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CURRENT PROBLEMS IN RESEARCH

Supernovae as Cosmic-Ray Sources

Nonthermal radio emission and polarized light illuminate an old problem.

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Where and how do cosmic rays originate? As yet, no one really knows, but reasonable hypotheses have been put forward, and this article focuses attention on supernovae as an important set of likely sources.

Since the discovery, about half a century ago, of the cosmic radiation, its manifestations on earth have been extensively explored and considerably elucidated. Within the atmosphere, the radiation comprises an almost bewildering mélange of atomic nuclei, electrons, positrons, energetic photons, and all of the other known "elementary" particles. Most of the latter were, in fact, first discovered in the cosmic radiation—for example, the penetrating muons (*1, 2*), the principal component at sea level. These radioactive particles arise mainly as the progeny of unstable pi mesons; the pions, in turn, are generated in violent nuclear collisions at higher altitudes.

Also spawned in these strong interactions are "strange particles"—the K-mesons and hyperons (*2*). Just a decade ago, the only source of these intriguing, short-lived particles was the cosmic radiation. In the ensuing years man-made "cosmic rays" have become available—at least up to energies of some tens of billions of electron volts (see appendix)—and giant accelerators are spewing forth fairly intense and well-directed beams of K-mesons and even anti-protons. So, today, the task of probing the nature and interactions of mesons, nucleons, and their antiparticles is mainly the province of laboratory high-energy physics (*3*), though at the higher particle energies yet unattainable with machines, cosmic rays are still a necessary tool.

Our concern in the present discussion is not with the rich assortment of secondary particles terrestrially produced, whether by nature or by machine. We are, rather, concerned with the *primary* cosmic rays per se, from outer space incident upon the earth from all directions. They consist, insofar as we know, of protons, helium nuclei, and still heavier nuclei, possessing kinetic energies E comparable to or exceeding their rest masses. They travel, accordingly, with speeds close to that of light, c.

It has long been known that the total energy arriving at the earth in cosmic rays is quite similar to that reaching us as starlight (sunlight excluded). This corresponds to an energy density in space of > 0.75 ev/cm^3. The comparison with starlight by no means implies that the respective source strengths required for the two types of radiation are comparable. In contrast to the copious loss of light from the galaxy that results from the rectilinear propagation and easy escape of photons, the cosmic-ray ions are, as we shall see, trapped and stored by the magnetic fields of interstellar space. Thus, a much lower rate of energy production than that required for starlight suffices to yield the observed energy density. Nevertheless, if a cosmic-ray energy density of similar magnitude characterizes all or much of the galactic space, then it follows that a formidable store of energy is concentrated in a relatively modest amount of matter. How this remarkable concentration of energy into relativistic particles comes about is one of the central problems confronting any theory of cosmic-ray origin.

It will be useful, before describing the supernova theory, to review certain salient features of the cosmic radiation and of the galaxy, and also to recall some of Fermi's ideas on the statistical acceleration of ions by "collisions" with moving clouds of plasma.

Primary Cosmic Rays

A theory of the genesis of cosmic rays must take account of their distribution in energy, their composition, their distribution in direction of arrival, and their time variations (or constancy). These features will be briefly outlined, in turn.

The particle energies of the primary nuclei, characteristically a few billion electron volts per nucleon, extend all the way up to about 10^{19} ev or higher. Cosmic rays approaching the earth are sorted out by its magnetic field so that only the more energetic ones reach the geomagnetic equator, while progressively larger numbers arrive at higher latitudes. The latitude-sensitive range of energies extends up to about 60 Bev for protons, though the threshold for vertically incident protons at the equator is about 15 Bev. For a given latitude and a given direction of incidence, particles having a certain minimum rigidity (see appendix) can arrive at the top of the atmosphere.

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Table 1. Relative abundances of the atoms at thermal energies and cosmic-ray energies.

Element	"General" abundance * (%)	Cosmic-ray abundance		
		At comparable energies per nucleon (%)	At comparable magnetic rigidities †	Absol. flux in peters ‡ (J)
Hydrogen	86.6	~ 94	~ 86	600 ± 30
Helium	13.3	~ 5.5	~ 13	89 ± 3
Elements with $Z \geqq 3$	0.14	~ 0.6	~ 1.4	10.1 ± 0.4

* According to Cameron's revision of the table of abundances by Suess and Urey (*11*). † Exceeding 4.5 Bv, at geomagnetic latitude 41°N (Texas). ‡ Peters = particles per square meter per second per steradian.

These "cutoff rigidities" can be translated into threshold energies per nucleon appropriate to the various incoming nuclei. Intensities observed in high-altitude balloon flights are plotted as a function of cutoff energy, and an integral energy distribution is thus deduced for each component.

In addition to data from the latitude effect, we have data from more direct energy determinations made over a wider energy range by other methods. For example, measurements of multiple coulomb scattering have been carried out along the tracks of helium and heavier nuclei in thick photographic emulsions (*4*). Above 10^{10} ev per nucleon, *relative* scattering of closely collimated tracks and angular distributions of the break-up products of heavy nuclei have proved useful. At still higher energies, measurements have been made on "jets"—nuclear interactions due to primaries of energy greater than or approximately equal to 10^{12} ev per nucleon—that generate prolific cascades of electrons and photons in the dense material of large emulsion stacks (*5*). Beyond 10^{13} to 10^{14} ev, information on energy spectra has come mainly from underground observations and studies of extensive air showers (*6*).

The following remarkable results have emerged: Over a wide range of energies W greater than 2.5 Bev per nucleon, *all* the primary groups (hydrogen, helium, and heavier nuclei) have integral energy spectra conforming to the inverse power law

$$J_{>W} = K_i W^{-1.5} \qquad (1)$$

where $J_{>W}$ is the intensity of particles whose total energy per nucleon (inclusive of rest mass) exceeds W. The coefficient K_i has one value for protons and another for each group of complex nuclei, while the exponent -1.5 remains the same within an experimental uncertainty of about 10 percent, at least up to 10^{13} ev, and quite possibly up to 10^{15} ev. There are indications that at higher energies the integral spectrum may fall off more rapidly, with an exponent of -2.1 to -2.3. Actually, the spectrum is not very well known above 10^{13} ev.

Our knowledge of the lower end of the cosmic-ray spectra is rather fragmentary, particularly at energies below 10^8 ev. We do know that at energies of several hundred million electron volts per nucleon (Mev/n) the energy spectra of both protons and heavier nuclei deviate sharply from a simple power law and, at times, show well-defined maxima. It should be noted that the lower-energy cosmic rays are the ones most readily modulated and generated by solar activity. Although much was learned about these solar effects during the recent International Geophysical Year, investigations of these phenomena are still in their infancy. Thus we are ignorant of the answers to such questions as these: Is there a fairly sharp lower limit to the spectrum of cosmic-ray energies, and especially to those of nonsolar origin? If so, is this cutoff a rigidity cutoff or is it a velocity cutoff (that is, one that corresponds to the same energy per nucleon for all primaries)? What is the shape of the spectrum at the very lowest energies? What are the energy flux and energy density in galactic space of these lower-energy particles? The advent of space probes makes it likely that we shall learn some of the answers in the not-distant future.

Evidence for primary energies up to 5×10^{19} ev has been gathered in the extensive air shower experiments at Volcano Ranch, New Mexico (*7*). A 2-square-kilometer array of detectors has been operated there by Rossi's M.I.T. group, and more recently, an 8-square-kilometer array. Among many showers having energies greater than 10^{17} ev, six had energies exceeding 3×10^{18} ev. Of these, three showers were produced by primaries above 10^{19} ev in energy. These extraordinary events are of great interest in connection with hypotheses of extragalactic origin.

Next, let us examine the chemical composition of the primary radiation (*8, 9*), as summarized in Table 1. It consists predominantly of hydrogen, as does the "thermal" matter of the universe, with helium less abundant by an order of magnitude. In Table 1, column 5, the absolute intensities of all particles with rigidity R_m greater than 4.5 Bv are given in "peters"—particles per square meter per second per steradian (srad). In column 4 these figures are given as percentages of the total particle intensity. Particularly for helium and more complex nuclei, these data are the best set available for a

Table 2. Abundances of the "heavier" elements relative to 10^5 hydrogen atoms.

Element	General abundance *	Cosmic-ray abundance †	Cosmic-ray/thermal * ratio
Hydrogen	10^5	10^5	1
L-group ‡ (Li, Be, B)	5×10^{-4}	110	$\sim 2 \times 10^5$
M-group (C, N, O, F)	150	400	~ 3
H-group ($Z \geq 10$)	15	150	~ 10
VH ($Z \geq 20$) §	0.7	40	~ 60

* Cameron's revision of the Suess and Urey data is employed here for the general (that is, "thermal") abundances (*11*). † The cosmic-ray abundances all refer to the same energy threshold (kinetic energy $E > 1.5$ Bev per nucleon). ‡ See *14*. § The very heavy (*VH*) component is a subgroup of the heavy (*H*) component.

single rigidity cutoff. They derive from determinations made in many balloon flights in Texas, at a geomagnetic latitude of about 41°N (*10*).

Table 1, column 3, gives the relative cosmic-ray abundances at kinetic energies greater than 1.5 Bev per nucleon, from flux data from two magnetic latitudes, about 41°N for the complex nuclei and about 51°N for protons. Since the rigidity depends on the ratio of momentum to charge, a given threshold of rigidity corresponds to a higher energy per nucleon for protons than for alpha particles or nuclei with $Z \geqq 3$. Thus, when one measures the abundances of the elements in the cosmic radiation at a single latitude (rigidity cutoff), the relative proportions of hydrogen and more complex nuclei are not the same as those at a single threshold of energy per nucleon. The latter comparison has been arbitrarily made in Table 2. It can be argued, since the acceleration and motion of cosmic rays are largely governed by magnetic fields, that an appropriate comparison would be with cosmic rays having the same rigidity cutoff. Actually, the qualitative conclusions to be drawn here would not be altered if the latter set of relative abundances were selected instead.

The cosmic-ray abundances can be compared with the "general" abundances of the atoms at thermal energies (Table 1, col. 2) based, for example, on stellar spectra, meteoritic analyses, and terrestrial surveys (*11*). The most striking feature of Table 1 is that the cosmic-ray nuclei heavier than helium appear to be at least 4 times as abundant (by comparison with hydrogen) as the corresponding atoms at thermal energies. This difference is shown more clearly in Table 2, where the abundances of the several components of the "heavier" elements have been normalized to 10^6 hydrogen atoms. Among cosmic-ray physicists it has been customary to lump the elements starting with lithium into a light (*L*) group, a medium (*M*) group, and a heavy (*H*) group. The respective constituents of these groups are shown in Table 2, column 1. Sometimes the elements from calcium on are listed separately under the designation "very heavy" (*VH*); these comprise a subgroup of the *H* component (*12*). Photomicrographs of the tracks of heavy cosmic-ray nuclei in nuclear emulsion are shown in Fig. 1.

Table 2, column 4, gives the ratios of relative cosmic-ray abundance to relative general abundance for each component. The most startling ratio is that for the light elements—lithium, beryllium, and boron. Their general abundance at thermal energies seems to be almost negligible, apparently because they are very rapidly "burned" in thermonuclear reactions. For a decade there has been a lively controversy as to whether the primary cosmic radiation contains a significant fraction of these light nuclei. Many conflicting results were reported, owing partly to uncertainties of charge identification but mainly to the difficulty of distinguishing secondary light nuclei, generated as collision products in the upper atmosphere, from the true primaries. Figure 2 illustrates the process (as seen in nuclear emulsion) of

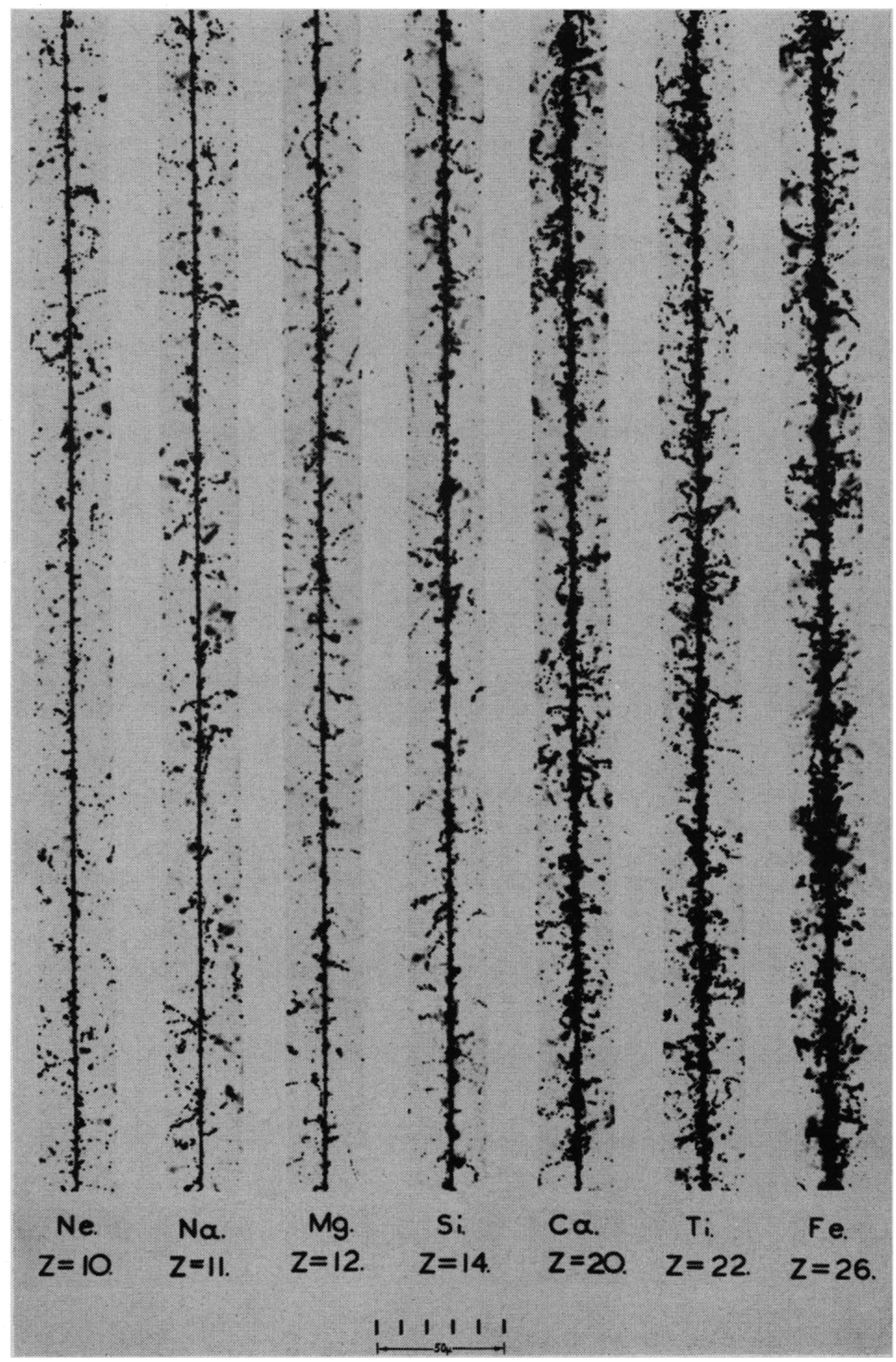

Fig. 1. Tracks of heavy cosmic-ray nuclei in a photographic emulsion exposed in the stratosphere. [Courtesy C. F. Powell]

the collision and breakup of a heavy nucleus.

Recently the lithium-beryllium-boron question has been resolved through exposure of a stack of photographic emulsion at an altitude of 134,000 feet (that is, at an atmospheric depth where the pressure is less than 0.3 percent of that at sea level). The ratio of light primary nuclei to all heavier ones at the top of the atmosphere was found to be 0.18 ± 0.04, and a lower limit of 0.14 could be assigned to

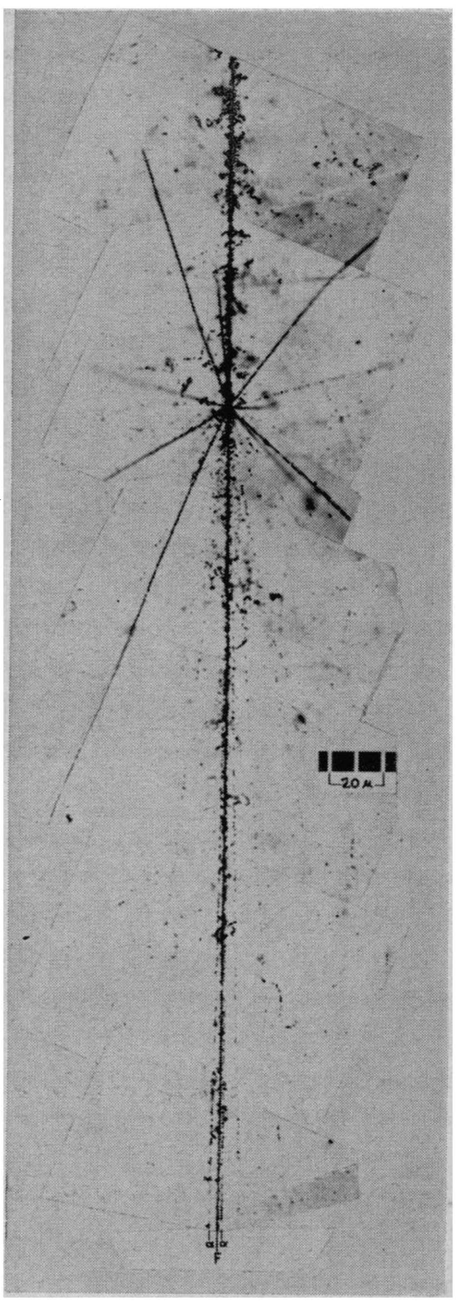

Fig. 2. Nuclear collision and break-up of heavy cosmic-ray nucleus. Secondary production of light nuclei results from fragmentations such as this occurring near the top of the atmosphere.

this ratio (*13*). Combining this information with the Suess-Urey-Cameron data, we see that the relative cosmic-ray abundance of lithium, beryllium, and boron is about 2×10^6 times greater than their relative general abundance (*14*).

Though not impossible, it is very unlikely that these elements abound so anomalously in cosmic-ray sources. A more reasonable interpretation is that these primary light nuclei originate in the fragmentation of heavier primordial nuclei by nuclear collision—mainly with hydrogen and helium—in interstellar space. If this is true, then the observed ratio of light to heavier nuclei indicates that the primordial radiation and its progeny travel, on the average, along paths of millions of light years before reaching the earth. This follows since the average atomic density in interstellar galactic space is less than one atom per cubic centimeter, and the material traversed in 1 light year ($\cong 10^{18}$ cm) is therefore less than $2\ \mu g/cm^2$. On the other hand, the collision mean free paths of heavy relativistic nuclei amount to several grams per square centimeter.

Table 2 shows that the medium and heavy nuclei also have cosmic-ray intensities disproportionate to that of hydrogen, though less spectacularly so than those of the light nuclei. A striking feature in the *M*, *H*, and *VH* groups is the progressive rise in the ratio of cosmic-ray to thermal abundance with increasing atomic weight (*15*). Calculations based on the work of Hayakawa *et al.* (*16*) suggest that this feature may be even more pronounced at the source, with cosmic-ray "overabundance" factors of about 4, 15, and 160 characterizing the *M*, *H*, and *VH* groups, respectively.

The question of the presence and intensity of electrons in the primary cosmic radiation has aroused renewed interest since the discovery within the past decade of nonthermal radio emission from essentially all directions in the galaxy. This radio noise has the properties of synchrotron radiation, and it represents the energy loss of relativistic electrons describing helical motions in a magnetic field. In comparison with the nuclear component—the only well-established component—of the primary cosmic radiation, primary electrons constitute at most a few percent of the intensity of protons with rigidities exceeding 0.3 Bv. Earl (*17*) recently reported a value of 3 ± 1 percent for this ratio, based upon observations made in a multiplate cloud chamber at very high altitude. Figure 3 is a cloud-chamber picture of a shower produced by a high-energy electron at a pressure altitude corresponding to about 0.5 percent of 1 atmosphere. Earl corrected for the contribution of secondary electrons. At about the same time, using quite different techniques, Meyer and Vogt (*18*) obtained a lower limit of 1 percent for the ratio of electrons to protons, and an upper limit of 3 percent, in the interval 0.1 to 1.3 Bv. About a decade ago Hulsizer and Rossi (*19*) found an upper limit of approximately 1 percent for electrons having rigidities above 4.5 Bv, while Critchfield *et al.* (*20*) obtained the same upper limit for a cutoff of approximately 1 Bv. As a result of the recent balloon flights, it seems fairly well established that there is a small but finite flux of primary electrons in the cosmic radiation.

To date there has been no clear evidence of cosmic-ray primaries other than the nuclei and electrons enumerated above. We may expect, however, that refined experiments—some performed in satellites—will reveal the presence of high-energy gamma rays, neutrinos, and neutrons (*21*) incident on the top of the atmosphere. Being uncharged, these particles will exhibit an intensity unaffected by the earth's magnetic field. When techniques of detection become sufficiently subtle and sensitive to permit observation of these particles, they will surely add important information that may compel us to revise drastically some of the present ideas on cosmic-ray origin. For the present, we must be content with the data provided by the charged primaries and with the significant clues recently provided by optical and radio-astronomical observations.

Constancy in Time, Isotropy in Space

At energies above 10 Bev per nucleon, the cosmic-ray intensity is nearly constant in time and isotropic in its directions of incidence upon the earth. The departures from the constancy occur mainly at lower energies and arise principally from solar effects.

The study of cosmic-ray time variations has in recent years become an effective probe for exploring the interplanetary medium and its magnetic fields. These variations may be roughly divided into two categories: (i) those arising from solar modulation of the galactic cosmic radiation by the emission of magnetized plasma clouds that envelop the earth and shield it from the lower-energy primaries (for example, Forbush decreases), and (ii) those due to the production of cosmic rays in the sun's atmosphere and their arrival at the earth. The latter occurrences are relatively rare. In 1959 and 1960 there were instances of solar activity in which both modulation and cosmic-ray production determined the pattern of intensity as a function of time, as observed at the earth.

The former effect—modulation—in addition to producing changes on a time scale of several days, also follows the 11-year solar cycle. At high latitudes, the magnetic shielding of the ionized gas emitted by the active sun reduces the over-all cosmic-ray intensity at the "solar maximum" by a factor of 2 to 4 below its mean value during the quiescent portion of the solar cycle.

In rare, sporadic outbursts the sun generates and emits particles with cosmic-ray energies, mostly below 1 Bev, but as high as tens of Bev in the more violent flares. In these exceptional events, the total "cosmic-ray" intensity at high latitudes may increase many-fold. All these solar effects are important mainly for particle energies of less than 10^{10} ev. This means, to be sure, that they affect a substantial portion of the total intensity. However, above 5×10^{10} ev the cosmic-ray flux may be considered essentially constant with time, at least over the span of decades in which measurements have been made. There are strong indications that in recent geologic time the average cosmic-ray intensity in the solar system has not differed notably from its present level (*22*). The conclusion is based on the abundance of radioactive and stable nuclides produced by cosmic rays in iron meteorites. The amounts of the various species are consistent with the assumption that the cosmic-ray flux has been essentially constant over millions of years.

Over a wide range of cosmic-ray energies, anisotropies exceeding 1 percent can be explained in terms of solar or geomagnetic influences. To a good approximation, the particles having energies of more than a few billion electron volts per nucleon arrive at the outer fringes of the terrestrial magnetic field with equal intensities from all directions. Particles with energies above 60 Bev per nucleon arrive at the top of the atmosphere with equal intensities from all directions. Anisotropies have been diligently sought for the very-high-energy particles, but none exceeding the statistical uncertainty (about 3 percent at 10^{17} ev) has yet been found. In summary, it may be said that cosmic-ray particles of energy above 10 Bev exhibit neither strong time variation nor strong anisotropy.

It may be useful at this point to re-enumerate a few of the salient properties of galactic cosmic radiation.

1) The energy spectra of the various nuclear components all conform to the same power law—that is, the integral flux is proportional to $W^{-1.5}$ when the components have energies ranging from a few Bev up to 10^3 or 10^4 Bev per nucleon.

2) Even at energies greater than 10^6 Bev there is evidence for a gradual rather than a sharp break, but the intensity does seem to fall off somewhat more rapidly at the highest energies (10^6 to 10^{10} Bev).

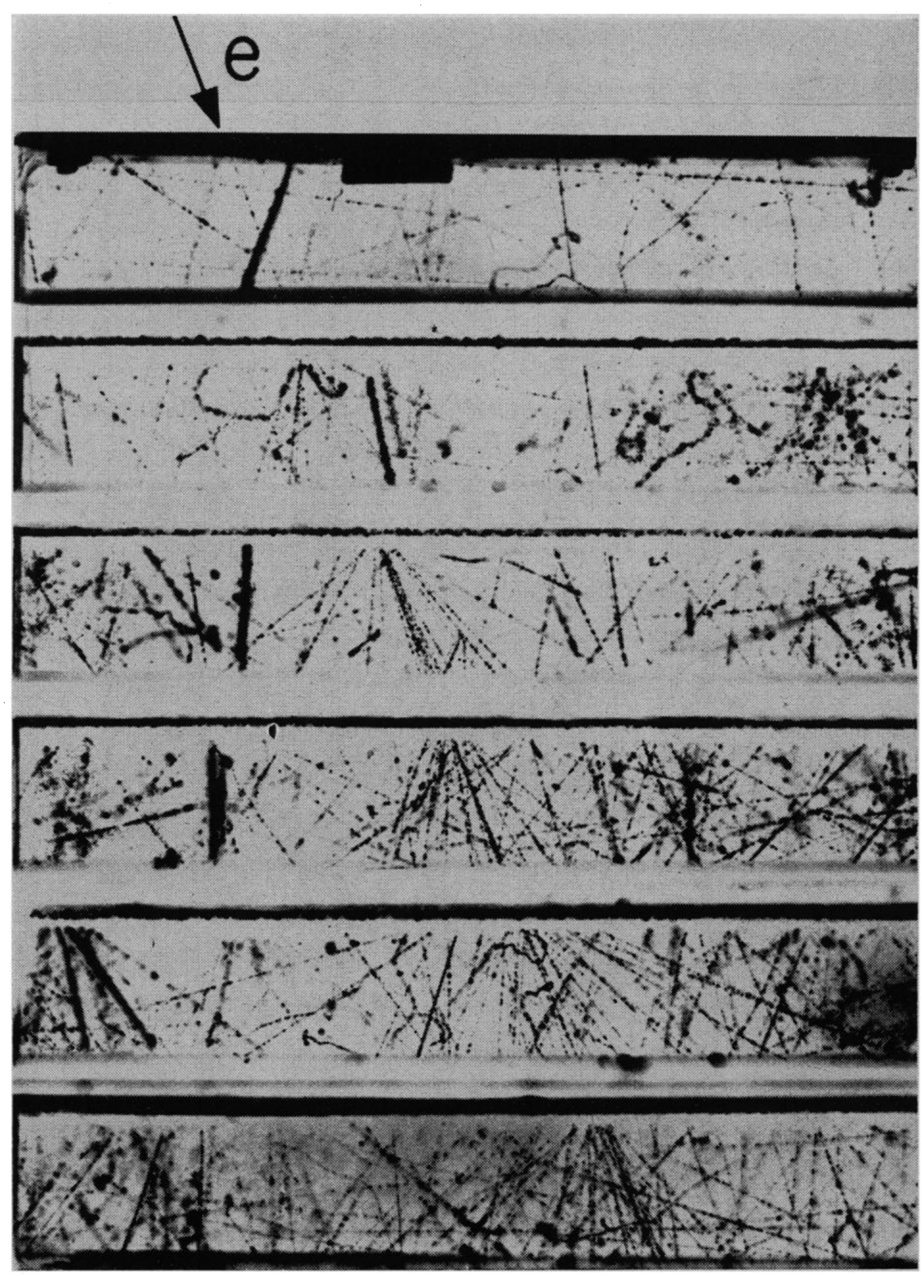

Fig. 3. Electron-photon shower produced by a cosmic-ray electron in a multiplate cloud chamber suspended from a balloon near the top of the atmosphere. From cascades of this type, the flux of primary electrons was deduced (*17*). [Courtesy J. A. Earl]

3) The energy density of the radiation in space is greater than 0.75 ev/-cm^3, when isotropy outside the earth's magnetic field is assumed.

4) Above 10^{10} ev the radiation is approximately isotropic and time-independent.

5) The relative abundances of cosmic-ray hydrogen and helium are similar to their thermal abundance in the sun and stars, while the elements lithium, beryllium, and boron are, comparatively, a million times more abundant.

6) The heavier cosmic-ray nuclei, starting with carbon, are also progressively "overabundant" relative to hydrogen; for example, the iron-hydrogen ratio is higher by nearly two orders of magnitude than in the general thermal distribution of the elements.

7) Electrons are probably present in the primary radiation, to the extent of 2 or 3 percent of the proton flux.

The Sun as a Source

It is known that, in association with extraordinarily powerful solar flares, streams of particles having relatively low cosmic-ray energies are ejected from the sun. These particles are characterized by much steeper energy spectra than the galactic radiation. Since the sun is capable of efficient, if sporadic, cosmic-ray production, one may ask whether the sun might be a major source of cosmic rays. Though the particles are injected only intermittently, could trapping and storage in the magnetic fields of the solar system smooth out the intensity in time and randomize the directions of the particles incident upon the earth?

This hypothesis is beset with many difficulties. First is the inverse correlation between solar activity and cosmic-ray intensity in the course of the sun's 11-year cycle. If the sun were responsible for a major portion of the high-energy particles reaching the earth, then we should expect a higher, rather than a lower, cosmic-ray intensity when the sun is most active. We should also expect a day-night effect, owing to the earth's rotation. Actually, the observed diurnal effect is very small, of the order of 1 percent or less. It is difficult to see how the cosmic-ray nuclei lithium, beryllium, or boron could originate in the sun. Lithium, beryllium, and boron are so scarce in the thermal distribution of elements in the sun that the cosmic-ray nuclei of these elements would have to be produced in collision by the breakup of heavier nuclei. But, even if allowance is made for a long, tortuous path in the solar system from the tenuous envelope of the sun to the earth, the total amount of matter traversed would be too small, by orders of magnitude, to account for their production by fragmentation. There is no evidence thus far for the emission of solar particles with energy of more than 30 Bev, and it is in fact difficult to imagine how particles of energies as great as 10^{13} or 10^{14} ev could be generated by the sun. But even if they were so produced, these particles could readily escape from the limited volume of the solar system, since the interplanetary magnetic fields are too weak to trap them. Hence, under the hypothesis of solar origin, we should expect to find anisotropy at these high energies, and this is not observed.

Thus we arrive at an assessment of the sun as a "cosmic-ray" source. There is no doubt that at energies below 10 Bev, and particularly below 1 Bev, the sun contributes appreciably, though spasmodically, to the "cosmic-ray" flux arriving at the earth. Indeed, for short intervals of time, some of the more powerful solar eruptions sharply increase this flux. However, according to the best available estimates, the time-averaged emission of high-enegy particles from the sun over a year, or a solar cycle, contributes only a small fraction of the cosmic radiation that reaches the earth. The great bulk of the intensity must come from more remote regions of the galaxy or from extragalactic space.

Since our sun is not an uncommon type of star, it follows that a very considerable proportion of the stars in the galaxy are capable of producing and emitting cosmic rays intermittently, at least at moderate energies up to 10^{10} or 10^{11} ev. What of the higher-energy cosmic rays? Many objects in the galaxy—and especially those considerably more active than the sun—have been suspected of serving as cosmic-ray sources—for example, the red giants and supergiants, the T Tauri stars, the magnetic stars, and even the magnetized clouds of gas roving in the spaces of the galaxy.

Especially suggestive evidence, however, points to the expanding nebulosities of supernova outbursts (and perhaps of nova explosions) as sites of particularly powerful and efficient acceleration. In the present brief account I therefore dwell on the following hypothesis: Cosmic rays are accelerated by the turbulent plasma clouds left in the wake of supernova explosions, and, upon emission, they are trapped and stirred by magnetic fields that roam the galaxy. These cosmic rays fill the galactic volume—some 10^{68} cm^3.

The Galaxy

Before we discuss the role of supernovae in cosmic-ray production, it will be useful to look at the modified picture of the galaxy revealed by radio astronomy. Our galaxy is a rotating, quasi-spherical ensemble of some 10^{11} stars, with great clouds of dust and gas occupying much of the space in between. The interstellar medium is pervaded by wandering masses of magnetized plasma. Figure 4, a highly schematic representation, gives some idea of the principal features of the galaxy and the distribution of some of its components. Most of the stars and dust and clouds of gas are to be found near the equatorial plane of the system, and within this disk much of the material is concentrated along spiral arms, and in the galactic core.

Some of the globular clusters, some Cepheid variables, and other faint stars are not confined to the disk but extend into the so-called "halo," or corona, of the galaxy. This is a vast region—an approximate ellipsoid of revolution with its axis normal to the equatorial layer, and having a volume some 50 times that of the disk. Also continuing, in attenuated form, out of the galactic plane into the corona are the plasma clouds that populate the disk. Nonthermal radio noise emitted from these masses of ionized gas revealed the existence of the galactic halo (*23*). A similar radio corona has been observed for the neighboring Andromeda galaxy (M 31, NGC 224).

The disk has a diameter of some 10^5 light years, but it has no well-defined edge, and some stars are found well outside this "boundary," which we have arbitrarily placed where the density falls to about 1 percent of that near the center. For the approximate thickness of the disk we may take a figure of about 10^3 light years; actually, this dimension is more nearly 700 light years viewed optically, and the disk is about twice as thick when "seen" by radio waves. Most of the mass is concentrated in the galactic nucleus, shaped something like a bulging pillbox, some 10^4 light years in radius. Curving out from the galactic core in the equatorial plane are the spiral arms, long suspected by astronomers and confirmed recently by radio astronomy. Our solar system is located in one of these arms, about 30,000 light years from the center. Inside the galactic disk large masses of dark material—presumably dust—obscure considerable portions of the celestial sphere.

The galaxy rotates differentially, its peripheral portions lagging behind the inner ones. The period of revolution of our sun around the galactic center is roughly 200 million years. Recent evidence indicates that the galaxy is considerably older than was once supposed. According to W. A. Fowler and F. Hoyle (*24*), the age of the galaxy is

$$1.5 \begin{smallmatrix} +0.5 \\ -0.3 \end{smallmatrix} \times 10^{10} \text{ years}$$

Though the mean density of interstellar matter in the disk is estimated at 10^{-24} g/cm^3 (roughly 1 hydrogen atom per cubic centimeter), there are considerable departures from this average. Dense clouds, tens of light years in extent, having more or less random motions, are thought to have densities of 100 or even 1000 atoms per cubic centimeter. On the other hand, the tenuous material through which they move, with velocities of the order of 25 km/sec, probably has only about 0.1 atom per cubic centimeter. In the galactic halo the density appears to be less by yet another order of magnitude.

Magnetic Fields

The dilute material that fills most of the galactic volume must be largely ionized by the photoelectric action of stellar light; for example, Fermi has estimated (*25*) that 99 percent of the hydrogen atoms are ionized. This tenuous plasma, stirred into motion by the denser clouds of gas that stream

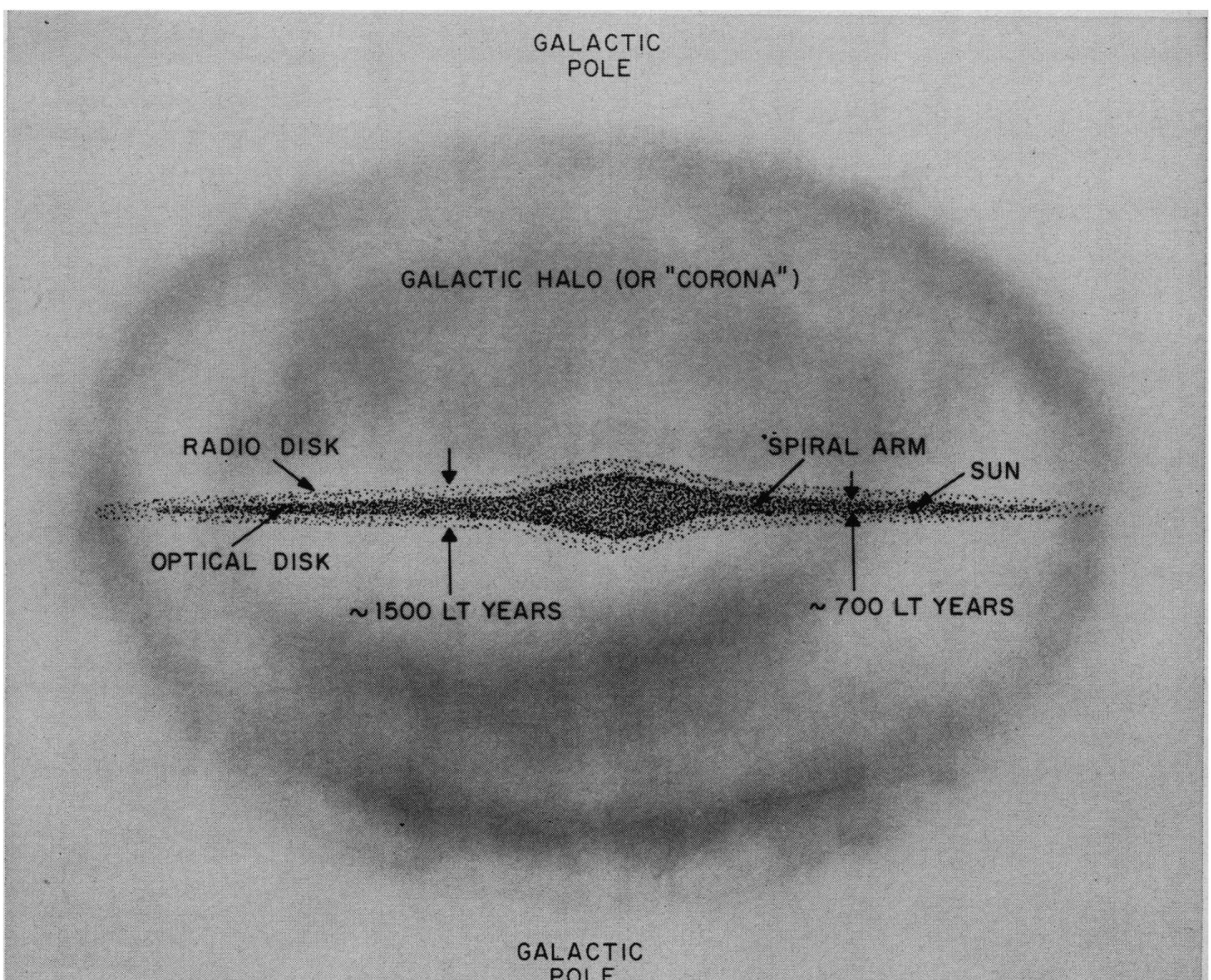

Fig. 4. Cross section through polar axis of the galaxy—a highly schematic sketch. Diameter of major axis, about 10^5 light years.

through it, converts part of its kinetic energy into magnetic energy. As Alfvén pointed out, the electrical conductivity of the interstellar medium is so high that magnetic lines of force become "frozen" to the streaming ions, and the magnetic field is thus carried along with the plasma. Because of the turbulent motions of the gas, we must expect to find chaotic, disordered magnetic fields in the galaxy. Superimposed upon these, however, are larger-scale, ordered fields. Evidence for both comes from measurements on the polarization of starlight. The polarization has been attributed (*26*) to the magnetic orientation of nonspherical dust particles through which the light has passed. There is evidence for the existence of a general magnetic field parallel to the direction of the spiral arm in which the sun is located. If this field were perfectly uniform along a spiral arm, we should expect to receive no synchrotron radiation from electrons spiraling in the field, for this radiation is emitted in the direction of the electron's motion, and the latter would then be in a plane normal to the line of sight. Actually, we do receive synchrotron radiation along the direction of the spiral arm, and this suggests the existence of disorder in the fields on a smaller scale.

In 1953 Chandrasekhar and Fermi (*27*) estimated a magnetic field intensity H_d in the galactic disk of 6×10^{-6} gauss by considering the balance between magnetic and gravitational effects in the spiral arm. Recently, at Jodrell Bank, Davies *et al.* (*28*) obtained an upper limit of the same magnitude from measurement of the Zeeman effect in the 21-centimeter absorption line resulting from the passage of radio waves through clouds of neutral hydrogen. On the other hand, an approximate lower limit to the value of H_d can be deduced from the energy density of the cosmic radiation (see appendix). If the latter is to be contained in the galaxy by magnetic trapping, its energy density cannot exceed that of the confining field; otherwise, the pressure of the cosmic-ray "gas" would push back the magnetic lines of force. So we may write

$$H_d^2/8\pi \gtrsim 0.75 \text{ ev/cm}^3 \gtrsim 1.2 \times 10^{-12} \text{ erg/cm}^3, \qquad (2)$$

from which it follows that

$$H_d \gtrsim 5 \times 10^{-6} \text{ gauss.}$$

It seems reasonable, provisionally, to adopt this estimate as a representative value of H_d until more definitive measurements are available. The average magnetic field in the galactic halo is presumably smaller, perhaps 1 to 3×10^{-6} gauss.

We have already implied that the galaxy can be viewed as a reservoir of magnetically confined cosmic rays thoroughly randomized in direction by turbulent clouds of magnetized plasma. In the course of their long, winding paths, requiring some 10^7 to 10^8 years for traversal, some of the high-energy particles are lost by nuclear collision, while others escape altogether from the galaxy, which is unlikely to be a perfect magnetic trap.

During the past decade this view has been bolstered by the findings of radio astronomy. In addition to radio emission from discrete sources (originally misnamed "radio stars"), it was found that there also exists a general galactic radio emission—a nonthermal radio continuum that streams from vast regions of the galactic halo where no discrete sources are discernible. Its characteristics correspond to the so-called "synchrotron radiation" emitted by relativistic electrons circling or spiraling in a magnetic field. These electrons radiate in accordance with the laws of electrodynamics by virtue of their centripetal acceleration (*29*). At suitably high particle energies in sufficiently strong magnetic fields, the electromagnetic radiation consists of visible light. At lower electron energies in the same magnetic field, or at high energies in weak magnetic fields, the radiation is emitted at radio frequencies. Today, with radio-astronomical evidence pointing to the ubiquitous distribution of relativistic electrons in the galaxy, it is not difficult to envisage the storage of high-energy *nuclear* particles as well. The question remains: How did these particles acquire their high energies? Even before the connection was established between the nonequilibrium radio emission and the presence of cosmic-ray electrons in vast regions of the galaxy, Fermi (*25*) devised a mechanism of cosmic-ray acceleration which can, under the right conditions, yield high energies with adequate efficiency. Alfvén's emphasis on the vital role of hydromagnetics in astrophysical phenomena, and some of Teller's ideas on cosmic-ray origin, influenced Fermi's approach to this problem.

Fermi Theory

Fermi proposed a statistical scheme of acceleration in which ions gain energy, on the average, by encounters with irregularities in moving magnetic fields. He postulated that this mechanism operates in interstellar space. He further assumed that the rate of production of cosmic rays is uniform in time, and that their lifetime is determined by nuclear collision (and, in a later version of his theory, by escape from the galaxy). As is well known, a charged particle entering the region of a stationary magnetic field is subject, in general, to a change in direction. If the magnetic field is in motion, the ion may change its *speed* as well, gaining energy from the field or losing energy to it.

Fermi distinguished two types of "collisions" between an ion and a magnetized cloud of plasma, whereby the general direction of the particle's motion may be reversed. In one of these, a particle executing a helical motion enters a region where the magnetic field is more intense. The pitch angle of the helix decreases until the plane of the particle's orbit is normal to the direction of the magnetic field, whereupon the spiraling ion returns to the region of weaker field (see Fig. 5, top). (This principle of reflection is exploited in the plasma-confining "mirror" devices that operate as magnetic bottles.) In the second type of "reflection" the particle spirals around guiding lines of force that bend sharply, in horseshoe shape. Figure 5, bottom, illustrates this type of motion.

In either of the two cases, if the magnetic field is stationary, the particle's direction is altered but not its speed. Suppose, however, that both the ion and the plasma cloud that it enocunters are in motion. Then, if their relative velocity is increased by virtue of the cloud's motion (for example, in a head-on collision), the ion will gain energy at the expense of the cloud. If, on the other hand, the ion must overtake the plasma cloud in order to "collide" with it, then the particle is decelerated. Because head-on collisions occur more frequently than overtaking collisions, more particles, on the average, gain energy than lose it. We may think of the encounters as collisions between small particles and huge ones. In a "gas" consisting of such objects, with most of the energy residing initially in the massive "particles" (that is, plasma clouds), there will be a tendency toward equipartition; the small particles (ions) will tend to gain energy from the big ones, and thus be gradually accelerated.

Fermi showed that his statistical mechanism of acceleration increases the energy of a relativistic ion at a rate proportional to its energy. This leads to an exponential increase of particle energy with time, which may be written:

$$W(t) = W_i \, e^{\alpha t} \tag{3}$$

Here W_i is the injection energy, and $\alpha = 1/T$, where T is the time for an e-fold increase in the particle's energy. To maintain the time constancy of cosmic-ray density in the galaxy, T must be comparable to the time τ required for loss of the particle by collision or escape. Now,

$$\frac{1}{\tau} = \frac{1}{\tau_c} + \frac{1}{\tau_e} \tag{4}$$

where τ_c is the mean time between nuclear collisions and τ_e is the mean time for escape from the galaxy.

In his earlier theory, Fermi assumed that τ is essentially determined by τ_c—that the loss of cosmic-ray particles is governed primarily by collision—and that τ_e would be considerably longer. Since he estimated the mean time between collisions of protons with atomic nuclei in the galactic disk to be of the order of 10^8 years, the time T required for increasing the energy by a factor e was taken to be of the same order. This led to a relatively slow, inefficient acceleration. A notable success of the theory, however, was that it led in a natural way to an energy spectrum of the type actually observed—that is, to a power law of the form

$$I \propto \frac{dW}{W^{\gamma}} \tag{5}$$

where I is the differential intensity, and

$$\gamma = 1 + T/\tau_c \tag{6}$$

Experimentally, the integral intensity $J_{>W}$ is proportional to $W^{-1.5}$ over a wide range of cosmic-ray energies (see Eq. 1). Hence, $T/\tau_c = 3/2$.

One of the difficulties in Fermi's theory was the following: Competing with the energy gain is loss by ionization, which occurs at a high rate especially in the early stages of acceleration, while the particle is still slow. Hence, in order for the statistical scheme of acceleration to work, injection is required at an energy above some critical value. Fermi did not specify how this injection occurs, except to suggest that certain types of stars might be responsible. It may be remarked that the question of injection is one of the thorny problems confronting any of the proposed mechanisms of acceleration. The rate of energy loss by ionization is particularly serious for the heavier nuclei, with their high charge; their critical injection energies are prohibitively high.

Another difficulty in the theory stemmed from its assumption that the cosmic-ray lifetime is governed by collision with atomic nuclei in interstellar space. However, the mean time between collisions is considerably shorter for the heavy nuclei than for hydrogen, and this difference is hard to reconcile with the observed similarity in the energy spectra of the various components. In a later modification of the theory, therefore, it was assumed that the loss of cosmic rays is determined by escape from the galaxy—that is, that $\tau_e < \tau_c$, with a value of some 10^7 years for the escape time. Therefore, in Eq. 6, τ_e replaces τ_c, and $T = (3/2)\tau_e = 1.5 \times 10^7$ years for the e-fold time of energy gain.

Also, in the later version of his theory, Fermi assigned a more important role to the sharp discontinuities in the galactic magnetic fields. He suggested that the spiral arms of the galaxy may operate as magnetic "bottles" and simultaneously as accelerators. The magnetic trap is analogous to the tube in a plasma "mirror machine" in which the lines of force are crowded together at the extremities of the tube (see Fig. 6). In a similar way, the magnetic lines of force along a segment of a spiral arm may converge to give more intense fields near the ends. Now, if the masses of magnetized plasma near the two ends of the tubular trap approach each other, the ion will not only be confined by reflection but will also be accelerated.

It seems likely that at least some of the cosmic rays that fill the galaxy are accelerated, as Fermi assumed, in the spiral arms, or even in other regions of interstellar space populated by drifting clouds of plasma. If, however, localized regions can be found having particularly favorable conditions for efficient acceleration, then these may turn out to be more powerful sources of cosmic rays. The expanding nebulosities left in the wake of supernova explosions seem to provide propitious conditions, and they have been investigated in some detail, especially by V. L. Ginzburg (*30, 31*), I. S. Shklovsky (*32, 33*), and their collaborators. S. Hayakawa *et al.* (*16*) have made noteworthy contributions.

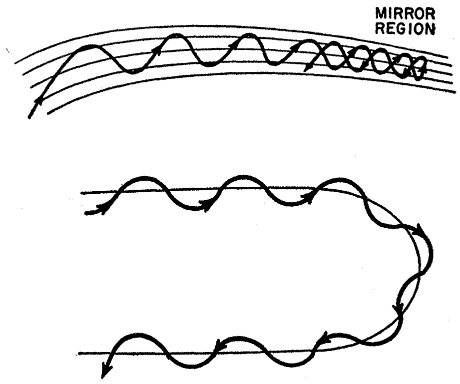

Fig. 5. (Top) An ion executing a quasi-helical path enters a region of intensified magnetic field and is reflected at the mirror point. (Bottom) "Reflection" of a charged particle moving helically around guiding lines of force that bend sharply. If the magnetic field is in motion, the particle may gain or lose energy.

The suggestion that supernovae in external galaxies give rise to cosmic rays was made in 1934, before the main composition of the primary radiation had been established, by Baade and Zwicky (*34*), who drew attention to the enormous energy released in a supernova outburst. They considered that the gross isotropy and time-independence of the cosmic radiation compel us to seek extragalactic sources. At the time, it was not realized that magnetic fields can stir and confine ions of very high energy within the galaxy. Some years later, D. Ter Haar (*35*), also relying on the energetics of supernovae, concluded that they probably serve as injectors of cosmic rays, which are subsequently accelerated in interstellar space by Fermi's statistical process. Soon, how-

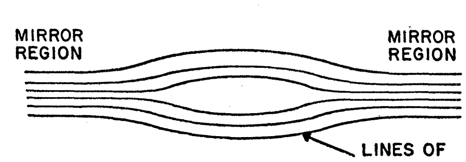

Fig. 6. Configuration of lines of force in a magnetic "bottle." An ion moving in a helical orbit toward either end is reflected in the manner shown in Fig. 5 (top).

ever, the epochal discoveries concerning the nature of the continuous light and radio waves emitted from the Crab Nebula were to lay the groundwork for a more inclusive conception of cosmic-ray production in supernovae. An attractive feature of the present theory is that it provides within our own stellar system a prolific source of high-energy particles—a source capable of acceleration as well as injection. We shall review briefly some of the relevant observations on supernovae and then see how these data fit into the theory of cosmic-ray origin.

Supernovae

On 4 July in the year 1054, an extraordinary new star, about as bright as the planet Venus, appeared in the constellation Taurus. It was visible even in daytime, and its position was recorded by Chinese astronomers. Nearly 900 years later it was noted (*36*) that the Crab Nebula (M 1, NGC 1952) occupies approximately the same position in the sky as the outburst of 1054. The gases in the nebula were found to be expanding radially at a rate such that about nine centuries would have been required for the nebula to attain its present size.

With the advent of radio astronomy, discrete sources of radio emission were discovered and investigated. The first of these to be clearly identified with a visual object was the very intense source Taurus A, whose position corresponds, within observational error, to that of the Crab Nebula (*37*). Within our galaxy at least two other important supernovae have flared up in recent centuries—Tycho's star in Cassiopeia in 1572, and Kepler's star in 1604. Both have been identified with discrete radio sources.

More than 50 supernova explosions have been observed in the last 75 years—all of them in other galaxies. Many of these were discovered in a systematic search with the 18-inch Schmidt telescope on Palomar Mountain (*38*). It is noteworthy that in each of three galaxies as many as three supernova outbursts have been seen in less than 50 years. At its peak luminosity a supernova may shine almost as brightly as the whole galaxy in which it occurs. So prodigious is the flare-up that the change in brightness amounts to 20 magnitudes in extreme instances. This explains how supernovae can be detected in remote stellar systems millions of light years away.

What of our own galaxy, in which supernovae can be seen with the unaided eye? Have no "local" outbursts been observed in the long history of astronomy other than the three since 1054? Investigation of ancient but well-authenticated Chinese astronomical records has revealed (*33*) that three supernovae were also observed in the preceding millennium, in the years 185, 369, and 1006. The first two of these correspond in position to discrete sources of radio emission, and the remains of the supernova of A.D. 369 may be the most powerful radio source known, Cassiopeia A (*39*), though evidence for this is inconclusive. The position of the event of 1006 is poorly defined. Thus, of six recorded supernovae in our own galaxy, the remnants of five have been identified with known sources of radio noise.

It would appear that, on the average, supernova explosions occur in our galaxy once in three or four centuries. However, the actual frequency is probably higher. Additional outbursts, occurring over the past two millennia in more remote parts of our galaxy, may have been unrecorded, or records of them may have remained undiscovered. It has been estimated that the remnants of the six supernovae enumerated above all lie in or near the galactic disk and less than 10,000 light years from the sun (*33*). It seems highly improbable that the neighborhood of our sun is the exclusive domain of supernovae in the galaxy. If, instead, the supernovae were distributed fairly uniformly in the disk out to 30,000 light years from the galactic center (that is, just beyond the radial distance of the sun), then the relevant volume in which supernovae occur would be greater by an order of magnitude, and the corresponding galactic frequency of occurrence would be more nearly once in four decades than once in four centuries. An even higher rate has been observed in a few spiral galaxies—three in several decades. For purposes of calculation, we assume that, on the average, supernova explosions occur in our galaxy about once in a century.

Supernovae have been classified (*40*) into two classes. Those of type 1, which include the three visually observed eruptions in our own galaxy, are the brightest, some attaining absolute magnitudes of −18 or −19. Within 100 days their luminosity diminishes by about four magnitudes, and thereafter it declines exponentially, the light output dropping to one-half its value in about 55 days (see Fig. 7). The gaseous envelope, having a mass of about 0.1 solar mass ($M_\odot$), is ejected with a velocity of about 1000 to 2000 km/sec. Hydrogen is scarce in the expanding shell. Supernovae of type 1 are found in populations of old stars, while those of type 2 appear to be young stars occurring in the arms of spiral galaxies.

Outbursts of type 2, which occur several times as frequently as the more spectacular type 1, seem to be more closely related to flare-ups of ordinary novae. Their brightness at maximum is intermediate between the brightness at maximum of novae and of type 1 supernovae. Their light curves do not exhibit the simple exponential decay of type 1. Hydrogen is abundant in their gaseous ejecta. The mass of the expanding shell amounts to several solar masses, and its rate of expansion approaches 5000 km/sec. Type 2 supernovae are a less homogeneous group than type 1. From the observational evidence, and from considerations of stellar evolution, Hoyle and Fowler (*41*) have suggested that supernovae of type 1 are stars of near-solar mass, while those of type 2 are stars of large mass, some 30 $M_\odot$. In both types, it is generally believed, the explosive energy is provided by the sudden fusion of nuclear fuel. The detailed mechanisms of explosion are, however, considered to be different for the two types.

Nuclear Processes in Supernovae

The most reasonable explanation for the exponential tail in the light curve of type 1 supernovae is that this shape of the curve is attributable to the decay of a radioactive species (*42*). This nuclide has been identified as californium-254, whose half-life against spontaneous fission is the same as the luminosity-decay period of a type 1 supernova (*43*). Though the total energy liberated in a supernova explosion is about 10^{50} ergs, the amount emitted after the onset of exponential decrease in luminosity is about 10^{47} ergs. This energy can be

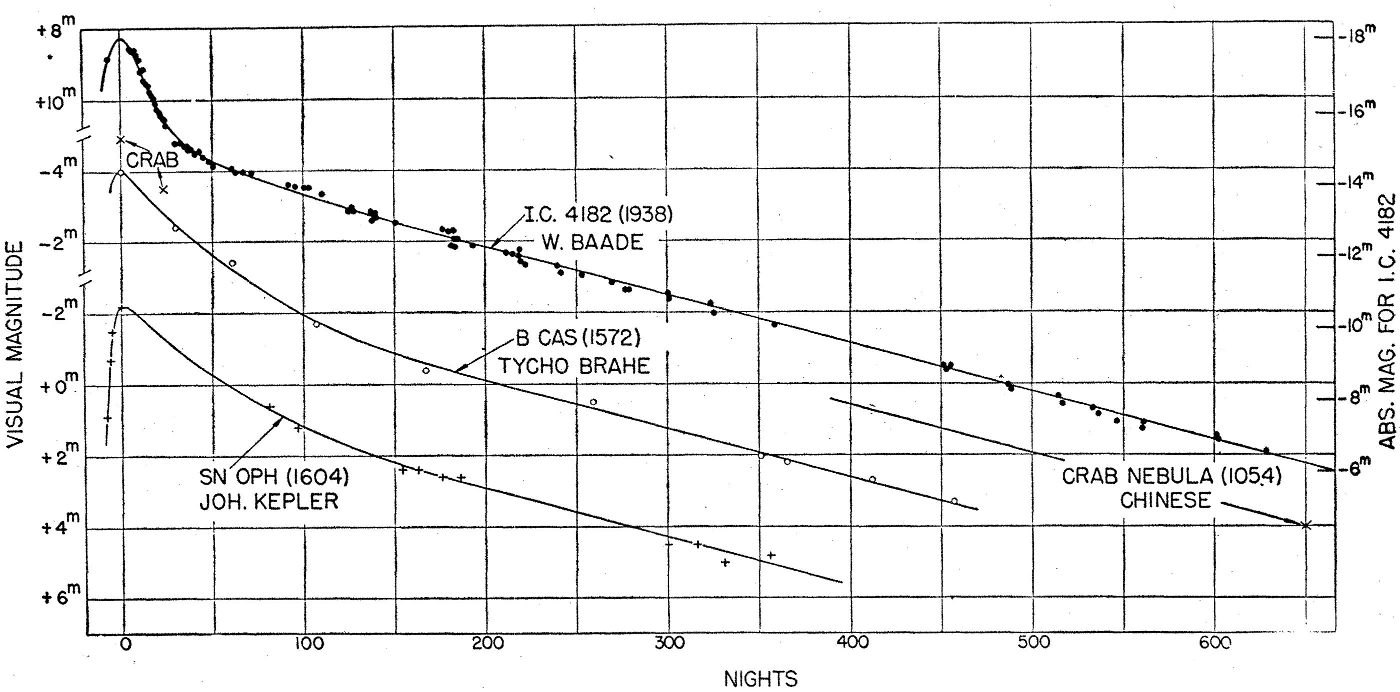

Fig. 7. Light curves of several type 1 supernovae. [After Baade]

supplied by californium-254, with its 200 Mev per fission, provided that about 5×10^{-5} $M_{\odot}$ of this nuclide is produced in a supernova flare-up. How can so considerable an amount of an element as heavy as californium-254 be produced in the very short time available?

The synthesis of heavy elements in supernovae and the nuclear processes involved in their explosion have been investigated by Burbidge *et al.* (*44*). As a star becomes older it gets hotter, and it produces progressively heavier nuclides in its core. At any stage in its development the star burns a nuclear fuel appropriate to its central temperature and is steadily depleted of this fuel. Meanwhile, as energy leaks out of its interior, the star slowly shrinks, and its internal temperature rises, thereby increasing the thermal pressure required for mechanical support. The shrinkage may be interrupted for a time by the onset of a new group of exothermic nuclear reactions that compensate for the radiative loss. In this way the star is first depleted of hydrogen, then, at higher temperatures, helium is burned. At about 1 to 3 billion degrees the synthesis of alpha-particle nuclei (for example, carbon-12, oxygen-16, neon-20) can take place. At higher temperatures, photodisintegration of nuclei occurs frequently, liberating energetic particles; these fuse with other nuclei into heavier nuclei. Thus, at 3 to 5 billion degrees, the most stable elements—that is, those in the vicinity of iron—are produced. These various processes may be effective simultaneously in different regions of the star, the iron-peak nuclei being formed in the hot core while the alpha-particle nuclei are being produced in the surrounding layers. The relatively cool outer layers of the star may still contain some helium or even hydrogen. The fusion of successively heavier nuclei becomes possible as the coulomb barrier is overcome by the rising thermal energies of the reacting nuclei.

In order for explosive fusion reactions to take place in a star, it must have a supply of thermonuclear fuels that release enormous energy ($\sim 10^{17}$ ergs/g) in a matter of seconds—that is, in less than the time required for the star to explode (*41*). Pure hydrogen and helium react too slowly to fulfill this condition, but somewhat heavier nuclei (for example, carbon-12, oxygen-16, neon-20) do fulfill it at sufficiently high temperatures ($\sim$ 2 billion degrees). In describing the conditions that give rise to supernova explosions, I shall first sketch the "implosion$\rightarrow$explosion" hypothesis which was at first assumed (*44*) to be operative for both types of supernovae. Then I shall touch upon the recent revision of the theory, according to which implosion is necessary only for stars with nondegenerate nuclear fuels (type 2), not for type 1.

Let us consider a highly evolved star, its core depleted of helium and consisting largely of the iron-peak elements. As we shall see, a slight further rise in temperature results in instability and leads to implosion. This follows from detailed arguments of statistical equilibrium (*44*). Above 7 billion degrees, iron is rapidly converted to helium. This endothermic process requires too much energy to be sustained by the thermal content of the central material. The energy is supplied by shrinkage of the core. Indeed, so much of the gravitational potential energy is soaked up by nuclear transmutation that too little is available for the increase in thermal pressure required to provide mechanical support. A catastrophic collapse of the core ensues within seconds, and the outer layers, in turn, fall in. These outer regions still had substantial concentrations of light elements—for example, carbon-12 and oxygen-16 (and, in the case of type 2 supernovae, even hydrogen). As this thermonuclear fuel is suddenly heated by the implosion, it burns so explosively that the envelope of the star may be blown off.

What of the californium-254 that is invoked to explain the light curve of type 1 supernovae? If a rich supply of neutrons ($\sim$ 100 per iron-56 nucleus) is available during the explosion, a rapid process (the so-called *r*-process) of successive neutron capture results in the build-up of the heaviest elements. This neutron capture chain must occur on a

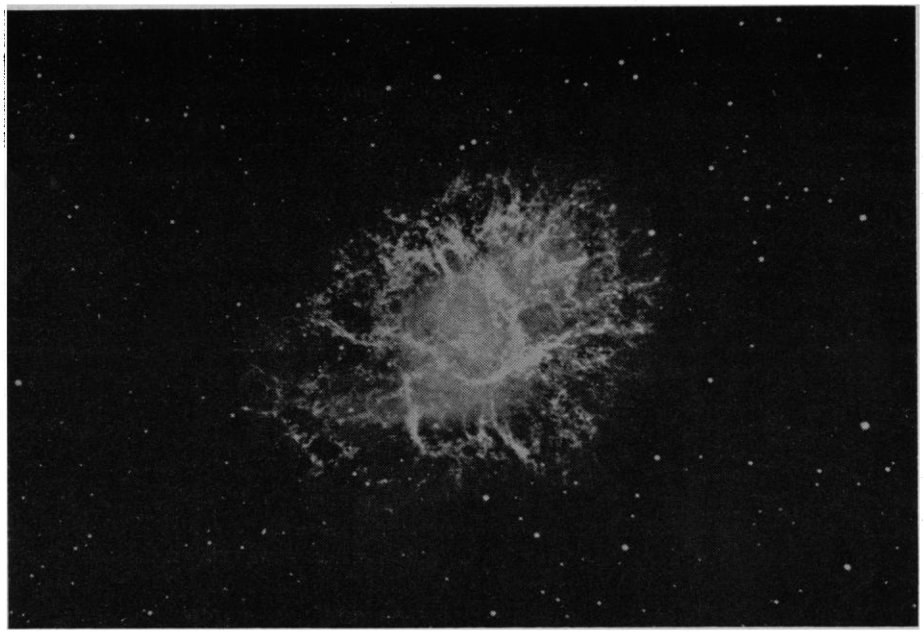

Fig. 8. The Crab Nebula, showing the filaments. [Baade, Mount Wilson and Palomar Observatories, Carnegie Institution]

time scale of seconds if nuclides with large neutron excess are to accumulate faster than they disappear by beta decay. That such synthesis can happen on an even shorter time scale (of the order of microseconds) was demonstrated by the thermonuclear test explosion of November 1952, in which californium-254 was produced. Additional support for the *r*-process is provided by calculations of relative nuclidic abundances; these are in fair agreement with empirical abundance curves. Now, other heavy transuranic nuclides that disintegrate mainly by spontaneous fission decay much faster than californium-254. Hence they do not build up to comparable concentrations. After the more explosive phase of the supernova upheaval is over, the californium-254 thus predominates in energy release, and its 55-day "signature" appears in the declining light curve.

The prolific neutron source required for the *r*-process is hard to find, but the following has been suggested (*44*). In the explosion the small concentration of hydrogen is used up to form proton-rich nuclides that decay by positron emission. Some neon-21 is thus produced (from sodium-21), and it interacts with helium, releasing neutrons (*45*). This requires a low concentration of hydrogen, which is characteristic of type 1 supernovae. In the presence of too much hydrogen (as in type 2), insufficient neon-21 can accumulate, as its radioactive parent sodium-21 is converted by proton capture before it can decay. Thus, the high neutron flux required to synthesize californium-254 is lacking, and accordingly, type 2 supernovae do not display the exponential decline in luminosity characteristic of type 1.

Recently Hoyle and Fowler (*41*) reexamined the astrophysics of stellar explosions, and they concluded that these can originate in two different ways—by implosion of the core, or by the ignition of a degenerate nuclear fuel in the core. Implosion is a necessary precondition for supernovae of tye 2, in which the nuclear fuels are nondegenerate—that is, for massive stars. For the flare-up of a type 1 supernova (typical mass $\sim 1.3\ M_{\odot}$), implosion is unnecessary, since the star's degenerate nuclear fuels are inherently unstable. The resulting explosion may be sufficiently violent to shatter the whole star.

From the theory of nucleogenesis in supernovae it is expected that, in the ejecta of these outbursts, the abundance of elements such as carbon and oxygen will be enhanced relative to that of hydrogen and helium, and that the abundance of heavier elements will certainly be enhanced as compared to their general universal abundance. This corresponds to what is known of the cosmic-ray abundances.

Fig. 9. The Crab, taken with a filter that admits the continuous radiation from the amorphous mass of the nebula. [Baade, Mount Wilson and Palomar Observatories]

Nature of Radiations from the Crab Nebula

Of the known supernova remnants in our galaxy, the expanding envelope of the Crab Nebula is by far the most conspicuous. This remarkable nebula has been well explored by both optical and radio-astronomical techniques, and these have uncovered many revealing clues to its nature. The Crab is a huge, irregular object of quasi-elliptical shape, some 3500 light years away (*46*). Its "major axis" is about 6 light years long, its "minor axis" about 4.

Figure 8 shows the elaborate filamen-

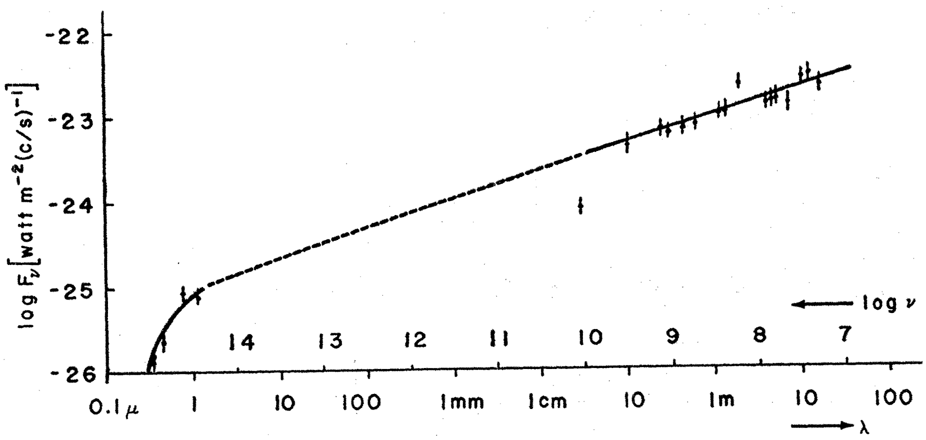

Fig. 10. Continuous spectrum of the electromagnetic radiations from the Crab Nebula, from optical to radio wavelengths. [After Shklovsky, (*33*, Harvard Univ. Press)]

tary structure of the nebula. This network of filaments, which emits a line spectrum, stands out prominently in the light of the H_α region. When the Crab is photographed with a filter that masks the emission lines and admits the continuous spectrum, the lacy filaments disappear and a diffuse, amorphous mass shows up (see Fig. 9). In such photographs, two central stars are visible, and one of these may be the star that flared up in the year 1054. According to Baade (*47*) and Minkowski (*48*), the filaments comprise a peripheral system, while the diffuse, somewhat S-shaped mass fills up the inner structure. This amorphous mass emits an intense continuum that accounts for most of the light radiated by the Crab. In its peculiar distribution of intensity this continuous spectrum differs from that of a black body, and from the spectra of other gaseous nebulae. For a time, the light was thought to result from free-free and free-bound transitions of electrons in a strongly ionized gas, an interpretation that ultimately proved untenable (*49*). Clues to a more satisfactory explanation of this light were to come in later years from an unexpected source—the radio emission of the nebula.

However, before turning to this subject, I digress to mention another noteworthy optical observation: Pictures taken at intervals since the turn of the century show that some local features of the Crab have been changing, though its gross structure has remained unaltered. Bright "ripples" have been observed by Baade to move out from the central zone of the nebula (*50*) at prodigious speeds (~ 0.1 the velocity of light), "almost as though the nebula were breathing" (*33*).

The Crab Nebula has an unusual radio spectrum that differs sharply from the radio spectra of other discrete sources. The intensity remains almost constant over a remarkably extended range of wavelengths, from 25 to 750 centimeters. Shklovsky showed that this radio emission cannot be considered thermal radiation, and he suggested that it is, instead, the synchrotron radiation (magnetic bremsstrahlung) of relativistic electrons trapped in the magnetic fields of the expanding nebulosity (*51*). This interpretation of the nonthermal radio emission from Taurus A gave tremendous impetus to amplification of the hypothesis that the remnants of supernova explosions can be powerful cosmic-ray sources.

The idea that the radio emission from certain celestial sources is due to relativistic electrons emitting synchrotron radiation was advanced by Alfvén and Herlofson (*52*). They pointed out that the emission from "radio stars" is very unlikely to be produced by any object as small as a star. They suggested instead that it originates in cosmic-ray electrons that fill a vastly larger volume —the magnetic trapping field surrounding a star. Kiepenheuer (*53*) and Ginzburg (*54*) attributed the general *galactic* nonthermal emission to the magnetic bremsstrahlung of cosmic-ray electrons, and Ginzburg showed that the calculated spectrum agrees with the observed one. As we have seen, Shklovsky concluded that the same mechanism, that of synchrotron radiation, can be invoked to account for the radio emission from the Crab. He went further and showed that the optical continuum emitted from the amorphous mass of the nebula is also readily explained as the higher-frequency, synchrotron radiation of electrons having energies higher by several orders of magnitude than the energies of electrons emitting the radio waves (*49*).

Thus, two widely disparate regions of the electromagnetic spectrum of radiations from the Crab were boldly connected. Figure 10 illustrates Shklovsky's conception of the common origin of the optical and radio emissions, the former due to electrons of energy about 10^{11} to 10^{12} ev, and the latter, to electrons of energy about 10^8 to 10^9 ev.

Ginzburg (*55*) and, independently, Gordon (*56*) pointed out that if the continuum from the Crab consists of synchrotron radiation, it should be polarized. This important prediction was confirmed the same year by means of photoelectric (*57*) as well as photographic (*58*) techniques. Polaroid filters have been employed to transmit light with various orientations of the plane of vibration of the electric vector. With the 200-inch Palomar telescope, Baade (*59*) obtained some remarkable photographs, of which two are shown in Fig. 11. The plane of the electric vector for one exposure was perpendicular to that for the other, and the resulting pictures are strikingly different. Many features visible in one are absent from the other. Were it not for the matching positions of stars in the background field, the viewer might suppose that he is looking at two different celestial nebulosities. These arresting pictures provide vivid evidence of polarization.

Similar photographs at other orientations of the polaroid filter show that as the latter is rotated, each of the structures in the amorphous mass changes in brightness. As Baade observed, a structural feature tends to disappear when the electric vector is parallel to it—that is, when the magnetic field is normal to it. It is possible in this way to sketch the local direction of the magnetic field (*50*), and a revealing pattern emerges: The shapes of the structural elements in the diffuse nebulosity conform to the directions of the lines of force. Similar conclusions can be drawn from detailed photoelectric measurements of the polarization. From Fig. 12 it is evident that the direction of the electric vector changes in a fairly systematic way across the nebula (*60*) and that a correlation exists between the degree of polarization and the morphology of the diffuse mass. Woltjer (*60*) found polarizations stronger than 50 percent in some areas and nearly 100 percent in others.

Since the light of the continuum proved to be polarized, it seemed reasonable to search for polarization of the nonequilibrium radio emission as well. At first the result was disappointing, apparently owing to rotation of the plane of polarization by the Faraday effect when radio waves pass through a magnetized plasma (*33*). This effect is large at meter wavelengths, and even at 22 centimeters. However, at a wavelength of 31 millimeters, Mayer, McCullough, and Sloanaker (*61*) found a 7-percent polarization with the electric vector rotated only 11 degrees from the direction of the optical electric vector.

The discovery that the continuous light and the radio waves from the Crab are polarized provides evidence that both radiations consist of magnetic bremsstrahlung generated by energetic electrons moving helically in magnetic fields. Indirectly it also supports the hypothesis that the general, nonequilibrium radio emission of the galaxy likewise originates in the magnetic deceleration of relativistic electrons.

A crude upper limit for the average magnetic field intensity $\bar{H}$ in the envelope of the Crab can be estimated by comparing the magnetic energy stored in the field to the kinetic energy of the expanding shell.

$$\frac{\overline{H^2}}{8\pi} V_c < \tfrac{1}{2} m v^2$$

The volume V_c of the envelope is about 10^{55} cubic centimeters. If we take its mass

$$m \approx 0.1\, M_\odot = 2 \times 10^{32}\,\mathrm{g}$$

and velocity $v = 10^8$ cm/sec, then

$$\bar{H} < 5 \times 10^{-4}\ \text{gauss.}$$

From other considerations, Pikelner (*62*) has estimated $\bar{H}$ to be 3×10^{-4} gauss.

Supernovae as Cosmic Ray Sources

Certain characteristics of supernovae, inferred from the observations and theories described in this article, suggest that the young remnants of a supernova eruption constitute a powerful source of cosmic rays. Among these features are the following: an enormous energy release, a copious supply of relativistic electrons, large-scale magnetic fields, extended masses of plasma moving at high velocities, indications of the propagation of hydromagnetic waves (the light "ripples"), and relatively high concentrations of heavier elements. Hence, a very plausible theory of cosmic-ray origin in supernovae has been developed (*31, 33*).

According to this theory, the relativistic nuclei and electrons that fill the galactic volume originate in the tenuous remnants of supernova explosions, and perhaps in the ejecta of ordinary novae as well. The particles are somehow injected, and then accelerated by the action of magnetic fields in the supernova shell. The most prolific production of cosmic rays takes place in the early decades following the outburst (*33*), since in later epochs the continued expansion of the nebula counteracts the acceleration; it tends to "cool" the particles, much as a gas is cooled by adiabatic expansion. However, the particles are retained in the nebular envelope for a much longer time, perhaps several thousand years, after which the expanding shell is damped by and dissipated into the surrounding interstellar medium. The nebula tends to remain a "closed system" as long as its magnetic fields are much more intense than those in the interstellar vicinity, for then the ions tend to be reflected from the

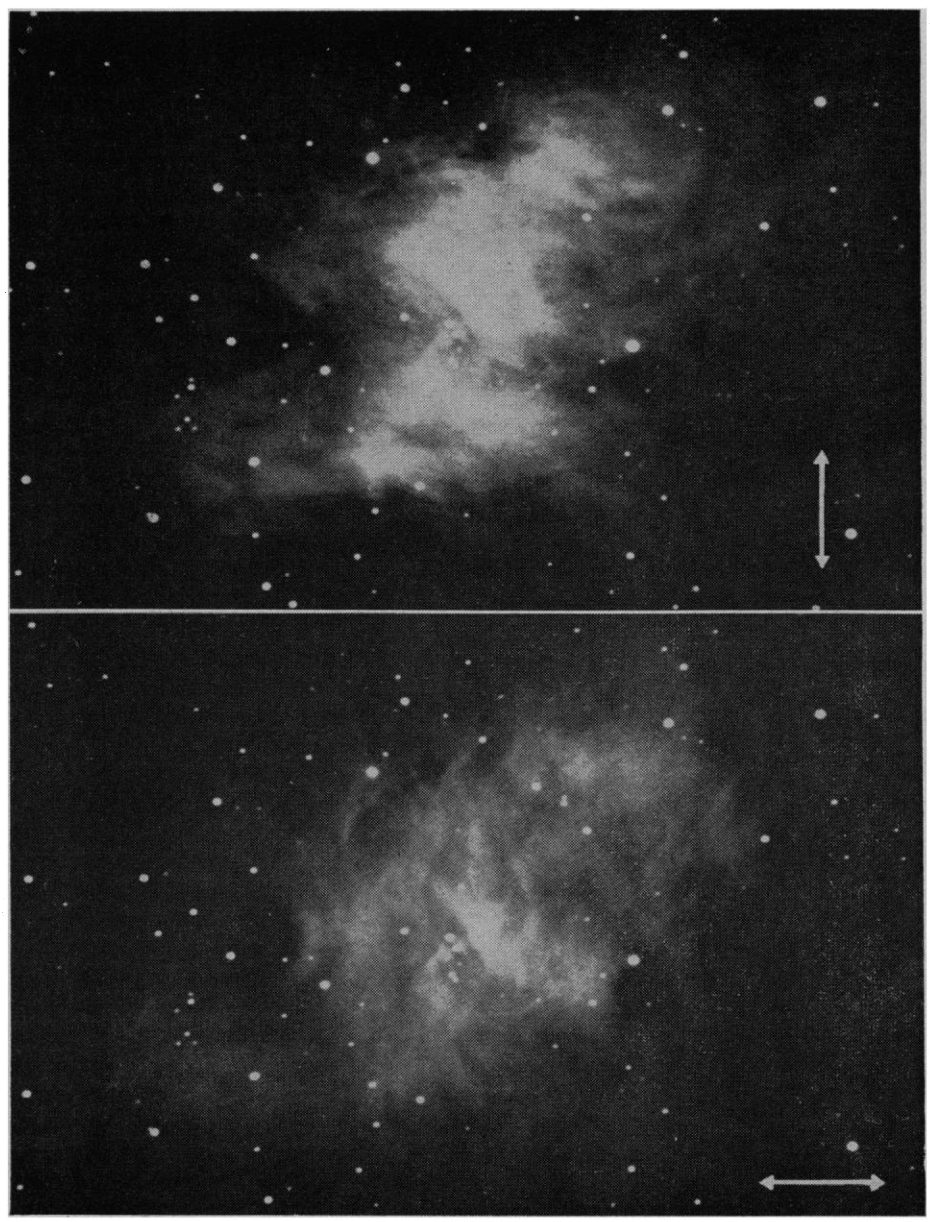

Fig. 11. The Crab Nebula, taken through polaroid filters, showing polarization of the light of the continuum. The polaroid filter was so oriented that the plane of vibration of the electric vector in one photograph was normal to that in the other. [After Baade (*59*)]

boundaries of the gaseous shell. Once the expansion has proceeded to a point where the magnetic fields become more nearly comparable to the external field, the cosmic-ray particles are less efficiently confined, and they leak out into the galaxy.

Then begins a process of slow diffusion, first in the galactic disk and then into the large volume of the galactic halo. The paths of the particles during their long period of diffusion are very tortuous, since they are not only spiraling in the magnetic fields of the galaxy but are also being scattered, from time to time, by drifting plasma clouds. Through these mixing processes the particles "forget" their original direction and tend to acquire an isotropic distribution. Meanwhile, the electrons —and especially the higher-energy ones —lose energy by magnetic deceleration, the nuclei lose energy through nuclear collisions, and both steadily drop out of the cosmic-ray reservoir in the galaxy. Both must be replenished if this "reservoir" is to be maintained, and the theory asserts that a fresh supply of relativistic nuclei is provided by new supernova explosions.

To ascertain the adequacy of the rate of supply, we can estimate the rate of particle loss and of energy loss and compare these with the output of supernovae. Since many astrophysical quantities are known only to within an order of magnitude, the reader should not consider the numerical values employed or deduced in the discussion that follows to be precise. In fact, as V. L. Ginzburg has aptly remarked, a formula worth remembering in the present state of the theory of cosmic-ray origin is

$$1 \approx 10$$

We assume that the average density of cosmic rays in the galaxy has been constant in recent geologic time. We shall compare the rate of production of relativistic particles in supernovae with their rate of disappearance in the entire galaxy. From the theory of synchrotron radiation, observations of the nonequilibrium radio flux at the earth, and estimates of the magnetic intensity, it is possible to compute the total supply of electrons N_e with energy exceeding 10^8 electron volts in the Crab, and in Cassiopeia A, the most intense radio source. Shklovsky (*63*) has deduced $N_e = 2 \times 10^{50}$ and 10^{52}, respectively, for these sources. We tentatively assume that the number N of relativistic nuclei produced is comparable to the number of electrons, and we take $N = 10^{51}$ as the total number supplied to the galactic reservoir by an "average" supernova. With a frequency of one galactic supernova outburst per century (that is, of 3×10^{-10} per second), the over-all cosmic-ray-source strength of supernovae in the galaxy is 3×10^{41} particles per second. If we add to this the contribution of ordinary novae (discussed in subsequent paragraphs), the production rate could be higher.

Next we estimate the rate of disappearance of relativistic protons from the galactic volume. We assume that the magnetic lines of force in the galaxy form a relatively closed system, so that reflection from the boundary will tend to keep particles in. (Some astrophysical data favor such a closed configuration.) Then the rate of loss of cosmic-ray nuclei—that is, their degradation to subrelativistic energies—will be determined by their rate of collision (*64*). The number so degraded per cubic centimeter per second is of the order $n\nu\sigma c$, where n is the mean density of galactic cosmic-ray nuclei, taken as 1.2×10^{-10} per cubic centimeter, the value near the earth (see appendix, Eq. *A5*); ν is the atomic density averaged over the galaxy (≈ 0.01 per cubic centimeter [the particles spend most of their time in the halo]); σ is the effective cross section for "destructive collision" of a proton [$\approx 2.8 \times 10^{-26}$ cm^2 (that more than one collision is required for a relativistic proton to lose most of its energy is taken into consideration) (*31*)]; and c is the velocity of the particles, taken as equal to that of light. Hence, the rate of loss is 10^{-27} nuclei per cubic centimeter per second, and in the whole galactic volume of 10^{68} cm^3, the rate is 10^{41} per second. When this number is compared with the average rate of production, the source strength appears adequate to account for the observed cosmic-ray flux.

It should be remarked that if we adopted an "open" model for the galaxy, with weak reflection of relativistic ions at the boundary, then leakage would enhance the rate of loss, and a larger rate of supply would be required to maintain the density in the galactic reservoir. However, this does not seem to present a serious difficulty, since, with due allowance for the uncertain values of the parameters, and for the possible contribution of novae, the rate of supply could be as great as 10^{42} per second or even higher.

We have estimated that the rate of particle output from supernovae suffices to maintain a steady flux of galactic cosmic radiation. Another, and perhaps more exacting, test would be to determine whether the energy lost by cosmic-ray particles in the galaxy can be supplied at an adequate rate by supernovae. The rate at which cosmic-ray nuclei lose energy in the galaxy can be estimated from the ratio:

$$\frac{\bar{u}V}{\tau_c} = \frac{\text{cosmic-ray energy in the galaxy}}{\text{lifetime of cosmic-ray nuclei}}$$

where $\bar{u}$, the mean energy density, is about 1.2×10^{-12} erg/cm^3 (see appendix, Eq. *A7*) and V is 10^{68} cm^3. To estimate the nuclear lifetime τ_c against destruction by collision, we take

$$\tau_c = \frac{\text{mean free path for absorption}}{\text{velocity of particles}} = \frac{1}{\sigma\nu c}$$

where σ, the effective absorption cross-section for protons colliding with interstellar gas atoms, equals 2.8×10^{-26} cm^2 (see *31*, table 5); ν equals 0.01 atom per cubic centimeter; and c is the velocity of the particles (approximately equal to that of light). Thus,

$$\tau_c = 1.2 \times 10^{17} \text{ sec}$$

or 4×10^9 years.

With this value for the lifetime, the rate of energy loss by cosmic-ray nuclei in the whole galaxy is

$$\frac{1.2 \times 10^{-12} \times 10^{68}}{1.2 \times 10^{17}} = 10^{39} \text{ erg/sec}$$

The rate at which the cosmic-ray electrons in the galaxy lose energy by magnetic deceleration has been estimated as 10^{38} erg/sec (*65*).

If supernovae were solely responsible for the entire production of galactic cosmic rays, then the cosmic-ray energy output required from an average supernova outburst (assumed to occur about once per century) is approximately

$$\frac{\text{Rate of cosmic-ray energy loss in galaxy}}{\text{Frequency of supernovae}} = \frac{10^{39} \text{ erg/sec}}{3 \times 10^{-10}/\text{sec}} = 3 \times 10^{48} \text{ ergs}$$

This energy requirement is large, but it does not appear unreasonably so; it is comparable in magnitude to the turbulent kinetic energy in the nebular envelope, and to the energy residing in the magnetic field. Hoyle and Fowler (*41*) have estimated the total energy output from a type 1 supernova explosion as 6×10^{50} ergs. Thus, only a fraction of 1 percent of the energy released would be needed to satisfy the requirement of a quasi-stationary cosmic-ray density in the galaxy. If ordinary novae were also contributing significantly to the cosmic radiation, the cosmic-ray energy output requirement for the supernovae could be correspondingly reduced.

Analysis of the nonequilibrium radio emission from the galaxy under the well-founded assumption that it is synchrotron radiation makes it possible to relate the observed frequency spectrum of this radiation to the energy spectrum of the electrons responsible for it. The differential energy spectrum so deduced can be expressed as a power law:

$$I\,dW \propto W^{-2.6}\,dW$$

Thus, within the uncertainty of measurement, the exponent of this spectrum has a value indistinguishable from that of the primary cosmic-ray spectrum near the earth. This circumstance may be fortuitous, but it seems at least suggestive, notwithstanding the fact that the primaries observed at the earth are almost entirely nuclei rather than electrons. A possible explanation for the similarity in the spectra will be mentioned below.

In a previous section we have reviewed the convincing evidence, both optical and radioastronomical, for the presence of rather strong magnetic fields in the Crab Nebula. In fact, we have seen how detailed studies of the polarization make it possible to map the magnetic lines of force. How does the magnetic field arise? It might happen in the following way. Let us assume the existence of a magnetic field (for example, the general galactic field) in the vicinity of the presupernova. After the outburst, turbulent motions inside the expanding gas will snarl up the magnetic lines of force and lead to intensification of the field.

The mechanism of acceleration is one of the important aspects of any theory of origin. Ginzburg (*66*) has proposed a statistical process of the Fermi type, with the important difference that the conditions inside a young supernova envelope are much more favorable for acceleration than those in interstellar space. The turbulent clouds of gas in the nebula have high velocities of the order of several hundred kilometers per second. Gradually, the kinetic energy of this large-scale mass motion is converted, in part, to the energy of cosmic-ray particles.

From our earlier discussion of the Fermi process we saw (Eq. 6) that the exponent γ in the differential energy spectrum is related to the time T of acceleration and the lifetime τ of cosmic rays, as follows:

$$\gamma = 1 + T/\tau$$

When the experimental value 2.5 is taken for γ, T is of the same order as τ.

Under conditions of acceleration in interstellar space, τ and T must both be of exceedingly long duration. Whether the lifetime be governed by collision or escape, τ is of the order of 10^8 or 10^9 years, and the acceleration process is correspondingly slow. Under the special conditions in a supernova shell, the frequency of accelerating "collisions" becomes much higher; thus T can be more nearly 100 or 1000 years, and the time τ for escape by diffusion from the region of acceleration would be of the same order. Hence, the statistical acceleration process seems much more efficient within a supernova nebula than in the vast spaces of the galaxy.

Other schemes of acceleration have been discussed (*16*)—for example, collisions between charged particles and hydromagnetic shock waves. I have alluded briefly to the fast-moving "ripples," or wisps of light that are observed to travel outward several times a year inside the Crab Nebula. These have been attributed to hydromagnetic shocks, and the energy in a single ripple has been estimated as 10^{43} ergs (*60*). Hayakawa *et al.* have concluded that a statistical mechanism would not be effective in accelerating electrons in the Crab, since their rate of energy loss by magnetic deceleration exceeds their rate of energy gain by a Fermi process. We shall return below to the question of the origin of the relativistic electrons.

Another apparent difficulty in applying the Fermi mechanism to acceleration in supernovae has been discussed by Peters (*67*). If comparable numbers of electrons and nuclei are accelerated, this could lead to storage of an excessive amount of energy in the nuclear component. Since, in the statistical type of acceleration, the energy gained by an ion is proportional to its rest mass, the energy acquired by the nuclear component would be at least 2000 times greater than that acquired by the electrons. The total energy requirement would then be excessive. This difficulty would be mitigated if nuclei were accelerated less efficiently than electrons. This could result, for example, if the major part of the electron component originated in the decay of radioactive atoms (as discussed below). The electrons would then start off with relativistic energies, and their subsequent acceleration would be greater.

Colgate and Johnson (*68*) have proposed a hydrodynamic origin of cosmic rays in supernovae. According to their hypothesis, cosmic rays are the "blown-off" surface layers of an exploding supernova. The energy liberated in the core of the star generates a powerful shock wave that speeds up in the decreasing density of the outer layers. The shock wave becomes relativistic well inside the mantle of the star, and the outermost layers are ejected with velocities close to that of light.

Let us return to the question of how the relativistic electrons originate. From the nuclear processes involved in a supernova explosion, it is clear that the ejected material contains large quantities of various radioactive species. The beta decay of some of these nuclides could inject electrons into the envelope of the supernova, where further acceleration could take place. These electrons, already relativistic at their initial energies (of the order of 1 Mev), would have a "head start" in the process of acceleration.

Another mode of origin suggested for the cosmic-ray electrons is that some, or even most, of them arise as progeny of pi mesons born in collisions of the nuclear component. The pi mesons decay into muons, and these, in turn, disintegrate into electrons. In this process, whether it occurs in a supernova shell or in interstellar space, the energies acquired by the electrons can be fairly high, depending, of course, on the energy of the parent nuclei. We have already encountered two circumstances that tend to support this secondary mode of origin for the electrons. One is the similarity between the spectrum of the electrons responsible for the nonthermal galactic radio noise and the spectrum of the cosmic-ray nuclei arriving at the earth. The other is the observation that the rate at which the relativistic electrons stored in the galactic volume lose energy appears to be less by an order of magnitude than the rate of loss by the nuclear component of the galactic cosmic radiation. This is what we should expect if the electrons were predominantly of secondary origin. Another result we might expect if this mode of origin were predominant is the occurrence of comparable numbers of positrons and electrons, since positively and negatively charged

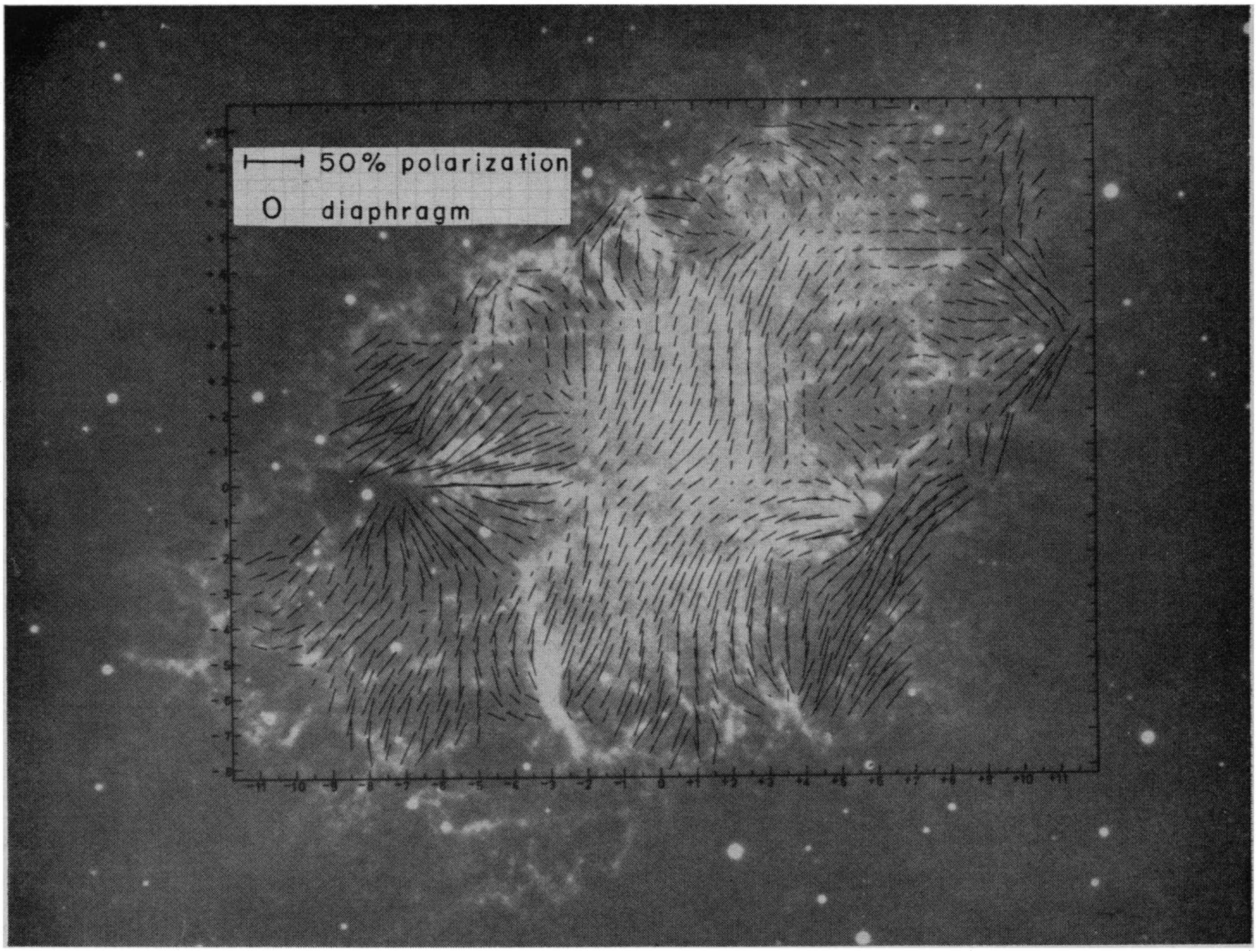

Fig. 12. Mapping of the degree of polarization in the Crab Nebula. At each point the magnetic field is normal to the direction of the electric vector. [After Woltjer (*60*)]

pi mesons are generated in approximately equal numbers. Evidence for the presence of positrons among the primaries in the vicinity of the earth would tend to confirm the hypothesis of secondary origin. Experiments on the primary electron component near the earth are still in their infancy, and we do not yet know the details of their charge composition or spectrum.

It is, however, noteworthy that in recent balloon-flight experiments (*17*, *18*) a primary cosmic-ray electron density at the top of the atmosphere of approximately 10^{-12} per cubic centimeter has been detected. This density is of the same order as that which must be ascribed to the galaxy as a whole in order to account for the observed flux of synchrotron-type radio emission.

Thanks to radio astronomy, we can now "observe" cosmic-ray particles in distant parts of the galaxy, both in sources such as supernovae and in the general galactic volume where they are stored. However, it is only the cosmic-ray *electrons* whose presence is revealed in remote regions of the galaxy through their synchrotron radiation. Relativistic *nuclei* are too massive to lose energy by magnetic deceleration. Nevertheless, their presence (and their production) in supernova nebulae appears extremely likely. Whether the electrons acquire their energy through a Fermi process or through some other electromagnetic acceleration, there is no reason to doubt that positive ions present in the same region will also be accelerated. Of course, if a considerable part of the electron component originates as secondaries (through π-μ-e decay) of nuclear collisions, this would imply a large flux of relativistic nuclei.

If the cosmic-ray nuclei are accelerated in accordance with a Fermi stastistical mechanism, then they could acquire maximum energies about 10^3 times as great as those of the electrons, since the energy gained is proportional to the rest mass of the particle. Hence, the energies per nucleon could go up to 10^{15} or 10^{16} ev, and the energy acquired by an individual nucleus (say iron) could be as high as 10^{17} or 10^{18} ev.

What, it may be asked, is the maximum energy at which magnetic confinement within the galaxy is still effective? In other words, at what radius of curvature do particles readily escape from the galaxy? (For particles with higher energies, we may be compelled to seek an extra-galactic origin.) In trying to answer this question, let us base our estimate on a rather stringent requirement for trapping: that the particle's radius of curvature be less by two orders of magnitude than the linear dimensions of the galaxy—that is,

$$r < 10^{-2} \times 10^{23}\ \text{cm} \approx 10^{21}\ \text{cm}$$

or about 10^3 light years. It should be remembered that particles need not be confined to the galactic disk but may diffuse into the halo. When the average magnetic field strength $\bar{H}$ in the galaxy is taken to be 2×10^{-6} gauss, we find from Eq. A4 (see appendix) that

$$E_n = EA < 300\, Z\bar{H} r_{\max}$$
$$EA < 6 \times 10^{17}\, Z \text{ ev}$$

For protons, $E < 6 \times 10^{17}$ ev; for complex nuclei ($A \approx 2Z$), $E < 3 \times 10^{17}$ ev; for iron nuclei, the energy per nucleus is $E_n = EA < 1.6 \times 10^{19}$ ev.

As mentioned earlier, the largest air showers detected thus far (*6, 7*) were apparently produced by particles with energies of several times 10^{19} ev. If the upper limit of observed energies should continue to climb, as it has done hitherto, it may become necessary to ascribe an extragalactic origin to the most energetic particles. Whether we are already compelled to invoke this hypothesis to account for the observations to date is at least debatable.

Having sketched, albeit inadequately, the theory of cosmic-ray production in supernovae, I might list some of the features of the cosmic radiation that the theory seems capable of explaining. (i) The source strength appears adequate to account for the observed particle density and energy density in the galaxy. (ii) The energy spectrum of the primary cosmic-ray nuclei observed near the earth is consistent with a Fermi-type acceleration at the source, and with the galactic electron spectrum inferred from radio-astronomical observations. (iii) The isotropy and time-independence of the galactic radiation are natural consequences of the assumed diffusion and storage in the galactic halo. (iv) The overabundance of heavy elements in the cosmic radiation is to be expected from the nuclear processes involved in both the presupernova and its explosion. (v) The primary electron density observed with particle detectors at the top of the atmosphere appears to agree with the predictions of the theory.

I have mentioned the possible contribution of ordinary novae. These outbursts, though much less spectacular than those of supernovae, must also give rise to large masses of gas in chaotic motion; the conditions in their remnants could also favor the production of high-energy ions. The number of relativistic particles would be much smaller than those in a supernova, probably in proportion to the energy released by the explosion. In our galaxy, novae occur about 10^4 times as often as supernovae; the energy liberated in such an explosion is of the order of 10^{-4} times as large. Hence, the net contribution of the novae to the supply of cosmic radiation could be comparable to that of the supernovae. It will not be easy to verify this directly, since the supply of high-energy electrons in the ejecta of a nova would probably be too small to produce radio noise of a detectable intensity, unless the exploding star were in our immediate galactic neighborhood.

This last possibility brings up an interesting speculation by Krasovsky and Shklovsky (*69*). I have already mentioned indications from georadiochemical studies that the galactic cosmic-ray intensity in the vicinity of the earth has not differed much in recent geologic time from its mean level today. However, this situation may not always have prevailed. Suppose that at some remote epoch in geologic time a supernova had flared up in the neighborhood of the solar system (say, at a distance from it of less than 50 light years). Then the cosmic-ray intensity at the earth may well have risen by a large factor. This could have significantly increased the rate of mutation in terrestrial plants and animals. Since most mutations are harmful, the heightened exposure to radiation might have led to the rapid decline of many species (for example, the dinosaurs).

In the present article I have concentrated on a particular theory of cosmic-ray origin. Many other ideas on cosmic-ray origin have been advanced, and some of these have been combined in the eclectic approach of Cocconi (*70*), Morrison (*71*), and Hayakawa *et al.* (*16*). These authors acknowledge that supernovae appear to be significant cosmic-ray sources, mainly in the energy interval 10^{12} to 10^{16} ev. However, they attach considerable importance to the role, especially at lower energies, of sources such as red giants, supergiants, magnetic stars, and T Tauri stars. They regard the particles of very highest energy (say, above 10^{16} ev) as extragalactic origin. According to one view, the hydrogen and helium primaries originate mostly in red giants and supergiants, while the heavy nuclei come from supernovae (*16*). The observed power-law spectrum, notwithstanding its validity for the different nuclear components, is not attributed to a single process of acceleration but is, rather, explained as the summation of several power laws, each valid over a wide energy interval (*70*). An interesting, and quite different, theory developed by Biermann and Davis (*72*) explores the possibility that the cosmic radiation originated at an early stage in the evolution of the galaxy.

In conclusion, it should be remarked that the proponents of the supernova theory do not deny the possibility of contributions from other cosmic-ray sources. However, they consider these contributions to be of minor significance, and they believe that supernovae and ordinary novae can account for nearly all of the known facts about the galactic cosmic radiation.

The difficulties confronting the supernova theory cannot be lightly dismissed; we have been able to touch on only a few of them. Nevertheless, the impressive successes already achieved by the theory suggest that supernova remnants play a major role in cosmic-ray production.

Appendix

Notation, constants, and conversion factors (*73*).

1 A.U.	=	1.5×10^{13} cm
1 parsec	=	3.1×10^{18} cm = 3.3 lt yr
1 lt yr	=	0.95×10^{18} cm
1 ev	=	1.60×10^{-12} erg
1 Bev	=	1 billion electron volts
	=	10^9 ev
E	=	kinetic energy per nucleon
W	=	total energy per nucleon
	=	E + rest mass
A	=	mass number of nucleus
W_n	≡	AW; $E_n \equiv AE$

Unit of particle intensity:

$$\text{Peter } (J) = \frac{\text{particles}}{\text{m}^2/\text{sec srad}} = 10^4 \times \frac{\text{particles}}{\text{cm}^2/\text{sec srad}}$$

c = velocity of light
= 3×10^{10} cm/sec

Magnetic rigidity. The magnetic rigidity R_m of an ion moving normally to a magnetic field H is determined by the ratio of its momentum p to charge Ze:

$$R_m \text{ (in ergs per e.s.u.)} = \frac{pc}{Ze} = Hr \quad (A1)$$

Here c is the speed of light; pc is measured in ergs, e in electrostatic units (e.s.u.), H in gauss, and r, the radius of curvature of the ion's path, in centimeters. Magnetic rigidity has the dimensions of energy per unit charge. It is expressible in volts, if p is expressed in ev/c, and is then numerically equal to p/Z. Moreover,

$$R_m \text{ (in volts)} = 300\, Hr \quad (A2)$$

where the factor 300 arises in the conversion of e.s.u. volts to absolute volts. Thus, with p still expressed in ev/c,

$$r = \frac{1}{300}\frac{R_m}{H} \text{ cm} = \frac{1}{300}\frac{p}{ZH} \text{ cm} \quad (A3)$$

It should also be noted that at sufficiently high energies, $W_n \approx E_n \approx pc$; if the energy is expressed in electron volts, then

$$E_n = AE = 300\, ZHr \quad (A4)$$

Particle density, energy flux, and energy density of the galactic cosmic radiation. We shall estimate a rough lower limit to the cosmic-ray energy flux and energy density in the vicinity of the earth. Since we do not yet know the absolute cutoff energy (if any), we compute the energy flux of particles whose energy per nucleon exceeds an arbitrary threshold W_0. Let the integral particle flux (per square centimeter per second per steradian) above energy W be $J_{>W}$, let the corresponding flux of nucleons be $F_{>W}$, and let their mean energy (inclusive of rest mass) be $\bar{W}$. The particle density is then $(4\pi/c)J_{>W}$, the energy flux is $F_{>W}\bar{W}$, and the energy density is $(4\pi/c)F\bar{W}$. (To a sufficient approximation, all the primaries considered in this calculation travel with the velocity c of light.) The particle density is given by

$$n = \frac{4\pi}{c} J_{>W_0} = \frac{4\pi\,(0.28)}{3 \times 10^{10}}\ \mathrm{cm}^{-3} = 1.2 \times 10^{-10}/\mathrm{cm}^3 \qquad (A5)$$

where W_0 is as specified below and $J_{>W_0} = 0.28$ particle per square centimeter per second per steradian.

For a spectrum having the form $J_{>W} = K/W^{1.5}$ and extending to very high energies, it can readily be shown that the mean energy $\bar{W}$ per nucleon of particles whose energy exceeds W_0 is simply $3W_0$. We arbitrarily choose $W_0 = 1.7$ Bev per nucleon, corresponding to a mean energy $\bar{W}$ of 5 Bev per nucleon. The particle fluxes $J'_{>W_0}$ (in peters) are 2660 (for protons), 155 (for helium), and 17 (for heavy nuclei). To convert the particle fluxes $J'_{>W_0}$ to nucleon fluxes $F'_{>W_0}$ (also in peters), we adopt the following mean mass numbers $\bar{A}$ for the three components: $A_{\mathrm{H}} = 1$, $A_{\mathrm{He}} = 4$, and $A_{\mathrm{HN}} = 17$. The combined nucleon flux $F'_{>W_0}$ is thus $(2660 \times 1) + (155 \times 4) + (17 \times 17) = 3570$ nucleons per square meter per second per steradian, or 0.36/cm² sec srad, and the energy flux is

$$F_{>W_0}\bar{W} = 0.36 \times 5 \times 10^9 = 1.8 \times 10^9\ \mathrm{ev/cm^2 sec\ srad} \qquad (A6)$$

Thus, for the energy density, we have

$$\frac{4\pi}{c}(F_{>W_0}\bar{W}) = \frac{4\pi \times 1.8 \times 10^9}{3 \times 10^{10}} = 0.75\ \mathrm{ev/cm^3} = 1.2 \times 10^{-12}\ \mathrm{erg/cm^3} \qquad (A7)$$

The energy density of starlight has about the same magnitude. The values of cosmic-ray flux and density computed here should be considered as lower limits, since there are certainly primary cosmic rays having energies below the arbitrary threshold W_0 that we have employed.

References and Notes

1. These are sometimes called mu "mesons," but *meson* is a designation better reserved for the π and K mesons.
2. For a recent and concise review of fundamental properties of mesons and hyperons, see, for example, G. Snow and M. M. Shapiro, *Revs. Modern Phys.* **33**, 231 (1961).
3. For insight into the experimental methods that sparked many of the advances in cosmic rays and high-energy physics, see *Handbuch der Physik*, vol. 45, S. Flügge, Ed., (Springer, Berlin, 1958), pts. 1 and 2; see also *Techniques of High Energy Physics*, D. Ritson, Ed. (Interscience, New York, 1961).
4. C. F. Powell, P. H. Fowler, D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (Pergamon, New York, 1959); M. M. Shapiro, "Nuclear emulsions," in *Encyclopedia of Physics*, vol. 45, S. Flügge, Ed. (Springer, Berlin, 1958), pt. 2, p. 342.
5. D. H. Perkins, in *Progress in Elementary Particle and Cosmic Ray Physics*, J. G. Wilson and S. A. Wouthuysen, Eds. (North-Holland, Amsterdam, 1960), vol. 5, chap. 4; see also M. M. Shapiro, in *Photographie Corpusculaire*, P. Demers, Ed. (Presses Universitaire de Montreal, Montreal, 1959), vol. 2, p. 423 ff.
6. B. Rossi, *Sci. American* **201**, 135 (1959); W. Galbraith, *Extensive Air Showers* (Academic Press, New York, 1958).
7. J. Linsley, private communication. A description of one of the 10¹⁹-ev showers is given by J. Linsley, L. Scarsi, and B. Rossi, *Phys. Rev. Letters* **6**, 485 (1961).
8. I have drawn on C. J. Waddington's recent review in *Prog. in Nuclear Phys.* **8**, 1 (1960).
9. Earlier summaries are S. F. Singer, in *Progress in Elementary Particle and Cosmic Ray Physics*, J. G. Wilson and S. A. Wouthuysen, Eds. (North-Holland, Amsterdam, 1958), vol. 4, p. 204; B. Peters, *Progress in Cosmic Ray Physics*, J. G. Wilson, Ed. (Interscience, New York, 1952), vol. 2, chap. 4.
10. It is noteworthy that the ratio of helium to hydrogen found at this latitude agrees quite well with the ratios observed at 3°N and 10°N, where the absolute fluxes are much lower. See, for example, M. M. Shapiro, *Trans. N.Y. Acad. Sci.* **20**, 697 (1958).
11. H. E. Suess and H. C. Urey, in *Handbuch der Physik*, vol. 51, S. Flügge, Ed. (Springer, Berlin, 1958) p. 296; *Revs. Modern Phys.* **28**, 53 (1956); A. G. W. Cameron, *Astrophys. J.* **129**, 676 (1959).
12. It is unfortunate that the designation *H* has become conventional for the heavy group; it should not be confused with hydrogen.
13. F. W. O'Dell, M. M. Shapiro, B. Stiller, *Proc. Conf. on Cosmic Radiation, Moscow, 1959* (1960) vol. 3, p. 118 (preliminary report); final results (in press) reported by M. M. Shapiro at the Washington meeting of the American Physical Soc., Apr. 1961; see also Waddington (*8*) and I. J. van Heerden and B. Judek, *Can. J. Phys.* **38**, 964 (1960).
14. There are indications that this estimate of the ratio will be revised upward as more precise determinations are made of the "general" abundance of lithium, beryllium, and boron. Thus, for example, a refined measurement of the abundance of beryllium in chondrites, by C. W. Sill *et al.*, lowers by a factor of 25 the value given in the Suess-Urey table (private communication from H. C. Urey and J. R. Arnold).
15. A. A. Korchak and S. I. Syrovatsky have shown how preferential acceleration of heavier nuclei could take place [*Doklady Akad. Nauk S.S.S.R.* **122**, 792 (1958); *Soviet Phys. "Doklady"* **3**, 983 (1959).
16. S. Hayakawa, K. Ito, Y. Terashima, *Progr. Theoret. Phys. (Kyoto) Suppl.* **6**, 1 (1958).
17. J. A. Earl, *Phys. Rev. Letters* **6**, 125 (1961).
18. P. Meyer and R. Vogt, *ibid.* **6**, 193 (1961).
19. R. I. Hulsizer and B. Rossi, *Phys. Rev.* **73**, 1402 (1948).
20. C. L. Critchfield, E. P. Ney, S. Oleska, *ibid.* **85**, 461 (1952).
21. Because their mean life is approximately 11 minutes, any neutrons observed are likely to be of solar origin, except possibly those having energies enormously greater than their rest mass. For those, the relativistic time dilation would permit longer survival against radioactive decay.
22. J. R. Arnold, M. Honda, D. Lal, "The record of cosmic ray intensity in the meteorites," in press; see also J. R. Arnold, "Nuclear effects of cosmic rays in meteorites," *Ann. Rev. Nuclear Sci.*, in press.
23. I. S. Shklovsky, *Astron Zhur.* **29**, 418 (1952); S. B. Pikelner, *Doklady Akad. Nauk S.S.S.R.* **88**, 229 (1953).
24. F. Hoyle, *Am. Scientist* **49**, 188 (1961).
25. E. Fermi, *Phys. Rev.* **75**, 1169 (1949).
26. L. Spitzer and J. W. Tukey, *Astrophys. J.* **114**, 187 (1951); L. Davis and J. L. Greenstein, *ibid.* **114**, 206 (1951).
27. S. Chandrasekhar and E. Fermi, *ibid.* **118**, 113 (1953).
28. R. D. Davies, *Discovery* **22**, 99 (1961).
29. D. Iwanenko and I. Pomeranchuk, *Phys. Rev.* **65**, 343 (1944); J. Schwinger, *ibid.* **75**, 1912 (1949).
30. V. L. Ginzburg, *Uspekhi Fiz. Nauk* **51**, 343 (1953).
31. V. L. Ginzburg and S. I. Syrovatsky, *ibid.* **71**, 411 (1960) [Engl. trans., *Soviet Phys. Uspekhi* **3**, 504 (1961)].
32. I. S. Shklovsky, *Astron. Zhur.* **30**, 577 (1953).
33. ———, *Cosmic Radio Waves* (Moscow, 1956) (Harvard Univ. Press, rev. English ed., Cambridge, Mass., 1960).
34. W. Baade and F. Zwicky, *Proc. Natl. Acad. Sci. U.S.* **20**, 259 (1934).
35. D. Ter Haar, *Revs. Modern Phys.* **22**, 119 (1950).
36. K. Lundmark, *Publs. Astron. Soc. Pacific* **33**, 225 (1921).
37. J. G. Bolton and G. J. Stanley, *Australian J. Sci. Research* **A2**, 139 (1949).
38. F. Zwicky, in *Handbuch der Physik*, vol. 51, S. Flügge, Ed. (Springer, Brlin, 1958), p. 766.
39. I. S. Shklovsky and P. P. Parenago, *Astron. Tsirk.* **131**, 1 (1952).
40. R. Minkowski, *Publs. Astron. Soc. Pacific* **52**, 206 (1940); *ibid.* **53**, 224 (1941); *Proc. Natl. Acad. Sci. U.S.* **46**, 13 (1960).
41. F. Hoyle and W. A. Fowler, *Astrophys. J.* **132**, 565 (1960).
42. L. B. Borst, *Phys. Rev.* **78**, 807 (1950).
43. G. R. Burbidge, F. Hoyle, E. M. Burbidge, R. F. Christy, W. A. Fowler, *ibid.* **103**, 1145 (1956).
44. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Revs. Modern Phys.* **29**, 547 (1957); see also A. G. W. Cameron, *Ann. Rev. Nuclear Sci.* **8**, 299 (1958).
45. The efficacy of this neutron source has recently been questioned by Hoyle and Fowler (*41*), who propose an alternative means of obtaining a high neutron flux for the *r*-process.
46. This distance is not yet firmly known; estimates run as high as 6000 light years.
47. W. Baade, *Astrophys. J.* **96**, 188 (1942).
48. R. Minkowski, *ibid.* **96**, 199 (1942).
49. I. S. Shklovsky, *Doklady Akad. Nauk S.S.S.R.* **90**, 983 (1953).
50. J. Oort and T. Walraven, *Bull. Astron. Inst. Neth.* **12**, 285 (1956).
51. I. S. Shklovsky, *Astron. Zhurn.* **30**, 15 (1953).
52. H. Alfvén and N. Herlofson, *Phys. Rev.* **78**, 616 (1950).
53. K. O. Kiepenheuer, *ibid.* **79**, 738 (1950).
54. V. L. Ginzburg, *Doklady Akad. Nauk S.S.S.R.* **76**, 377 (1951).
55. V. L. Ginzburg, *Trudy Soveshchaniya Voprosy Kosmogonii* **3**, 258 (1954).
56. I. M. Gordon, *Doklady Akad. Nauk S.S.S.R.* **94**, 413 (1954).
57. V. A. Dombrovsky, *ibid.* **94**, 1021 (1954).
58. M. A. Vashakidze, *Astron. Tsirk.* **147**, 11 (1954).
59. W. Baade, *Bull. Astron. Inst. Neth.* **12**, 312 (1956).
60. L. Woltjer, *ibid.* **14**, No. 483 (1958).
61. C. H. Mayer, T. P. McCullough, R. M. Sloanaker, *Astrophys. J.* **126**, 468 (1957).
62. S. B. Pikelner, *Astron. Zhurn.* **33**, 785 (1956).
63. I. S. Shklovsky, *Doklady Akad. Nauk S.S.S.R.* **91**, 475 (1953).
64. Fermi assumed in the later version of his theory of acceleration in interstellar space that the lifetime of cosmic-ray nuclei is governed primarily by escape from the galaxy. However, this was before the radio evidence for the galactic halo had enlarged the known available volume for magnetic trapping from the limited confines of the galactic disk to a huge quasi-spherical volume. Actually, we cannot yet be sure whether collision or escape determines the lifetime.
65. V. L. Ginzburg, *Nuovo Cimento Suppl.* **8**, No. 2, 430 (1958).
66. ———, *Doklady Akad. Nauk S.S.S.R.* **92**, 727 (1953).
67. B. Peters, *Nuovo Cimento Suppl.* **14**, No. 2, 436 (1959).
68. S. A. Colgate and M. H. Johnson, *Phys. Rev. Letters* **5**, 235 (1960).
69. V. I. Krasovsky and I. S. Shklovsky, *Doklady Akad. Nauk S.S.S.R.* **116**, 197 (1957).
70. G. Cocconi in "Symposium on astronomical aspects of cosmic rays," *Astrophys. J. Suppl.* **4**, No. 44, 369 (1960); also P. Morrison, E. P. Ney, J. A. Simpson, and T. Gold, *ibid.*
71. P. Morrison, *Handbuch der Physik*, S. Flügge, Ed. (Springer, Berlin, 1959), vol. 46, p. 1.
72. L. Biermann and L. Davis, Jr., *Z. Naturforsch.* **132**, 909 (1958); ———, *Z. Astrophys.* **51**, 19 (1960).
73. For the purposes of this article the numbers are given with adequate precision.