 10^{39} ergs/sec in cosmic rays. It seems quite possible that that would be enough to fill the whole sphere with cosmic rays to the appropriate density, at least between 10^{10} and 10^{14} ev.

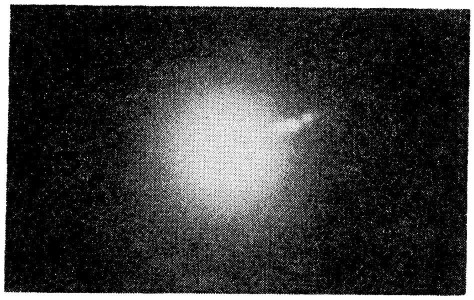
What is the reason for the radio source in the sphere which surrounds the galaxy? This is again electron synchrotron radiation, perhaps from secondary electrons produced by cosmic-ray primaries, away out there far from the stars, but in weak magnetic fields where it is no longer possible for them to make optical radiation yet quite possible for them to make radio radiation. This establishes the consistency of the argument that the cosmic rays must be stored throughout the galactic volume, finally reaching the edge, and leaking out.

With all this I would like to remark upon the high-energy cutoff. Its absence is hard to understand. It

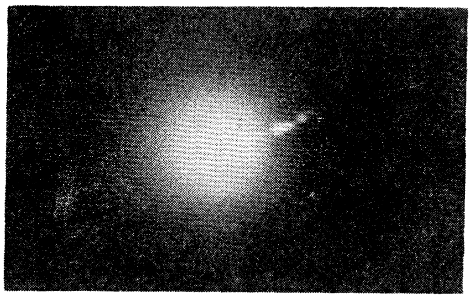
(a)

(b)

FIG. 6. The Crab nebula again seen by its continuous emission, but now through a polarizing filter in two perpendicular planes of polarization. The white arrows mark the direction of the electric vector passed by the filter in each case. Note how the structures tend to be aligned at right angles to the electric vector. The directions taken by the wispy structures at each point are the directions of the magnetic field there. (Photographs kindly supplied by Professor W. Baade of Palomar Observatory.)



(a)



(b)

Fig. 7. The bright central portion of the spherical galaxy M87 or NGC 4486, in the Virgo cluster. Note the broken linear structure extending up and right from the center. It is called the jet of M87. The two photographs are taken with differing directions of the electric vector, showing a marked polarization of the light from the different knobs within the jet [from W. Baade, Astrophys. J. **123**, 550 (1956)].

would be very nice if a cutoff were to be found. We thought, a couple of years ago, that we had good arguments why there would either be a failure of isotropy or a fall-off of intensity in the spectrum at 10^{15} or 10^{16} ev. Neither occurs.

Perhaps there is no cutoff in the spectrum because the source produces an abundance of fast particles; we can't be sure about that. Those high-energy particles that moved a long way through the galaxy and were kept in would still be of high energy, but those that leaked out into the general halo would have gone away from us; therefore even in this case anisotropy would be seen at high energy. The high-energy particles might come, say, from some spiral arm or even from the center of the galaxy, or from somewhere where there might be very special accelerating conditions. But there is no visible anisotropy, and there is no change in the energy spectrum so far up to 10^{18} ev. I say this with some misgivings; it is hard to interpret the giant-shower experiments which are the basis of the statement. Perhaps one is not fully certain of this; there are certain loopholes. But I think it is fair to say that one must be prepared to make cosmic rays about in the same intensity up to 10^{18} ev, maybe more. Now it is very hard to do that, because a particle of let us say 10^{17} ev, which is still to be accelerated by the factor 10 somewhere, would have a radius of curvature bigger than the Crab nebula even in the very strong fields of the Crab nebula. Certainly nothing in the Crab nebula is ever going to accelerate it by repeated events, if it cannot bend it even once. A linear accelerator with high electric fields over those distances is incredible.

How can one manage to avoid the cutoff? This is a rather dark question. A thousand-light-year mean free path in the galactic magnetic fields is what we have here; and a thousand light years takes us out of the galaxy in ten or a hundred steps. It is not very easy to accelerate in that time. There is, however, some hope. It is the usual hope of astrophysicists. When they learn of two things they don't understand, they say that probably these things are connected.

There is a large cluster of galaxies in the constellation Virgo, a cluster about twenty million light years away from us. A conspicuous member of the cluster, known as M87, is a sober-looking nearly spherical galaxy, as large as our own, but without a trace of spiral structure or disk flattening. It is a beautiful sphere of so-called Population II stars, very heavily populated in the center, and fading out to a thin haze of stars and star clusters a hundred-thousand light years from the center. In Fig. 7 the center portion of the object is shown in a rather short exposure. Note the extraordinary structure coming out of the central star mass; it is called the jet of M87. It is two- or three-thousand light years long, and a few hundred light years in diameter. Nothing like it is known in the heavens.

The two photographs (again from Professor Baade) show the object in two directions of polarized light. The knobs within the jet are plainly polarized. Measurements show about thirty or forty percent polarization along several directions. The polarized light is again a bluish continuum. It resembles nothing else ever seen except the light of the Crab nebula, but that light it closely resembles. The whole galaxy, not just the jet, is a strong radio source as well. These facts can hardly be interpreted otherwise than by saying that here too is a region of strong magnetic field, a great source of synchrotron radiation and of fast electrons which within the jet radiate the polarized optical continuum, and then leak out into the weaker fields which fill this whole galaxy, there to radiate in the radio region only.

The M87 jet is, however, built on a wholly different scale from the Crab nebula. Locally, it seems much the same, with perhaps a somewhat higher density of relativistic electrons. But it has perhaps ten million times the volume of the Crab nebula, and contains proportionately even more energy. Such a thing cannot arise in any part of the evolutionary history of a star. It may somehow obtain its energy from the collision of galaxies. We simply do not understand its origin. But there it is; its interpretation seems clear. Within it, assuming that it resembles the Crab except in scale, cosmic rays of energies up to 10^{21} ev or even higher might well be made, slowly to leak out into extragalactic space, and to us.

Perhaps such an object—one or a few might exist in most great galactic clusters—can explain the absence of a high-energy cutoff. Our general picture of the cosmic-ray energy spectrum leads to the idea that increasing energy of the particle implies both longer time since its injection and greater distance to its birthplace. The bulk of the energy, at the low-energy end of the spectrum, reflects the long storage of these easily-contained rays in the local region of our galaxy, and their birth from stars and novae, perhaps, with some acceleration from the magnetic clouds of the galactic arms. The great range of energies from a few tens of Bev up to, say, 10^{14} ev or more, come from the pooled contributions of supernovae, with a density smoothed out over the whole spherical volume of our galaxy, not just the arms or the disk. Finally, with a spectrum very slowly decreasing with energy, but with a very low absolute density, the whole of extra-galactic space may be filled more or less uniformly with particles of energy up to well beyond the top experimental range. Isotropy is everywhere maintained by the diffusing fields; long storage times yield no major change in mass spectra, because the regions of storage contain smaller and smaller densities of matter as their volumes become bigger and bigger. The power law spectrum loses its simple origin, and decomes a smoothed-over statistical summation, with some still poorly-understood connection between local fields and extent of a magnetic region responsible for the nearly-constant value of the exponent.

One great question remains: how can the energy of a solar flare, a supernova remnant, or a galactic jet, be converted to cosmic rays with efficiencies of at least some percent (and indeed a thousand percent efficiency can follow from a naive faith in the data!). The answer to this problem, surely of hydromagnetic kind, is still only dimly seen. The solar flare is our nearest laboratory, and will receive close study in the years to come.

Now, I come to treacherous speculative ground, which I would prudently avoid had not Fred Hoyle gone there already. The working out of the evolution of elements makes clear that it is a mistake to ignore even the difficult paths pointed out to us by such a guide. Can any role be assigned in all this strange process to the possible presence of antimatter somewhere in the universe? There may be a sign or two that some such thing is involved. One very curious primary particle, of doubtful interpretation, has been seen. It just might be a nucleus of anti-silicon. The annihilation of anti-protons might play some role either in the injection of fast electrons or even just barely in the source of energy for the M87 jet. Surely it has no large place in the history of the Crab supernova. It is still uneconomical to postulate anti-matter, but it cannot be excluded either.

There are many holes in this discussion, but I will close as I began, with the remark that for the first time the origin of the cosmic rays must be discussed in a context which is so broadly related to a variety of astrophysical experience that we may think at last, even if the details are all wrong that the broad road is finally visible.

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FIG. 1. A spiral nebula seen edge on. A galaxy of the Coma Berenices cluster, photographed at Mt. Wilson, NGC 4565.

FIG. 2. Our neighbor galaxy, the spiral NGC 224, the Great Andromeda Nebula. In the optical telescope it appears as a tilted flat disk of stars.

FIG. 4. The Crab nebula, Messier 1, NGC 1952. Photographed at Mt. Wilson in the light of $H\alpha$ (6300–6700 A filter)

FIG. 5. The Crab nebula viewed in a portion of the spectrum without emission lines, seen in the light of its continuum only. (7200–8400 A filter.)

(a)

(b)

FIG. 6. The Crab nebula again seen by its continuous emission, but now through a polarizing filter in two perpendicular planes of polarization. The white arrows mark the direction of the electric vector passed by the filter in each case. Note how the structures tend to be aligned at right angles to the electric vector. The directions taken by the wispy structures at each point are the directions of the magnetic field there. (Photographs kindly supplied by Professor W. Baade of Palomar Observatory.)

(a)

(b)

Fig. 7. The bright central portion of the spherical galaxy M87 or NGC 4486, in the Virgo cluster. Note the broken linear structure extending up and right from the center. It is called the jet of M87. The two photographs are taken with differing directions of the electric vector, showing a marked polarization of the light from the different knobs within the jet [from W. Baade, Astrophys. J. **123**, 550 (1956)].