Origins of cosmic rays

Each new means of detection shows cosmic rays to be more complex than we had thought, so that more and more bravery is demanded of astrophysicists who propose sources for these rays.

Ramanath Cowsik and P. Buford Price

Laymen are probably more aware of the spectacular recent discoveries in astrophysics than in any other science. Newspapers and magazines have conditioned their readers to accept the reality of quasars, pulsars, black holes, gravitational waves, 2.7-K blackbody radiation, interstellar molecules, solar wind and ancient moon rocks, to name only a few currently fashionable topics.

Although the study of cosmic radiation predates all these phenomena, only in the last decade or so has the importance of the dynamical interaction of cosmic rays with the other constituents of the universe been recognized. Before the time of big accelerators, and before the space age, cosmic rays were studied primarily by elementary-particle physicists, who discovered in them the positron, several kinds of mesons and many of the so-called "strange particles." With the development of high-altitude balloons, rockets, satellites and new detecting instruments, the definition of cosmic rays has been broadened to include many forms of extra-solar-system radiation that do not penetrate as deeply into the earth's atmosphere as do the high-energy protons and their interaction products. Now we find that all these forms of cosmic radiation are intimately related to each other as well as to the rest of the universe, and emphasis has shifted to the role of cosmic rays in astrophysics.[1]

The origin of cosmic rays remains a mystery to astrophysicists. Enrico Fermi, in 1949, was first to propose an explanation for their high energies; he postulated that cosmic rays are repeatedly scattered against clouds of magnetized plasma in interstellar space. His theory, as we shall see, does not agree with some of the more recently observed properties of cosmic rays. Alternatives have been proposed: Cosmic rays are the result of supernova explosions, or may have been shot off from rapidly spinning neutron stars. Our point of view here is that white dwarfs may be the source of the bulk of the cosmic rays that we see. We shall discuss some of the properties of the three classes of cosmic rays—the nuclei, the electrons (negatrons and positrons) and the electromagnetic component—with an eye to explaining the mystery of their origins.

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The nuclear component

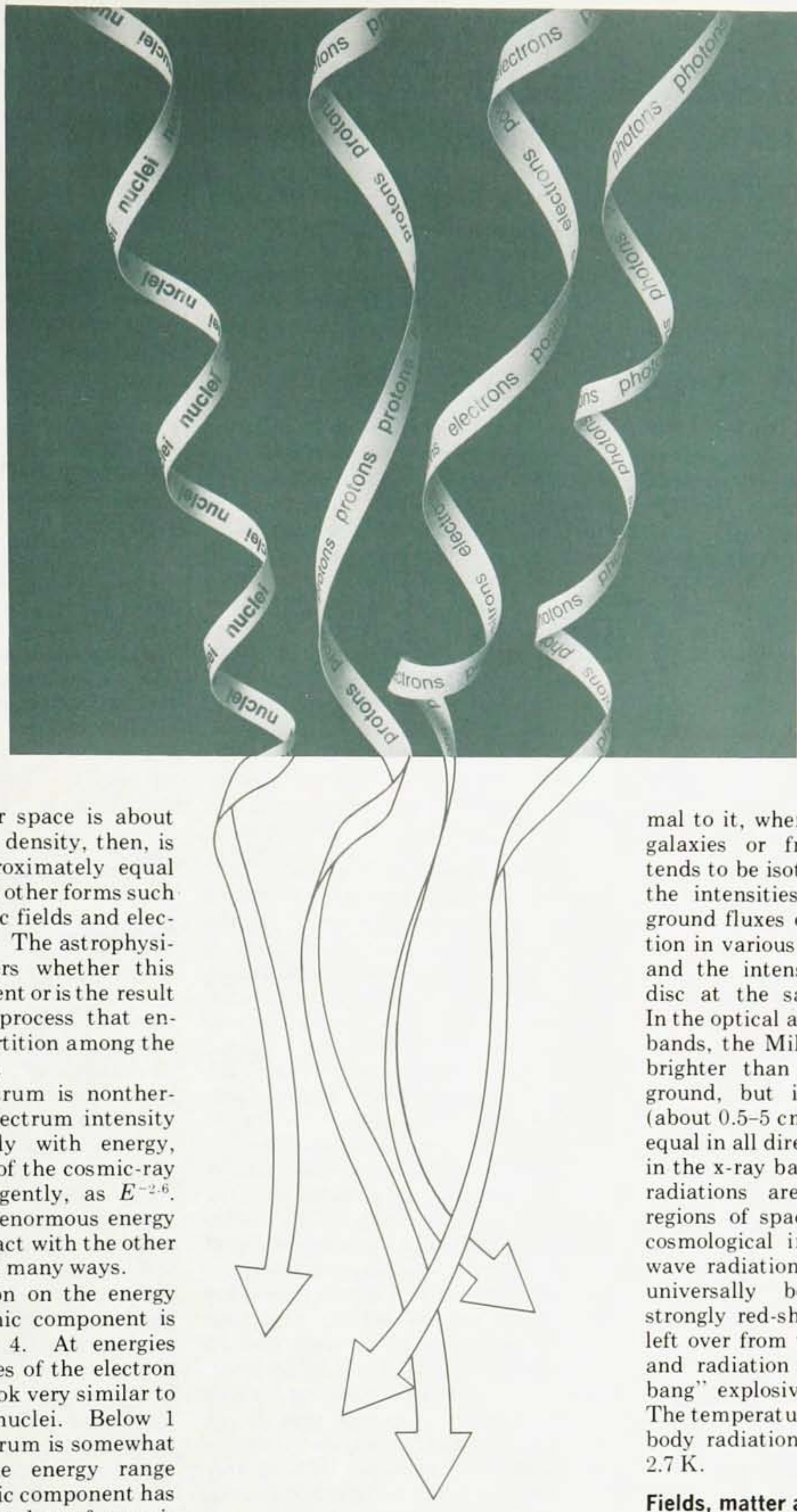
Protons dominate the nuclear component, contributing almost 90% of the flux at the top of the atmosphere. Helium nuclei contribute another 9% and the remaining 1% are heavier nuclei. The relative proportion of antinuclei is less than 0.02% of the nuclei (and may be zero).[2] In figure 1 we compare the cosmic-ray charge distribution with a reference distribution sometimes called the "cosmic" or "universal" distribution of the elements, but which actually represents abundances measured in the solar atmosphere or in meteorites.

Although the general trends of the two distributions are rather similar, important differences can be seen. Hydrogen and helium have much lower relative abundances in the cosmic rays. Lithium (Li), beryllium (Be), boron (B) and odd-Z nuclei are more abundant in the cosmic rays and are produced largely by transmutations of heavier nuclei during their passage through the interstellar medium. The nuclei at the end of the periodic table are greatly enhanced in cosmic rays and provide restrictions on theories of cosmic-ray origin.

Energy spectra

In figure 2 we summarize the available information on the energy spectrum of the nuclear component. The spectrum extends smoothly from about 10 MeV to 10^{20} eV, more than 13 decades in energy and 32 decades in intensity! A variety of observational techniques (see figure 3) have made such a wide range of energies and intensities accessible; the detectors range from balloon- and satellite-borne silicon wafers or plastic sheets, for studying the low-energy end, to the huge arrays of scintillators, Cerenkov counters and other detectors, spread over many tens of kilometers, that detect the combined nuclear-electromagnetic showers generated by the high-energy particles ($E > 10^{14}$ eV) in the air.

The mean particle energy of the Galactic cosmic-ray spectrum is about 1 GeV, and the number density of these



particles in interstellar space is about $10^{-9}/cm^3$. The energy density, then, is about 1 eV/cm^3, approximately equal to the energy density in other forms such as turbulence, magnetic fields and electromagnetic radiation. The astrophysicist frequently wonders whether this equality is a pure accident or is the result of some self-limiting process that enforces a kind of equipartition among the various forms of energy.

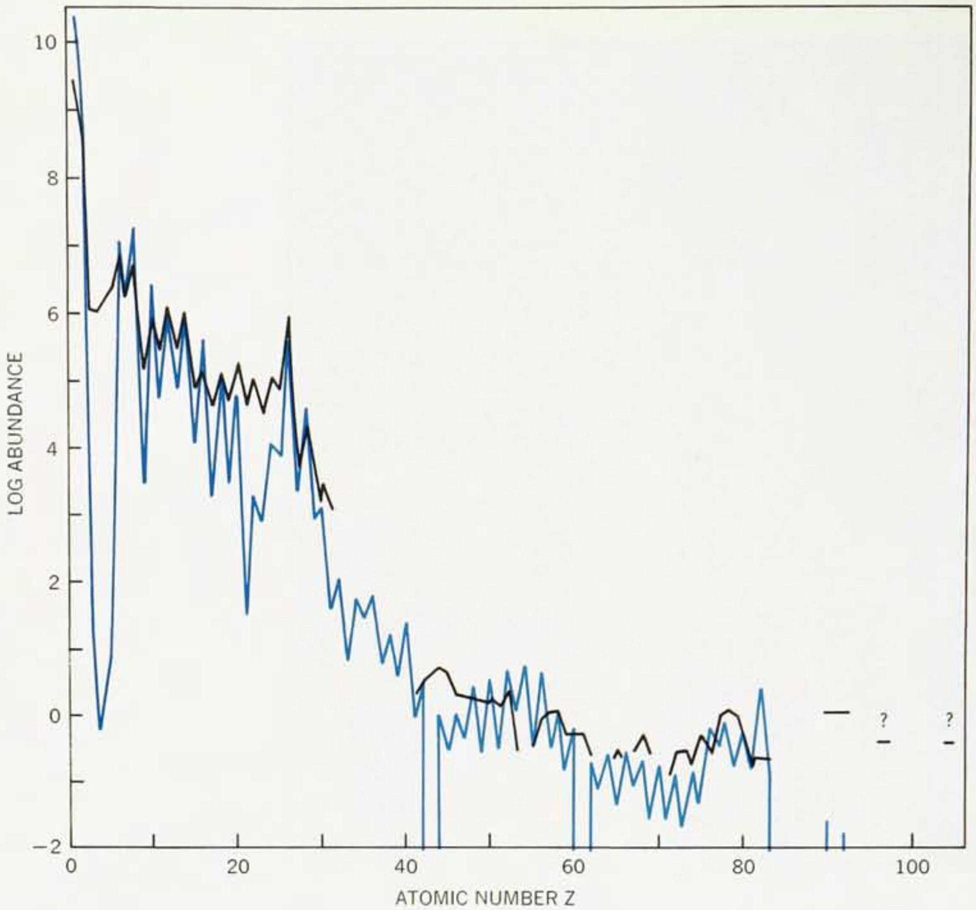
Note that the spectrum is nonthermal. In a thermal spectrum intensity decreases exponentially with energy, whereas the spectrum of the cosmic-ray nuclei falls off more gently, as $E^{-2.6}$. Because they span an enormous energy region, the nuclei interact with the other constituents of space in many ways.

Available information on the energy spectra of the electronic component is summarized in figure 4. At energies above 1 GeV the shapes of the electron and positron spectra look very similar to the spectrum of the nuclei. Below 1 GeV the electron spectrum is somewhat flatter. Although the energy range over which the electronic component has been studied is many orders of magnitude smaller than for the nuclear component, the electrons with their small mass participate in a larger variety of electromagnetic interactions than do the nuclei.

Our galaxy, like most spiral galaxies, has its most dense population of stars and gas in a thin, disc-like volume, the "Milky Way." Electromagnetic radiation of Galactic origin is thus more intense in the plane of the disc than normal to it, whereas radiation from other galaxies or from intergalactic space tends to be isotropic. In figure 5 we see the intensities of the isotropic background fluxes of electromagnetic radiation in various frequency bands (black) and the intensities from the Galactic disc at the same frequencies (color). In the optical and long-wavelength radio bands, the Milky Way or disc is much brighter than the general sky background, but in the microwave band (about 0.5–5 cm) the general intensity is equal in all directions. The same is true in the x-ray band, indicating that these radiations are coming from distant regions of space and may be of great cosmological importance. The microwave radiation, for example, is almost universally believed to consist of strongly red-shifted blackbody photons left over from the decoupling of matter and radiation that followed the "big-bang" explosive origin of our universe. The temperature of this universal blackbody radiation is now measured to be 2.7 K.

Fields, matter and cosmic rays

The Galactic magnetic fields—only a few microgauss—are weak by laboratory standards. But they are essential for confining the cosmic rays to the Galactic volume and for establishing a dynamical coupling between cosmic rays and interstellar matter. Instead of moving in straight lines, nuclei and electrons both gyrate around the magnetic-field lines, following circuitous and complicated paths before they escape into inter-



Charge distribution of nuclei in galactic cosmic rays near the earth (black) is compared with a reference distribution (color) that represents an average sampling of elements in the universe. Corrections to the cosmic-ray data for loss and transmutation would increase the relative abundance of heavy nuclei and would decrease the abundance of the rare nuclei lithium, beryllium and boron ($Z = 3,4,5$) as well as the odd-Z nuclei. Figure 1

galactic space. This complex motion has many interesting consequences. It prevents us from using the arrival directions of the charged component to pinpoint the sources of the cosmic rays. At best we can only search for slight gradients in intensity that would show up if the source distribution around us were not isotropic. And because the cosmic rays leave the galaxy circuitously, their time inside the galactic volume increases. For a given injection rate from the sources, then, the density of cosmic rays in the galaxy is higher than it would be if the particles left the galaxy in straight lines.

During their long residence time, nuclear cosmic rays interact with interstellar atoms, forming new species in the cosmic-ray "beam" as well as new species in the interstellar gas. The light elements Li, Be and B, as a famous example, cannot survive in the high-temperature thermonuclear furnaces inside stars, yet are present both in cosmic radiation and in the solar system. These elements result mainly from transmutations of the very abundant neighboring elements helium, carbon, nitrogen and oxygen in nuclear collisions with interstellar atoms. From cross-section data obtained in accelerator bombardments, and from the abundances of Li, Be and B in cosmic rays, it was calculated some years ago and is now generally accepted that the nuclear cosmic rays pass through a mean thickness of about 4 g/cm^2 of interstellar matter before they escape into extragalactic space. If the mean density of interstellar matter is about one hydrogen atom per cm^3, the relativistic nuclei must spend several million years in the Galactic disc to pass through 4 g/cm^2 of matter. In addition calculations show that during the lifetime of our galaxy (about 10^{10} years), enough Li, Be and B are created in the interstellar gas by these nuclear processes alone to account for what we observe within the earth and meteorites.

Electromagnetic interactions, particularly by the low-energy nuclei, with the atomic and free electrons in interstellar space lead to ionization and heating of the medium. At energies beyond 1 GeV, multiple meson production takes place in nuclear interactions, and these mesons decay into high-energy gamma rays and electrons that can be detected. Because of their large mass the protons and other nuclei in cosmic rays do not interact at moderate energies with magnetic fields and photons. But at very high energies when sufficient energy is available in the center-of-momentum system, processes such as electron–positron pair creation, photodisintegration and photomeson production take place, reducing the fluxes of the nuclear component. The highest-energy gamma rays ($\geq 10^{14}$ eV) are completely absorbed even in a distance as short as 10 kiloparsecs (a parsec is about 3×10^{18} cm) because of the reaction with the 2.7-K photons: $\gamma + \gamma_{2.7K} \rightarrow e^+ + e^-$. This reaction prevents us from using the straight trajectories of high-energy gamma rays to see distant sources.

Distribution in time and space

Meteorites and moon samples contain a "fossil" record of cosmic-ray bombardment covering the last 10^9 years or so of solar-system history. Measurements of abundances of nuclides created mainly by the interactions of multi-GeV protons with atoms inside these bodies tell us that the cosmic-ray sources have been emitting rather uniformly during this time. These measurements rule out long-term variations of more than about 50%, but do not rule out large, short-term variations that might arise from the motion of the solar system through the Galactic spiral arms past occasional, intensely emitting sources. Measurements of the fossil tracks of very heavy cosmic rays recorded in transparent crystals from meteorites and moon rocks (see figure 3a) indicate that the composition of the nuclear component cannot have drastically changed over at least the last 50 million years.

Is the intensity we measure near the earth characteristic of the entire universe, or of the galaxy, or of nearby interstellar space, or merely of the solar neighborhood?

We know that low-energy cosmic rays entering the solar system are convected away from the sun by the outward flowing solar wind, and that they lose energy in collisions with magnetic irregularities in the field that threads the solar wind.

The fluxes of both nuclei and electrons at energies below about 1 GeV are progressively depleted compared with their intensities in the local interstellar space. The dashed lines in figures 2 and 4a indicate the "demodulated" intensities expected in interstellar space, beyond the influence of the solar wind. At energies below about 100 MeV the modulating effect of the solar wind is quite large and uncertain, but at energies above about 10 GeV it is safe to assume that the observed spectrum is representative of nearby interstellar space.

On the Galactic scale, nonthermal radio emission by cosmic-ray electrons from various regions of space indicates that, except for some discrete "sources," the general cosmic-ray level is the same within a factor of five everywhere in the Galactic disc. Beyond the Galactic boundaries, however, in the intergalactic space, cosmic-ray intensities must drop to less than 0.1% of the galactic intensities. If this were not so, then the cosmic-ray electrons in intergalactic space, by Compton collisions with the 2.7-K blackbody photons that fill the universe, would produce higher fluxes of x and gamma rays than we observe.

As the table on page 38 shows, outside of galaxies only the energy density in the 2.7-K blackbody radiation is significant, and we can confine most of our discussion to those cosmic rays that appear uniformly to fill our Galactic disc.

Energetic solar particles

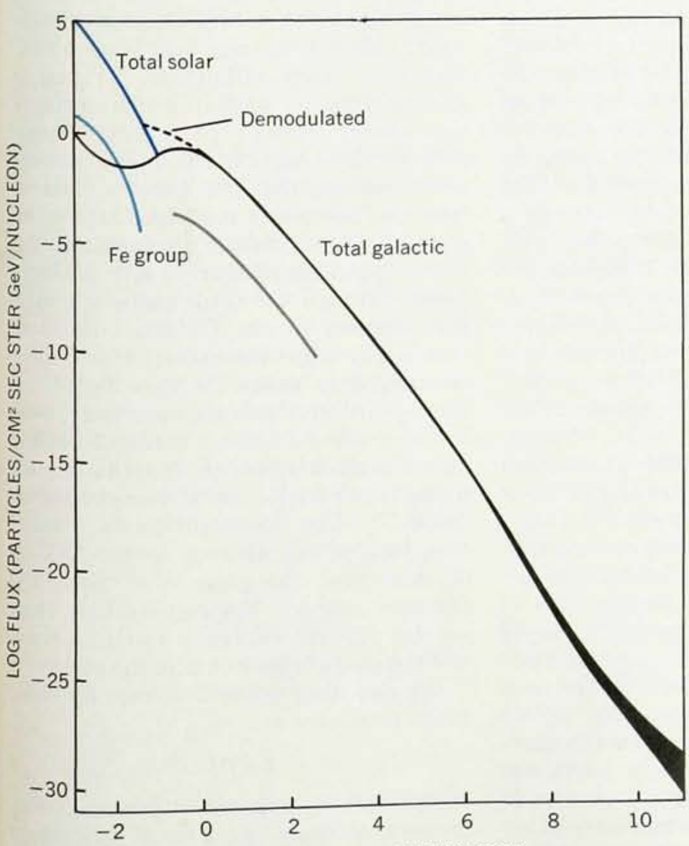
During the period of maximal sunspot activity, solar flares sporadically contaminate the solar system with low-energy particles. Tracks and induced radioactivity near the surface of moon rocks indicate that flares have been a regular feature of solar activity over at least millions of years. Solar flare particles have a steeply falling energy spectrum (see figure 2) and diffuse out of the solar system in a few days. Flares allow us to study the operation of a nearby cosmic accelerator, which may contain clues to the much more powerful accelerators responsible for the Galactic cosmic rays.

Track-recording nuclear emulsions[3] and plastics[4] carried aloft in rockets are used to assay the more abundant solar particles from hydrogen up to nickel. Although the composition of these nuclei bears a strong resemblance to the composition of the solar atmosphere in which they originated, there is evidence for a preferential emission of heavy nuclei relative to light ones.[5] The evidence appears to be strongest for the lowest-energy nuclei. These nuclei may be incompletely ionized, so that they are accelerated and escape from the sun at a rate that depends in a complicated way on their mass and degree of ionization. It is, we see, premature to assume that cosmic-ray nuclei are ejected from their sources without regard for such properties as their charge, mass or ionization potential.

Composition at sources

What do we learn by comparing the abundances of nuclear cosmic rays and the universal or solar-system abundances shown in figure 1? The major features of the solar-system abundances have been accounted for by nuclear astrophysicists in terms of various processes of element synthesis in stars, followed by their ejection into the interstellar medium and eventual incorporation into the sun and planets. But the nuclear cosmic rays provide us with a direct view of high-energy interstellar debris that may not have formed in the same way, or in the same objects, as did the low-energy debris that makes up our solar system and the interstellar gas. Given the chemical composition of cosmic rays near the earth, we must deduce the nature of the sources after we have corrected for nuclear transmutations in space and for possible preferential emission of heavy or easily ionizable nuclei.

By assuming that the cosmic rays have traversed a mean thickness of several g/cm^2 of matter between sources and Earth, we can account reasonably well for the abundances of the rare nuclei Li, Be, B, elements 15 to 25 and odd-Z nuclei in general. At the same time we must correct for the more rapid destruction of heavy nuclei than light ones during their traversal. The cross-section for breakup increases from about 40 mb for hydrogen to 200 mb for carbon to 2 b for uranium. The ratio of observed cosmic-ray abundance to universal abundance shown in figure 1 is an increasing function of atomic number. After correction for transmutations, the ratio increases much more strongly, by a factor of several hundred in going from hydrogen to uranium.



Energy spectrum of nuclear cosmic rays. At lower energies, solar flares contribute most of the particles, which tend to mask the galactic contribution. Away from the influence of the solar wind, the galactic contribution at about 1 GeV would probably be greater (dotted line), and the solar-flare contribution would be absent. The iron-group spectrum has been determined separately; in both the solar (light color) and galactic (gray) contributions, the iron spectrum is not significantly different from the total spectrum. Figure 2

Tracks of cosmic rays with $Z \approx 92$. Huge balloon-borne packages record tracks in nuclear emulsions (top)[6] and in plastics (middle).[7,8,17] Great length of track in moon rock (bottom), about 1mm, indicates a nucleus at the end of the periodic table. Shorter tracks are of iron nuclei, with $Z = 26$.
Figure 3

A successful theory of cosmic rays must account for this strong enhancement of heavy cosmic rays relative to the "universal" distrubution, which is usually assumed to be representative of interstellar gas and of the surfaces of ordinary stars like the sun.

Transuranic cosmic rays

At the end of the periodic table the universal distribution is dominated by a lead (Pb) peak. The heavier elements are all radioactive and can be synthesized only in environments where there is a very high density of neutrons that can be captured by lighter elements on a very short time scale (the so-called "r-process"). In our 4.5×10^9-year-old solar system only thorium and uranium have survived; the rest have decayed into lead. In the interstellar gas, exploding stars in their final stages of evolution replenish the radionuclides until secular equilibrium is established. Relative to U^{238} (4.5×10^9-year halflife), the concentrations of Pu^{244} (8×10^7-year halflife) and Cm^{247} (2×10^7-year halflife) are not expected to exceed about 2% and 0.5%. All the other known radionuclides have shorter halflives and would be present at an even lower level. Thus if cosmic rays originate in sources with this composition, the proportion of transuranic nuclei may be far below our present level of detectability.

But if cosmic rays are generated in the very same explosions in which the heavy elements are synthesized, their relative abundances would depend on their mean "age," or the travel time between sources and Earth. If their age is no more than a few million years we might then detect Pu^{244}, Cm^{247} and even Np^{237} (2×10^6-year halflife), and we would expect the Pb peak to be less pronounced relative to the lighter neighboring elements osmium, iridium and platinum, which are readily made by rapid neutron capture.

The distribution of the heaviest cosmic rays in figure 1 favors r-process synthesis, but at this stage the evidence for transuranic nuclei[6-8] cannot yet be regarded as decisive (hence the question marks at the data points in figure 1). The difficulty is experimental. The difference in ionization rate between a uranium and a plutonium nucleus with the same velocity is only 4%, and one does not always know the velocity accurately. Furthermore, in a two-day balloon flight, an array of plastics and nuclear emulsions about $20m^2$ in area will collect no more than three or four tracks of trans-Pb nuclei. Moon crystals (see figure 3b) provide a collecting time measured in millions of years but suffer from uncertain charge resolution.

Research on the heaviest cosmic rays is spurred on by the theoretical predictions that superheavy nuclei with Z above 110 may be synthesized by rapid neutron capture, and that one or more of these nuclides may, because of shell effects, have a halflife as long as 10^8 years.[9] This halflife would be too short for the element to survive in terrestrial rocks but long enough for it to survive in cosmic rays. Perhaps when long exposures of large detectors in earth-orbiting satellites can be achieved, it will be possible to add superheavy elements to the list of fundamental particles discovered in the cosmic rays.

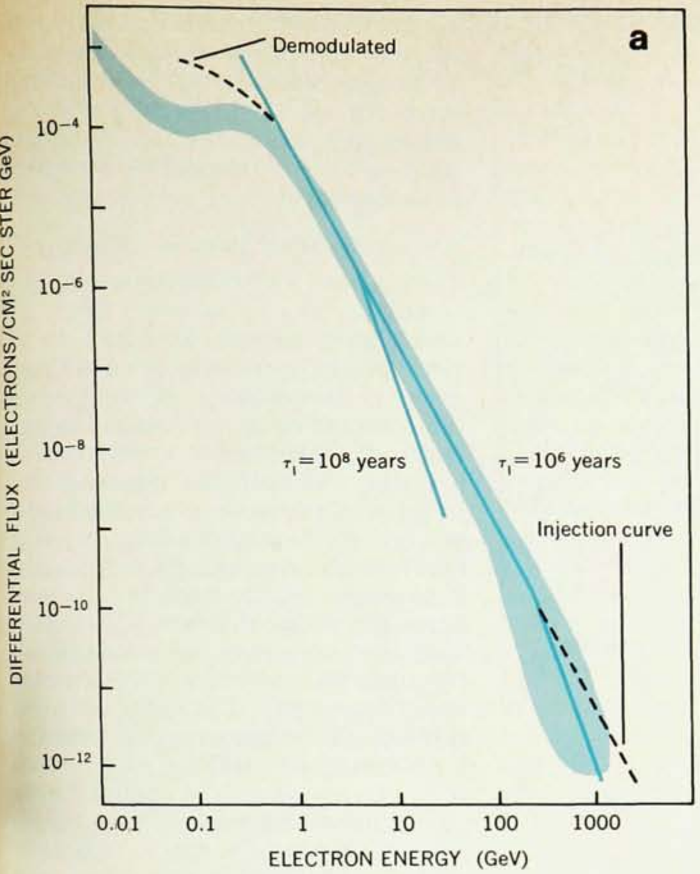
Electron component

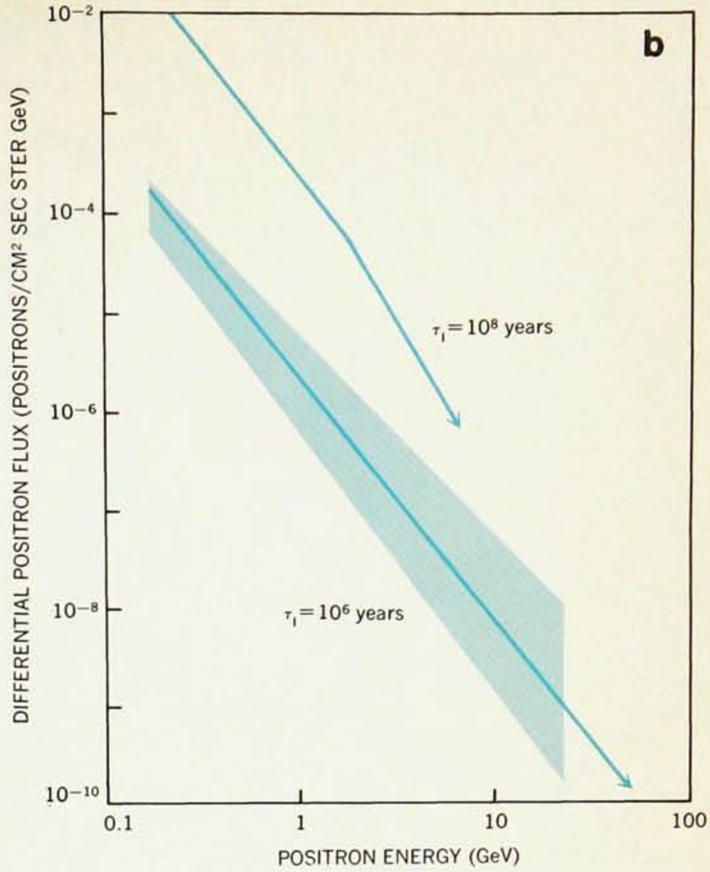
Cosmic electrons are about one percent as abundant as nuclei in the same energy interval, and positrons form about one tenth of this electron component. Electrons carry and transmit information very efficiently. Figure 6 summarizes the ways in which electrons lose energy through generation of photons as they participate in electromagnetic interactions in space. Ionization loss is more or less constant for the energies of interest; bremsstrahlung losses increase linearly with energy; losses through Compton collisions with the photons in the Galactic disc and through synchrotron radiation in Galactic magnetic fields increase faster, as the square of the electron energy, and become the dominant mode of energy loss at high energies; annihilation of positrons is not important at energies above 10 MeV. The dominant mode of electron loss at energies up to 100 GeV is leakage from the galaxy, as shown by the gray curve. We assume here that *all* the particle energy is lost in a time τ_l if the particle leaks out of the galaxy.

We can also define lifetimes for each of the processes as

$$\tau_i = E/(dE/dt)_i$$

where i is a particular process. For bremsstrahlung, $\tau_B \approx E/(dE/dt)_B$, and because $(dE/dt)_B$ increases linearly





with energy, τ_B is independent of the electron energy. As we have noted, the rates of energy loss through Compton scattering and synchrotron radiation increase as E^2, so that the lifetimes for these processes decrease as electron energy increases.

The τ's add harmonically; for example the lifetime $\tau_{c,s}$ against combined Compton and synchrotron losses is given by

$$1/\tau_{c,s} \approx 1/\tau_c + 1/\tau_s$$

$$\tau_{c,s}(E) = \tau_{c,s}(1)/E$$

where $\tau_{c,s}(1)/E$ is the combined lifetime against Compton and synchrotron losses for 1-GeV electrons. In the disc (see table on page 38) with a starlight density of 0.5 eV/cm³, 0.25 eV/cm³ in the 2.7-K photons and 1 eV/cm² in magnetic fields of 5×10^{-6} gauss, the lifetime $\tau_{c,s}(1)$ is about 200 million years.

What kind of information do we get from the cosmic-ray electrons?

Residence time in the Galaxy. We take $S(E) = S_0E^{-\beta}$ as the number of cosmic-ray electrons injected per unit volume per unit time in the disc. With such a source the equilibrium density of electrons will be

$$j(E) = S(E)\cdot\tau_{eff}(E)$$

where τ_{eff} is the effective period over which the electrons are stored.

$$1/\tau_{eff} = 1/\tau_l + E/\tau_{c,s}(1) + \ldots \approx [\tau_l E - \tau_{c,s}(1)]/\tau_l\tau_{c,s}$$

Thus, at relatively low energies, at which the leakage dominates, $\tau_{eff} \approx \tau_l$, and the equilibrium spectral shape of the electrons is

$$j(E) \approx \tau_l S_0 E^{-\beta}$$

which has the same energy dependence as the injected spectrum. At higher energies, however, the Compton and synchrotron losses take over (see figure 6) and the equilibrium spectral shape becomes

$$j(E) \approx \tau_{c,s}(1)S_0E^{-\beta}/E = \tau_{c,s}(1)S_0E^{-(\beta+1)}$$

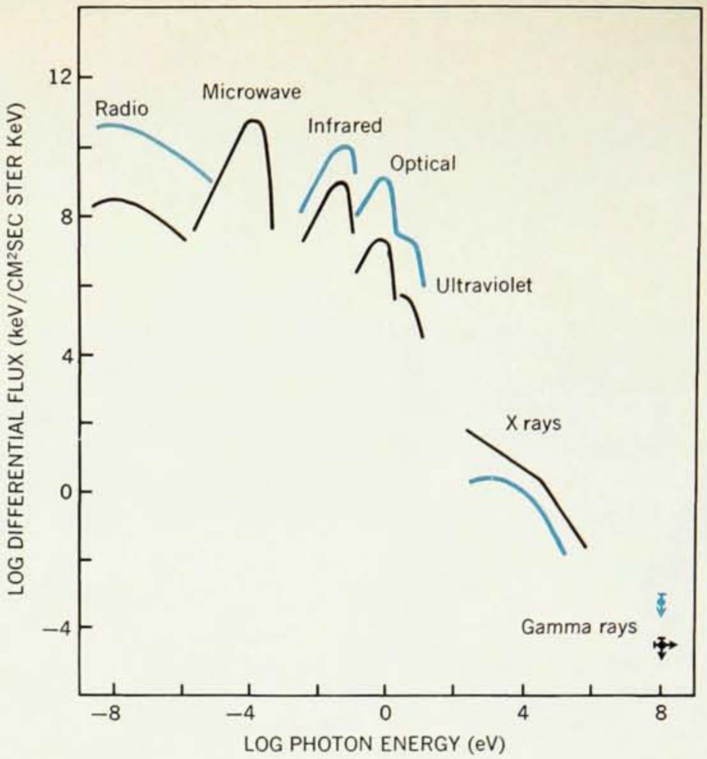
That is, the spectral slope is steeper by 1 (see figure 4), and an observation of steepening of the cosmic-ray electron spectrum at some energy E_c would allow τ_l to be determined through the relation $\tau_l = \tau_{c,s}(E_c)$. The measured electron spectrum does not show any slope change up to at least 100 GeV, but a slight steepening appears at 200 GeV or so. If we take $E_c > 100$ GeV, we find that cosmic electrons leak out of the galaxy in a time less than 2 million years. In this time the electrons, moving with a velocity about equal to the velocity of light, traverse a thickness $\rho c\tau_l$ g/cm² of matter. If the time is spent in the disc of density 10^{-24} g/cm³ (see table), the matter traversed turns out to be 2–4 gm/cm², consistent with the values derived from the abundance of Li, Be and B.

Positrons. The absence of antinuclei in cosmic rays[2] essentially rules out antimatter sources. The positrons that make up about a tenth of the electronic component in the GeV region are thus not primary but are generated in high-energy interactions of the nuclear component with interstellar matter: The π-mesons that are produced decay to muons, and a positively charged muon decays to a positron and two neutrinos. Because the cross section for meson production, the matter density in interstellar space and the equilibrium flux of cosmic-ray nuclei at high energies ($\sim$1 GeV) are known, this process defines the injection rate of positrons into the Galactic volume. By comparing this rate with the observed positron intensity, we derive the storage time of positrons, which turns out also to be about 2 million years. We see then that all the various cosmic-ray components in the energy region 1–100 GeV leak out of the galaxy in a few million years.

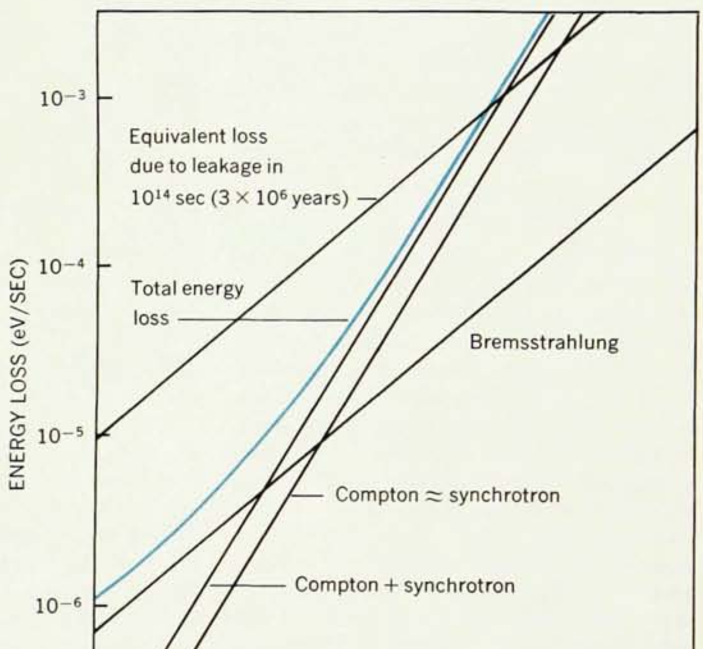
Electron and positron spectra. For electrons (a) the range of experimental data (light-colored area) is compared with curves calculated for two values of storage time in the galaxy, 10^6 and 10^8 years (solid color lines). The dip in the observed spectrum disappears (top dotted line) when correction is made for modulation by the sun. The observed spectrum curves away from the injection spectrum (dotted line at bottom), which is assumed to be a simple power-law distribution of energy, in a way that indicates the age of the cosmic rays is close to 10^6 years. The observed positron spectrum (b, light-colored area) also indicates an age of about 10^6 years. Figure 4

Electrons as probes

Electrons transmit information about the strengths of magnetic fields and



Electromagnetic radiation distribution. Contribution from within the galaxy (color) is negligible compared with the isotropic background flux (black) in the microwave region. This isotropic microwave radiation is believed to be largely a remnant of the "big-bang" origin of the universe. Figure 5



Electron energy loss. At low energies, leakage of electrons out of the galaxy (gray) is the dominant loss process, and the observed spectrum is the same as that coming out of the sources. At higher energies (about 100 GeV), losses through Compton collisions and synchroton radiation become important, and the slope of the spectrum steepens (see figure 4a). Figure 6

radiation fields in distant regions of space by generating photons that travel in straight lines and can be detected at the earth. A single electron of energy E gyrating in a magnetic field H radiates photons with a frequency distribution peaked at about

$$\nu \approx (E/mc^2)^2[eH/2\pi mc] = \gamma^2\nu \text{ cyclotron} \quad (1)$$

which lies in the radio band for 1–10GeV electrons. The process is called magnetic bremsstrahlung or synchrotron radiation. For a power-law electron-energy distribution $E^{-\beta}$, it is well known that the corresponding frequency distribution of the radio photons emitted is proportional to $\nu^{-\alpha}$, where $2\alpha + 1 = \beta$. From the observed value $\beta = 2.5$ for the high-energy cosmic-ray electrons (see figure 4a), we see that $\alpha \approx 0.75$, and indeed the nonthermal radio background from the Galactic disc (figure 5) has about this slope. The radiation intensity depends on the strength of the Galactic magnetic field as $\sim H^{(\beta+1)/2} \sim H^{1.8}$. To reproduce the observed radio intensities at high frequencies one needs magnetic fields of about 10^{-5} gauss in the Galactic disc.[10]

The electron spectrum observed near Earth shows a flattening below 2 GeV, and we might expect, from equation 1, to find a flattening of the radio spectrum below about 160 MHz. Such a flattening of the radio spectrum is indeed observed, indicating that the electron spectrum everywhere in the Galactic volume does have a shape similar to that near Earth and that the magnetic fields are indeed about 10^{-5} gauss in the disc. This value of the field is somewhat larger than values deduced from Faraday rotation of the radio signals from various pulsars. We have no definite explanation of this discrepancy; it may result from directional anisotropy of the field, because the Faraday rotation measures the mean value of the component of the field along the line of sight, $\langle B_l \rangle$, whereas the synchrotron intensity measures the transverse component $\langle B_t^{1.8} \rangle$.

In addition to a general radio brightness of the sky in the direction of the Galactic disc, one notices intense radio emission from rather narrow regions of the sky. Some of these "sources" are essentially points and cannot be resolved; others are extended and diffuse. The diffuse sources are identified with supernova remnants such as the Crab Nebula, Cassiopeia-A and Tycho, and with distant galaxies. The point sources are identified with pulsars and quasars. The main mechanism of radio emission here is probably synchrotron radiation by the cosmic-ray electrons generated in these sources. Straightforward reasoning, based on assumed equipartition of energy among various modes in the sources and on a knowledge of their distances from us, leads us to conclude that 10^{50}–10^{52} ergs are stored in galactic supernova sources and 10^{60}–10^{63} ergs are stored in the radio galaxies and quasars. This information is essential to the problem of the origin of cosmic rays.

Intergalactic electrons

High energy electrons can convert low-energy photons into x rays and gamma rays by Compton scattering. The energy of a soft photon is increased by a factor $(E/mc^2)^2$. Just as with synchrotron radiation the logarithmic slope α of the frequency spectrum of the hard quanta bears the relation $2\alpha + 1 = \beta$ to the slope of the electron spectrum. The electromagnetic spectra from various galaxies give us a measure of the densities and spectra of cosmic-ray electrons within them. If these leak out of all the galaxies at an average rate equal to the rate of leakage from our own galaxy, that is in 10^6 years, then we can estimate the intensity and spectral shape of the electrons in intergalactic space.

Most galaxies have a spectrum of electrons like our own, with $\beta \approx 2.5$, which steepens because of energy losses in the intergalactic space to a slope of about 3.5; the Compton-scattered x-ray spectrum from such an electron spectrum would have $\alpha = 1.25$. Looking out of the plane of our Galactic disc so that we see mainly extragalactic radiation, we indeed find that the spectrum of the isotropic x radiation (see figure 5) has a slope 1.25 in the energy range 50–500 keV. Further, we get the right intensity if we assume that the celebrated 2.7-K blackbody photons are indeed universal. This generation of hard quanta by Compton scattering of low-energy quanta (which may also be generated through synchrotron radiation of the very same electrons) is one of the important mechanisms operating in many of the x-ray sources that have been discovered in recent years.

Origin of cosmic rays

What can we now say about the mystery of the origin of cosmic rays and the ways they reach high energies? Fermi suggested that cosmic rays are repeatedly scattered against the clouds of magnetized plasma that move at about 30 km per sec in interstellar space. Cosmic rays tend to achieve kinetic equilibrium with the clouds, but because they also leak out of the Galaxy, the result is a steady state. The total kinetic energy of all the particles in a plasma cloud is virtually infinite ($M_0V^2 = 10^{33} \times (3 \times 10^6)^2 = 10^{46}$ ergs $\approx 10^{58}$ eV!), so that the maximum energy attainable by a single scattered particle is limited only by the fall off of the scattering cross section at very high energies. Using a simple exponential distribution of Galactic residence times for cosmic rays, Fermi showed that this process generates the observed power-law spectrum of cosmic rays.

Unfortunately, this "Fermi process" cannot explain the observed cosmic rays, because with velocities of 30 km per sec and cloud densities of 10^{-3}/parsec^3, residence times in excess of 2×10^8 years are needed before the cosmic rays gain enough energy from the collisions, whereas we have seen that the residence times are about 100 times smaller. Many different processes based on essentially the same principle of scattering against moving magnetic irregularities have been proposed, but none has adequate efficiency to generate the observed cosmic rays.

We conclude that cosmic rays originate in localized regions, where the activity is much more violent, and there is no better example than the Galactic Center, where violent gas motions and intense emission in the infrared are observed. We do not believe, however, that the bulk of the cosmic rays seen near the earth originated in the Galactic Center. The intense radiation fields there would drain all the energy away from cosmic-ray electrons of energy greater than about 100 GeV, and we would see none of these at the earth, whereas observations indicate a rather smooth electron spectrum extending well beyond 100 GeV.

Supernova sources

An extremely attractive suggestion first made some 20 years ago[11] is that both the nuclear and electronic components are produced and accelerated in supernova explosions. We have seen that radio observations indicate a rather intense flux of high-energy electrons in supernova remnants. With 10^{50}–10^{51} ergs emitted as cosmic rays per supernova and one supernova occurring in the Galaxy every 30 years, the injection rate would be $10^{54.5}$–$10^{55.5}$ ergs per 10^6 years. Cosmic rays have an energy density of about 10^{-12} erg/cm^3 in the Galactic volume of 10^{67} cm^3, and are to be replaced about every million years. The energy needed is 10^{55} ergs/10^6 yrs, in reasonable agreement with the available power.

After the initial supernova implosion a shock wave goes out from the core, reaching extreme relativistic velocities in the tenuous outer layers of the star. This shock accelerates particles to energies ranging from 10^8 to 10^{21} eV, consistent with the observed power-law energy spectrum.[12] During the explosion intense fluxes of neutrons are generated, and nuclides extending into the ultraheavy region may be synthesized by rapid neutron capture. The overabundance of extremely heavy cosmic rays and the possible existence of transuranic cosmic rays thus provide support for the supernova model.[6,7]

Against this positive evidence for supernova sources we must weigh a very unattractive feature. With one supernova explosion detonating every 30 years and an effective period of 1000 years for the dispersal of cosmic rays from the remnant, at any moment there are only about 30 supernovas in the Galaxy contributing to the local cosmic-ray intensity. We also note that the thickness of the disc is less than a thirtieth of the diameter, so that effectively less than one supernova would be contributing to the intensity. Under these circumstances it is hard to understand the observed high degree of isotropy and constancy in time of the nuclear component.

Cosmic rays from pulsars?

Pulsar observations in the last two years have given impetus to much theoretical work on the acceleration of high-energy particles near rotating magnetized bodies such as neutron stars. Here the gravitational energy of the collapse is stored as rotational energy of the neutron star. With masses typically comparable to that of the sun, and rotational periods of 10^{-2} sec, the rotational energy that is stored in a neutron star with a radius of 10^6 cm is about 10^{50} ergs.

Intense surface fields (10^{12} gauss) are believed to be generated during the collapse by the compression of the stellar magnetic field. Two mechanisms for acceleration of charged particles have been considered.[13] Suppose the rotation axis of the neutron star does not coincide with the magnetic moment (assume a simple dipole field). Intense magnetic dipole radiation must then be emitted from the neutron star, and charged particles near it would be phase locked onto this outward expanding spherical wave and reach relativistic velocities. In another version of the theory the rotating neutron star is a homopolar dynamo with an induced electric field $[(\Omega \times \mathbf{r})/c] \times \mathbf{B}$, where Ω is the angular-momentum vector and $\mathbf{r}$ is the position vector. Thus there is a field of about 10^{16} volts/cm near the neutron star, and particles are accelerated in the crossed electric and magnetic fields.

Calculations indicate that pulsars may be able to generate the highest-energy cosmic rays, beyond 10^{14} eV, but do not efficiently generate the majority of the cosmic rays, which have energies of only 10^9–10^{12} eV. And, as in the case of supernovas, there are probably too few sources at any moment to generate the remarkable degree of isotropy and constancy of the cosmic rays. Finally, the surface of the rotating neutron star is probably nearly pure iron, and we meet difficulties in accounting for the composition of the nuclear cosmic rays unless we suppose that gas of the right composition, originating outside of the neutron star, is accelerated in the pulsar field.

White dwarfs provide isotropy

The absence of any detectable anisotropy in arrival directions of cosmic rays at energies up to about 5×10^{13} eV strongly suggests that the sources are many and are widely distributed in the galaxy. It is very tempting to see if the rather elegant pulsar-acceleration mechanisms operate in weaker but more numerous sources to generate isotropic cosmic rays with energies peaked at 10^9 to 10^{10} eV, as observed. White dwarfs appear to be ideal candidates. There are about 10^{10} of them, populating a disc roughly 1 kiloparsec high, considerably thicker than the Galactic disc populated by normal stars. Because they have evolved from normal stars by collapse to about 1% of their original radius, their magnetic fields are believed to have increased by 10^4 (megagauss fields have recently been observed in three white dwarfs[14]), and their rotational periods have decreased by a similar factor to as little as 10 or 100 sec.

We can treat white dwarfs as baby pulsars,[15] with estimated fields of 10^6 V/cm near their surfaces. Within a distance comparable to the radius of a white dwarf, 10^8 cm, we believe that cosmic rays can be accelerated to energies of 10^8 to perhaps 10^{14} eV. The rotational energies of white dwarfs are 10^{46-49} ergs; given 10^{10} white dwarfs one may just be able to supply the required cosmic-ray power over the life of the galaxy. Because the surface of a white dwarf appears to be depleted in heavy elements,[16] we would have to account for the composition of nuclear cosmic rays by a process in which interstellar gas from outside the white dwarf is accelerated, with an enhancement of the heavy elements. Establishing an iron-clad case for the existence of trans-uranic cosmic rays would, however, pose a major stumbling block to our white-dwarf model, as well as to the pulsar model, of cosmic-ray origin.

Our ideas on white dwarfs as cosmic-ray sources are sufficiently recent that they have not yet been subjected to the critical scrutiny of the astrophysical community. But the white-dwarf model can eventually be tested experimentally: As the nuclei and electrons accelerated at a white dwarf diffuse away from it, the electrons will suffer Compton scattering in the intense photon fields around the star, generating MeV gamma rays. With a well collimated detector, these gamma rays might be observable from the nearest white dwarfs against the isotropic background.

We have argued that the acceleration of cosmic rays may involve transfer of rotational energy of astronomical bodies through magnetic fields to the particles, be they pulsars generating cosmic rays up to 10^{20} eV or white dwarfs and similar bodies contributing to the lower end of the spectrum. When we sum the contributions of these objects over their life history as cosmic-ray sources, we may have the solution to the mystery of why the cosmic rays have such a smooth spectrum, extending over some 13 decades of energy with essentially the same spectral index, 2.5, in most of the galaxies. However, we repeat that the supernova model successfully accounts for many of the features of cosmic rays and has survived criticism for two decades. Finally, there is no reason to exclude novas, flare stars, magnetic stars and other active objects that may also contribute to the flux of cosmic rays in various energy bands. If they do, then we can expect compositional differences to become evident once a sufficiently broad range of energies has been studied.

Magnitudes in Cosmic-Ray Astrophysics

				Energy densities (eV/cm³)			
Region	Size (cm)	Matter density (atom/cm³)	Magnetic field (10^{-6} gauss)	magnetic	starlight	blackbody radiation	cosmic rays
Solar system	10^{14}	500	50	100	10^7	0.25	1
Galaxy (disc)	4×10^{22} by 2×10^{21}	1	5	1	0.5	0.25	1
Galaxy (halo)	4×10^{22}	$\leq 10^{-2}$	?	?	0.1	0.25	<1?
Universe	10^{28}	$\leq 10^{-5}$	<0.1	$<4 \times 10^{-4}$	0.003	0.25	$<10^{-3}$

Mean energy of starlight photon = 3 eV
Mean energy of 2.7-K blackbody photon = 6×10^{-4} eV

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