Cosmic rays—astronomy with energetic particles

What objects inside or outside our galaxy produce these extremely high-energy electrons and nuclei of the entire periodic table?

Peter Meyer, Reuven Ramaty and William R. Webber

Since the discovery of the cosmic radiation the question of the origin of these high-energy particles has been an astrophysical problem of foremost importance. Rapid progress toward an understanding of this problem has been made in the past ten to twenty years as experimental techniques became available that permitted a study of the cosmic radiation either near the outer fringes of the atmosphere, with high-altitude balloons, or in space, totally uninhibited by the Earth's atmosphere. The picture that has unfolded displays an enormous variety. All nuclei in the periodic table of the elements, as well as electrons and positrons, are present in the stream of cosmic-ray particles; their energies span the range from at least 10^6 eV to 10^{20} eV.

Why has the study of these energetic particles attracted so much attention? First of all, they constitute the only sample of matter from outside the solar system that reaches the Earth. This sample has some special properties. It has been accelerated to high energies in the recent past, recent compared to the age of our galaxy. While the composition and the energy spectra of the particles are modified during the time they spend traveling through the interstellar medium, this modification is minor, and hence the signature of the nature of the sources remains imprinted on these quantities. Perhaps the most important result of recent cosmic-ray research is the recognition that the abundance distribution of the nuclear cosmic rays points to a thermonuclear origin.

It has long been debated whether the cosmic radiation observed near the Earth originates in the galaxy or is extragalactic in origin, pervading the entire extragalactic space. Recent evidence, based on γ-ray observations, favors a galactic origin, at least for the cosmic rays with energy below 10^{11} eV. The flux of cosmic rays appears, however, to be isotropic up to the highest measured energies (10^{20} eV), reaching Earth with the same intensity from all directions. Above 10^{16} eV the particles have cyclotron radii in the interstellar magnetic fields that are comparable to galactic dimensions—hence their trajectories begin to deviate less and less from straight lines. Sources distributed only in the galactic disc should yield anisotropies for an observer on Earth, anisotropies that have not been observed. We therefore conclude that the particles with energy in excess of about 10^{16} eV may not originate in the galaxy.

Cosmic rays are not a unique property of our galaxy, but seem to be generally present in other galaxies. From the evidence of non-thermal radio emission we can conclude that cosmic-ray electrons exist with much larger intensity in radio galaxies and particularly in quasi-stellar objects than they do in our own galaxy. Of general significance is the recognition that the cosmic rays are an important factor in the energy balance and in the stability of the galaxy. While the cosmic-ray particles constitute a very tenuous gas, their energy density in the galaxy is about 1 eV/cm^3, and hence of the same order as the energy density of the galactic magnetic fields and of the turbulent motion of the interstellar gas. Cosmochemical evidence indicates that the cosmic-ray intensity has, on the average, been roughly constant throughout the age of the solar system.

The challenges that face cosmic-ray research today are manyfold. On the one hand they cover the problems of identifying the cosmic-ray sources and the acceleration mechanisms that lead to the high particle energies. On the other hand they deal with the nature of the interstellar medium through studies of particle propagation and interaction and the life span of cosmic rays in this medium. These interactions are diverse; they include nuclear collisions between the cosmic-ray nuclei and interstellar matter, as well as electromagnetic interactions between high-energy electrons and positrons and the interstellar magnetic fields and photon fields. Each of these interactions is of significant astrophysical importance in the understanding of the interstellar medium, and several of them tie cosmic-ray research to neighboring fields of astrophysics: radioastronomy (synchrotron radiation), x-ray and γ-ray astronomy and the studies of stellar evolution.

The observations

The astrophysical evidence contained in the cosmic radiation is extracted from the observations of: the abundance distribution and composition of the cosmic-ray particles; the energy spectra; and any directional anisotropies.

Figure 1 displays the present knowledge of the abundance distribution of the elements in the range from a few hundred MeV/nucleon to about one GeV/nucleon, and from hydrogen to the iron group. Today our most accurate knowledge of the extrasolar-element abundance distribution comes from the cosmic-ray evidence. For comparison, the solar-system abundances are also

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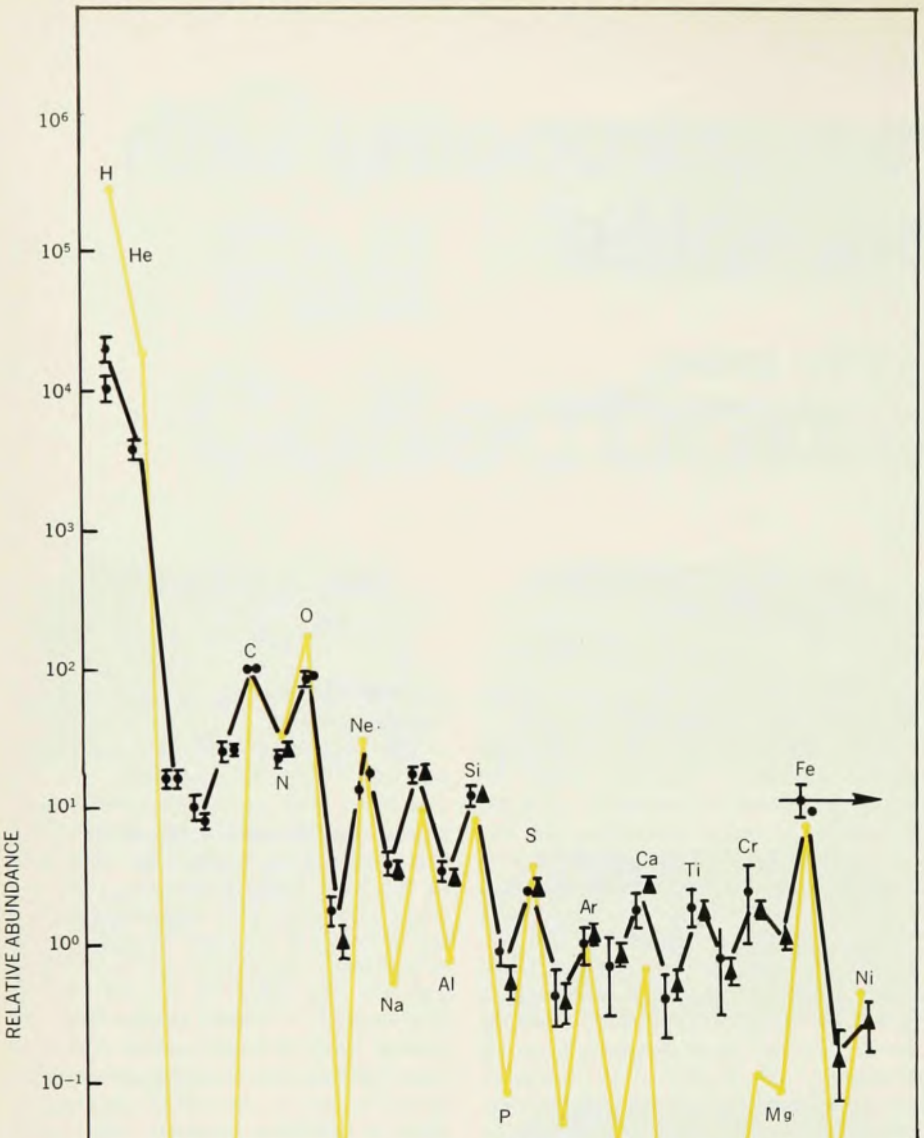


Relative abundance of the elements from hydrogen to the iron group, normalized to that of carbon (C = 100). The black points represent the cosmic-ray abundances measured near Earth. The colored dots represent the element abundances in the solar system. (Here and in the following figures results by different authors are given different symbols to indicate the level of agreement between different experiments.) Figure 1

shown in the figure. The similarities between the two distributions are striking, particularly the abundance maxima at carbon and oxygen and at the iron group, as well as the enhancement of even-atomic number nuclei compared to those of odd Z. Equally obvious, already on a qualitative basis, are several differences. The light nuclei Li, Be and B, very rare in the solar system, are abundant in the cosmic rays, and so are the nuclei between $Z = 15$ and 24, phosphorus to chromium. Their presence in the cosmic rays can be understood as fragmentation products originating in the collisions of heavier nuclei with ambient matter during the propagation of the cosmic rays from their sources to Earth.

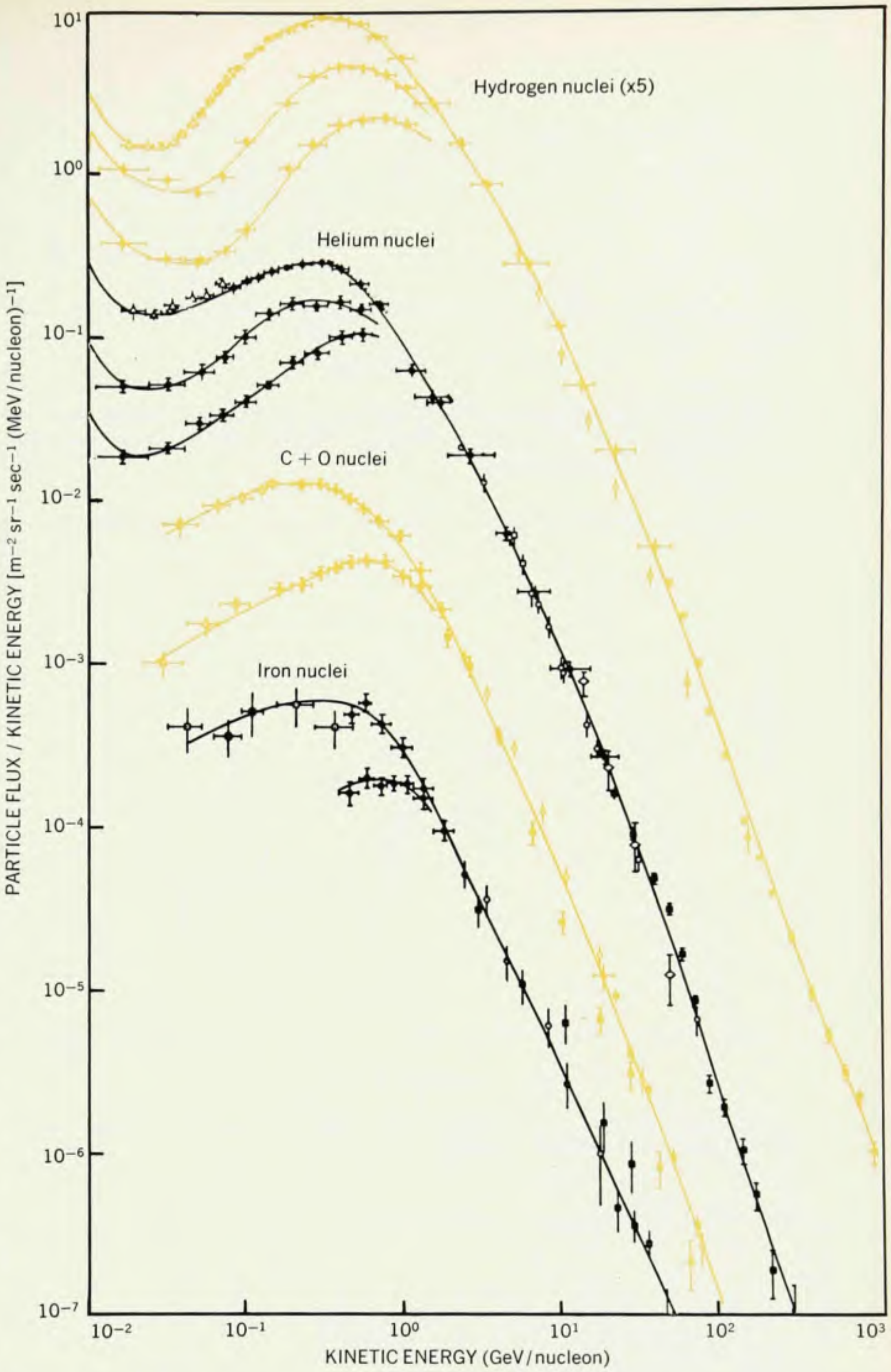
A most exciting part of the developments of the past few years was the discovery of nuclei beyond the iron group—which proved that the entire periodic system of the elements is represented in the cosmic radiation. It is one of the major goals of today's research to determine, with greater accuracy, the abundance distribution of these transiron nuclei and thereby to identify the specific kind of nucleosynthesis processes that led to it. Table 1 contains the abundance distribution of cosmic-ray nuclei with atomic numbers 35 and above, incident on the atmosphere and extrapolated to their sources. The rarity of these heavy elements, and hence the difficulty in measuring their abundance, is best demonstrated by noting that the numbers in the table are normalized to 10^6 iron nuclei. Perhaps the most outstanding feature in this distribution is the "platinum peak" of elements in the range of Z from 75 to 79.

An important pursuit of present cosmic-ray research that has already provided significant results is the elucidation of the energy spectra of individual particle species over a wide range, in order to determine the dependence of the cosmic-ray composition on particle energy. For many nuclear species, energy spectra have now been measured from a few MeV/nucleon to about 100 GeV/nucleon. As examples we show, in figure 2, spectra of the more abundant nuclei H, He, C + O and Fe. All these spectra are well described by power laws in total energy, $dJ/dE \propto E^{-\gamma}$, at energies that are sufficiently high to avoid major influences of the interplanetary medium, which tend to modulate the interstellar spectra. The slopes of the energy spectra of all nuclei are quite similar, having closely the same exponent, but measurable differences in the spectra of different nuclei have recently been discovered. These differences are most noticeable at high energies, showing that the relative abundance of the nuclear species is not completely independent of energy. Such changes in abundance serve as a clue toward understanding the nature of the cosmic-ray sources; they also provide information on the propagation of the cosmic-ray particles in interstellar space. Differences in the energy spectra lead to energy-dependent abundance ratios; the best-established examples of this are the ratios of (Li + Be + B) to (C + N + O) and of C + O to Fe. These are shown in figures 3 and 4 as a function of energy. Even the carbon and oxygen spectra exhibit differences at both high and low energies. Measurements of the carbon-to-oxygen ratio as a function of energy can be seen in figure 5. We shall discuss the implications of these observations shortly.

The energy spectrum of the electron component has now been measured from fractions of an MeV to almost 1000 GeV. The form of this spectrum is of great interest since electrons and nuclei possibly undergo different acceleration processes. Even more important is the fact that the electrons interact in an entirely different manner with the ingredients of the interstellar medium. Little affected by the interstellar gas, they lose energy through synchrotron radiation as they spiral about the magnetic fields, and through Compton collisions, mainly with the photons of the 2.7 K universal black-body radiation. We show, in figure 6, the measured energy spectrum of electrons together with the spectrum of protons.

Valuable information on the source distribution and propagation of the cosmic rays in the galaxy could come from anisotropy measurements. Unfortunately, these have proved to be among the most difficult and elusive of all cosmic-ray measurements. Below about 10^{11} eV, the effects of interplanetary magnetic fields grossly distort any local galactic anisotropy. Thus it is impossible to determine the anisotropy of the great bulk of cosmic rays. Evidence that the local anisotropy, δ, of galactic cosmic rays is less than about 2×10^{-4} has recently been reported by observers utilizing large-area underground detectors that respond to a mean energy of about 10^{11} eV. (The definition of the local anisotropy is $\delta = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensities.) This energy is not yet high enough to be free of significant scattering effects in the interplanetary medium. At still higher energies—even up to about 10^{18} eV—there is no evidence for any anisotropy in the cosmic radiation. The upper limits on δ range from approximately 10^{-3} at about 10^{14} eV to 10^{-2} at energies of about 10^{18} eV.

As a point of reference one should recall that the Compton–Getting anisotropies, $\delta = (2 + \gamma)\, v/c$, expected from Earth's orbital velocity (about 30 km/sec) or the relative solar velocity of about 20 km/sec in the galaxy, are approximately 3×10^{-4}. At the very least, one would expect to observe such anisotropies superimposed on any bulk flow of cosmic rays.

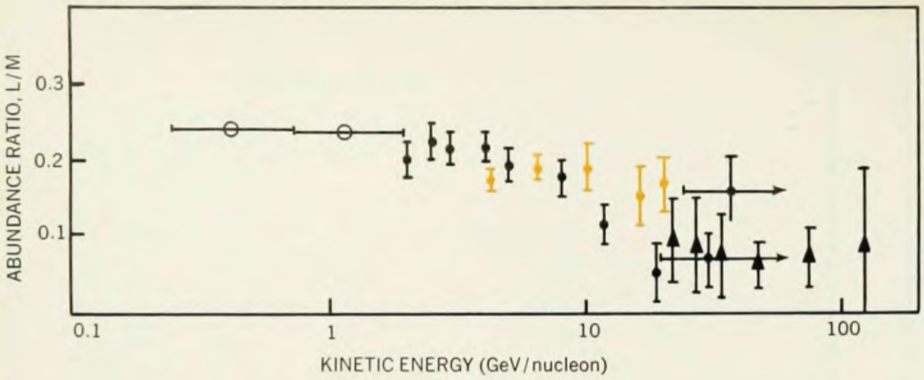


Cosmic-ray energy spectra of the more abundant nuclear species as measured near Earth. Below a few GeV/nucleon, these spectra are strongly influenced by modulation within the solar system. The different curves for the same species at those energies represent measurements at various levels of general solar activity, the lowest intensity being observed at the highest activity level. Figure 2

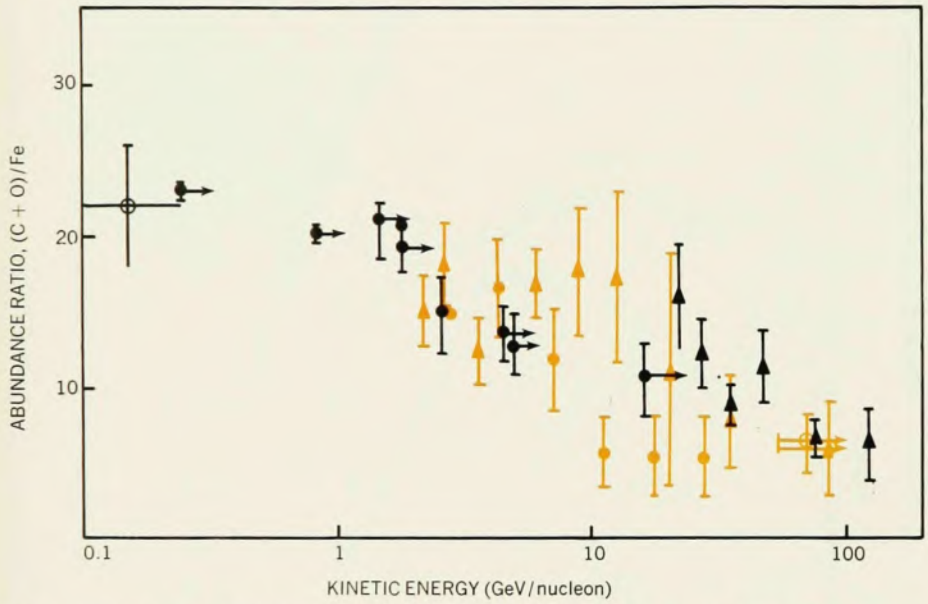
Cosmic-ray sources

Perhaps the most important astrophysical information that cosmic-ray observations can provide comes from the charge and isotopic composition of the components. These observations bear directly on the processes of element synthesis in the cosmic-ray sources, particularly on the synthesis of heavy nuclei.

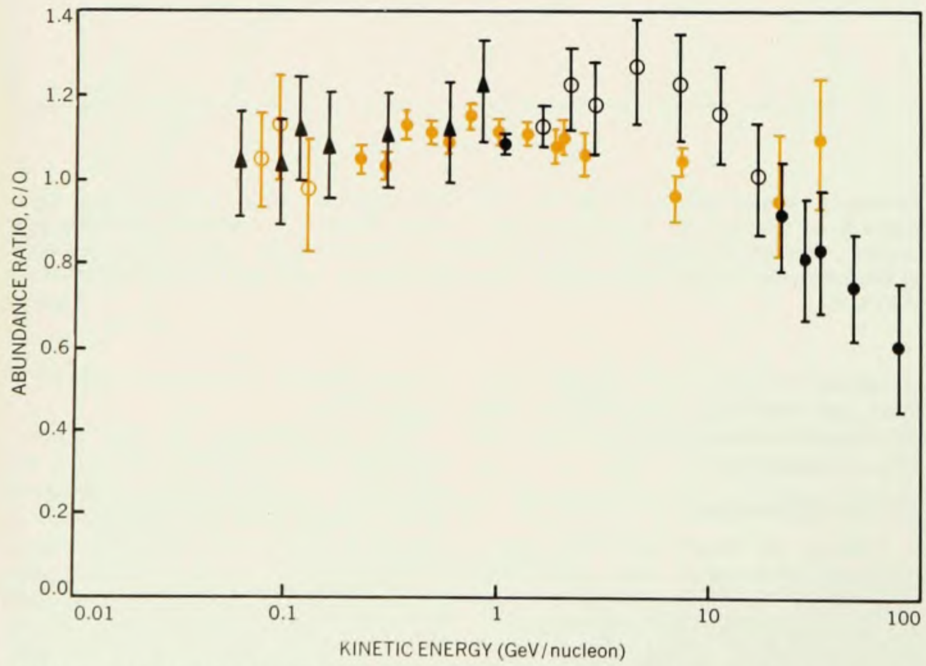
The development of our understanding of the nucleosynthesis of the elements in stellar objects has advanced hand-in-hand with the improvement in cosmic-ray elemental composition data. The pioneering work by E. Margaret Burbidge, Geoffrey Burbidge, William A. Fowler and Fred Hoyle has led to a recent upsurge of activity in connection with explosive nucleosynthesis in massive stars. Increasingly more detailed



The ratio of abundance of the light nuclei lithium, beryllium and boron to the medium nuclei carbon, nitrogen and oxygen in cosmic rays, as a function of energy. The light nuclei are mainly spallation products due to collisions in space. Figure 3



The cosmic-ray abundance ratio of the medium nuclei carbon and oxygen to the iron-group nuclei iron and manganese, as a function of energy. Figure 4



The cosmic-ray abundance ratio of carbon to oxygen nuclei versus energy. Abundance ratios such as this provide clues to the sources of the cosmic rays and their propagation. Figure 5

abundance predictions are now available for the elements up to $Z \approx 28$. At successively higher temperatures, ranging from about 10^9 K to about 6×10^9 K, the processes of explosive burning of helium, carbon, oxygen and silicon in the cores and shells of these massive stars combine to produce the elemental and isotopic composition of the lighter nuclei. Other processes, such as explosive H burning, and the so-called "CNO bi-cycle" modify the abundances of carbon, nitrogen and oxygen and produce some of the rarer isotopes of these nuclei.

The relative composition of most elements in the cosmic radiation, up to $Z \approx 28$, is now known to an accuracy of a few percent (figure 1). But the sample of cosmic rays observed at Earth has been significantly modified by nuclear fragmentation and cannot be used directly to infer the composition of the sources. As a result of nuclear interactions between cosmic-ray particles and ambient matter, the cosmic rays are enriched in the rare elements (such as lithium, beryllium, boron and other secondaries) and are depleted in some source nuclei such as iron. The phenomenon of cosmic-ray propagation, however, is sufficiently well understood to make reasonable extrapolations to the sources possible.

Consider the resultant cosmic-ray source composition for elements with $Z \leq 28$. It is useful to divide these elements into three groups. The first group (H, He, C, O, Ne, Mg, Si, Fe, Ni) consists of elements that are definitely present in the cosmic-ray sources. For every element in this group the observed abundance deviates less than about 20% from the source abundance as a result of fragmentation in interstellar space; hence the source abundances can be determined with reasonable accuracies. Except for neon, the solar system abundances of these elements are also quite well known. In figure 7 we show the ratio of the cosmic-ray source abundances to the solar-system abundances for elements in this group as a function of atomic number Z. With respect to the solar-system abundances, the cosmic-ray source abundance either is depleted in H, He, C and O or enriched in Mg, Si, Fe and Ni. No statement can be made for Ne because its solar-system abundance is poorly known.

The second group of elements (N, Na, Al, S, Ar, Ca, Cr, Mn) is probably also present in the cosmic-ray sources, but the source abundance cannot yet be determined accurately, since approximately 50% of the abundance observed at Earth is the result of interstellar fragmentation. Nonetheless, the picture obtained from the elements in group 1 appears to be supported by those in group 2, with the possible exception of S and Ar. There are, however, considerable uncertainties in the solar-system abundances of these elements.

The third group (Li, Be, B, F, Cl, K, Sc, Ti, V) consists of elements that, in the cosmic rays, are almost entirely due to fragmentation. Thus no conclusions can be drawn about their presence in the cosmic-ray sources, and they cannot provide information on the processes that accelerate the cosmic rays. On the other hand, our understanding of the propagation of cosmic rays depends strongly on the measured abundances of these nuclei.

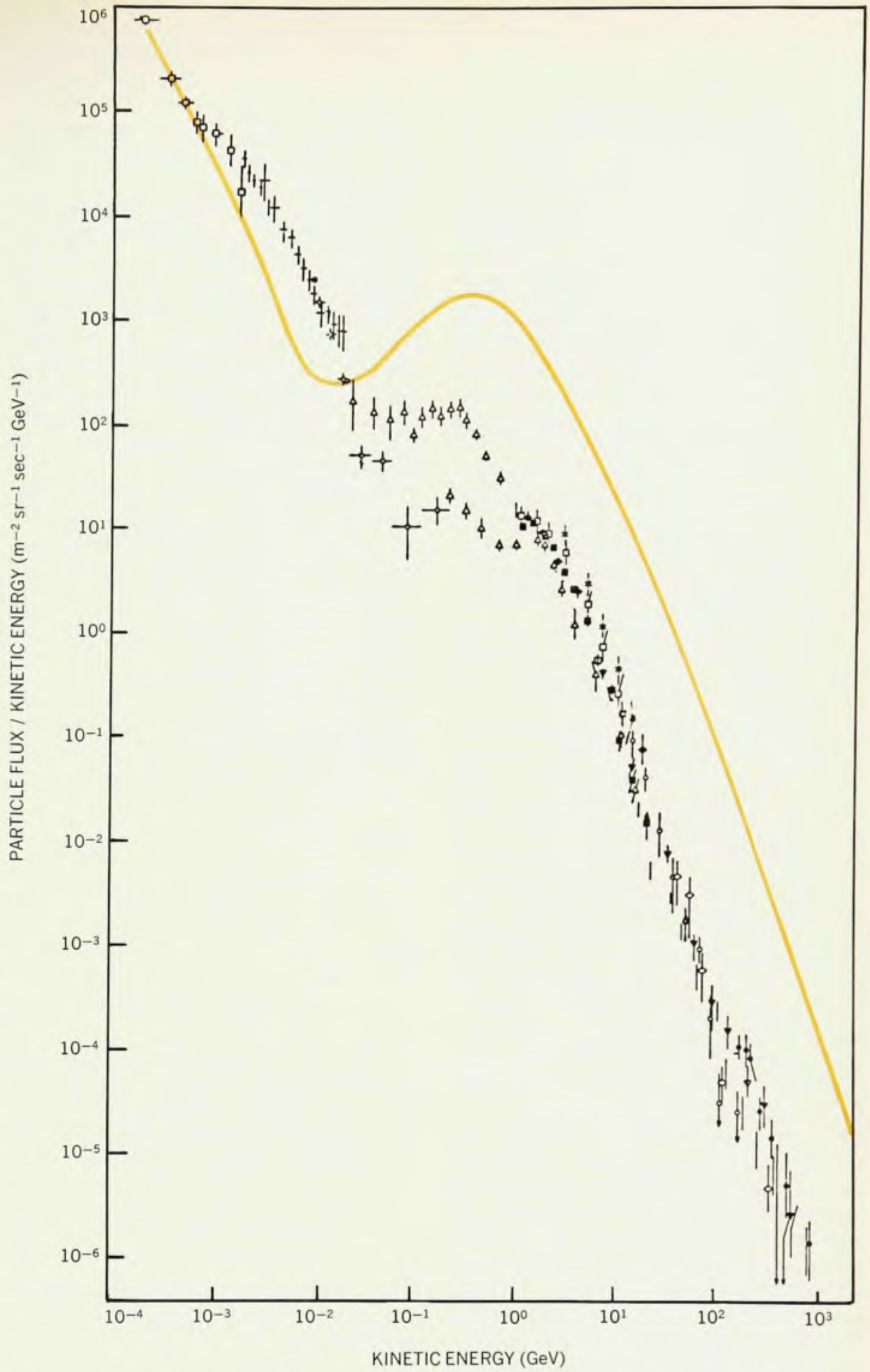
Detailed comparisons of abundances (based on calculations of explosive nucleosynthesis with those observed in the cosmic-ray sources, as discussed above) support the idea that the basic sources of lower-energy cosmic rays (< 100 GeV) are highly-evolved massive stars, with masses greater than about 5 solar masses.

One should remember that for many years supernovae have been regarded as one of the prime sources of cosmic rays. The arguments have been mainly on energy grounds. The location of the sources of cosmic rays in massive stars of advanced age would, of course, support the supernova hypothesis. The discovery of neutron stars or pulsars in some supernova remnants adds another potential source for energetic particles, although the mechanisms by which these objects may impart some of their energy to the particles are not well understood at this time.

Interactions and propagation

Let us now turn to the phenomena that determine the behavior of the cosmic rays in their travel between source and observer. Here we wish to consider such questions as the spatial distributions of the cosmic-ray sources, the interactions of the particles with the interstellar medium and their "age" (confinement time within the galaxy).

All of these topics involve the propagation of the energetic particles through interstellar space, and the conclusions contribute directly to an understanding of the properties of the interstellar medium. We first summarize the interactions. Interstellar magnetic fields prevent the charged particles from escaping along rectilinear paths. They are responsible for confining the cosmic radiation and for randomizing their trajectories through deflection and scattering on magnetic-field irregularities. The precise nature of these scattering processes is not well understood; it is possible that the cosmic rays themselves generate hydromagnetic waves on which they in turn are scattered, but there could also be other sources of turbulence that contribute to the presence of scattering centers. If the galactic



The energy spectra of cosmic-ray protons (line) and electrons (points) as measured near Earth. Below a few GeV, interstellar spectra are strongly influenced by the Sun. Figure 6

magnetic fields were closed, cosmic rays would be confined forever, unless, as a result of instabilities, magnetic field, interstellar gas and cosmic rays are pushed out. This occasionally happens near the edge of the galactic disc. The fact that the galaxy is a stable configuration implies that the outward pressures of the cosmic-ray gas, of the magnetic field and of the turbulent motion must be balanced by gravitational attraction. Therefore it is not by chance that the energy densities contained in each of these three ingredients—magnetic fields, cosmic rays, turbulence—are roughly the same, namely about 1 eV/cm^3.

All charged cosmic-ray particles are scattered and confined by interstellar magnetic fields, but the nuclear components and the electron–positron component exhibit quite different behaviors in other respects. Nuclei, through their strong interaction, undergo collisions with the ambient interstellar gas, leading to a loss of source nuclei and the creation of spallation products, the daughter nuclei (Li, Be, B, etc.). One should note that the shape of the energy spectrum—expressed in energy per nucleon—of the daughter nuclei should be very similar to that of the parent nuclei, and that the spectrum of the parent nuclei should remain unchanged, since the spallation cross sections appear to be nearly energy-independent at high energy. Hence the main effect of nuclear collisions is the production of secondary cosmic rays and the loss of heavy primary nuclei. The precise location of these collisions is not known. They could take place near the sources during the acceleration process itself, or during the propagation of the particles from their sources to Earth. But at least part of the cosmic-ray fragmentation must take place in the interstellar medium. Coulomb collisions or ionization losses are most important at subrelativistic energies, because of the increasing energy loss with decreasing energy. This process not only affects the low-energy cosmic rays, but also the interstellar medium. The cosmic rays may provide a significant part of the ionization and heat observed in the interstellar medium.

Relativistic electrons and positrons, in addition to being confined, undergo electromagnetic interactions. They produce synchrotron radiation while spiraling about the magnetic fields, and this radiation is observed by radioastronomers as a continuous spectrum emerging from the galactic disc. The rate of synchrotron loss is proportional to the square of the energy of the electrons. Similarly, high-energy electrons lose energy due to Compton collisions with photons. In both the interstellar and intergalactic media, the most important contribution to Compton losses is the 2.7 K universal black-body radiation. For electron energies less than 10^{14} eV this Compton energy loss is also proportional to E^2. Furthermore, because the energy density in the 2.7 K radiation field is comparable to the energy density in interstellar magnetic fields, Compton and synchrotron losses have approximately the same effect on cosmic ray electrons in the galaxy. Outside the galaxy, however, synchrotron losses are negligible in comparison with Compton losses. It is precisely because of these severe Compton losses in intergalactic space that we know that cosmic-ray electrons must be produced and confined in our own galaxy.

It is possible to combine the above mentioned effects into a cosmic-ray transport equation that treats the random spatial motion of the particles in terms of diffusion. Such a diffusion-energy loss equation can be written as

$$\frac{\partial n}{\partial t} - \nabla\cdot(D\nabla n) + \frac{\partial}{\partial E}(\dot{E}n) + \frac{n}{T} = Q \quad (1)$$

Here $n(\mathbf{r},t,E)$ is the density of cosmic rays per unit energy interval as a function of position, time and energy, D is the diffusion coefficient, $\dot{E}$ is the rate of energy loss, T is the lifetime against nuclear collisions for nuclei and $Q(\mathbf{r},t,E)$ is the cosmic-ray source strength per unit volume and unit energy interval, which also can depend on position, time and energy.

In general, the solutions of equation 1 are complicated and require many assumptions regarding the magnitudes and functional forms of the various terms as well as the boundary conditions of the cosmic-ray confinement volume. The available treatments, which attempt to achieve workable solutions, make many simplifications. Here we present a solution based on the following assumptions:

The cosmic rays are in a steady state and the source Q is a separable function of position and energy $Q = Q_1(E)\cdot Q_2(\mathbf{r})$. This means that the cosmic-ray production spectrum is the same everywhere. The functions D, $\dot{E}$ and T are independent of position, but can depend on energy. This means that the diffusion coefficient, energy loss rate and nuclear destruction time are the same everywhere in the galaxy.

The solution can then be written as

$$n(\mathbf{r},E) = \int_0^\infty dt \, \frac{\dot{E}(E_0)}{\dot{E}(E)} \times \exp\left[-\int_E^{E_0} \frac{dE'}{\dot{E}(E')}\right] Q_1(E_0)P(\mathbf{r},\tau) \quad (2)$$

Here

$$P(\mathbf{r},\tau) = \int d^3r_0 \, f(\mathbf{r},\mathbf{r}_0,\tau)Q_2(\mathbf{r}_0) \quad (3)$$

is the age distribution of the cosmic rays at $\mathbf{r}$, given in terms of an integral over the source distribution $Q_2(\mathbf{r}_0)$. The propagation function f from $\mathbf{r}_0$ to $\mathbf{r}$ satisfies the equation

$$\frac{\partial f}{\partial \tau} - \nabla^2 f = \delta(\mathbf{r} - \mathbf{r}_0)\delta(\tau) \quad (4)$$

with the same boundary conditions as the cosmic-ray density n; t and τ are determined by

$$t = \int_E^{E_0} \frac{dE'}{\dot{E}(E')}; \quad \tau = \frac{1}{D_0}\int_E^{E_0} \frac{D(E')dE'}{\dot{E}(E')}$$

Of course, t and τ are the same should D not be a function of E.

Some examples of age distributions are shown in figure 8. The simplest is a delta function corresponding to an age of 3×10^6 years. This distribution would imply that all cosmic rays have traversed a "slab" of matter of precisely the same amount, that is, that all cosmic rays were produced in a single event in the past. Also shown are an exponential distribution that results from treating the galaxy as a "leaky box" and, as an example of applying equations 3 and 4, the age distribution that is obtained by assuming a constant D throughout a galactic disc of semi-thickness 300 parsec, a totally absorbing boundary, and a uniform source distribution in a thinner disc of semi-thickness 150 parsec. Except for the "slab" all these distributions have the property of predicting the observed ratios of both light ($3 \leq Z \leq 5$) to medium ($6 \leq Z \leq 8$) nuclei and secondaries of iron to iron nuclei in the energy range from 0.1 to 1 GeV/nucleon. The slab distribution predicts too much fragmentation for iron nuclei. This is an important recent development in understanding the origin of cosmic rays: The cosmic rays can not have been produced in a single event sometime in the past.

The mean life τ_0 of a cosmic-ray particle in the galaxy is connected to the mean amount of matter it traverses (in gram/cm²) by

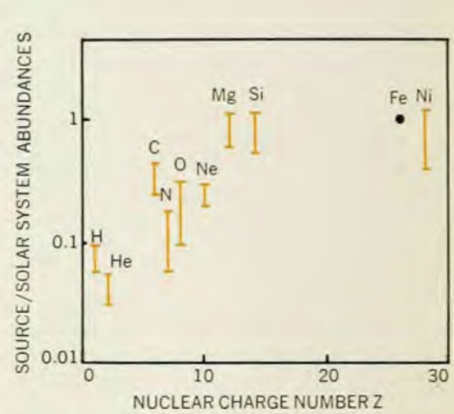
$$X_0 = \langle\rho\rangle\beta c\tau_0$$

where $\langle\rho\rangle$ is the mean interstellar density and βc the particles' velocity. One

Table 1. The abundance distribution of ultraheavy cosmic rays

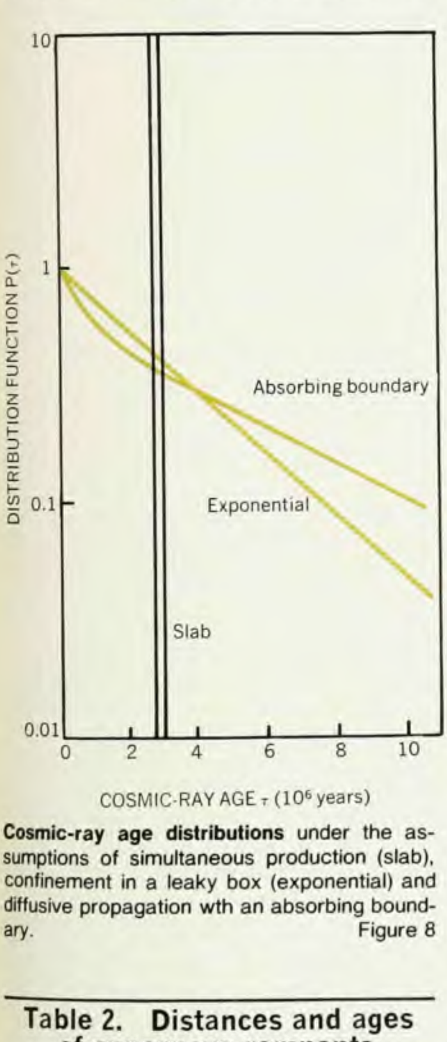
Atomic number Z	Cosmic-ray abundances: At top of atmosphere	Cosmic-ray abundances: Extrapolated to source*
26	10^6	10^6
35–39	65 ± 20	50 ± 22
40–44	35 ± 14	30 ± 16
45–49	4 ± 2	-0.3 ± 3
50–54	8.3 ± 1.2	5.0 ± 1.5
55–59	6.1 ± 1.2	4.0 ± 1.4
60–64	2.5 ± 0.6	0.0 ± 0.0
65–69	2.2 ± 0.6	-0.1 ± 1.0
70–74	2.3 ± 0.7	0.3 ± 1.0
75–79	4.7 ± 0.7	4.7 ± 0.7
80–84	2.0 ± 0.5	2.0 ± 0.5
85–89	1.1 ± 0.5	1.4 ± 0.6
90–94	1.5 ± 0.4	2.4 ± 0.6
≥95	0.1 ± 0.1	0.2 ± 0.2

* On the assumption that X_0 = 5 gm/cm².



The ratio of abundances of various nuclei in cosmic-ray sources to that in the solar system as a function of the nuclear charge number, normalized to unity for iron nuclei. Figure 7 measures X_0 to be about 5 to 7 gram/cm^2, leading to a τ_0 of a few million years under the assumption that the interstellar density is about one hydrogen atom per cubic centimeter, and that all interactions take place in the interstellar medium rather than in a denser medium near source. The "measurement" of X_0 from the abundances of daughter elements requires detailed knowledge of a large number of production cross sections. Much effort is going into measurements of such cross sections or, where this is not yet possible, into the development of semiempirical approaches which permit reliable estimates.

An extremely attractive method to determine the cosmic-ray confinement time, not yet fully explored, is the use of radioactive clocks. The collection of isotopes that are produced in the spallation process contains many radioactive species including several whose halflife is comparable to the expected confinement time. Notable examples are Be^{10} (halflife 1.6×10^6 years), Al^{26} (0.74×10^6 years), and Cl^{36} (0.30×10^6 years). Survival of the isotope indicates a confinement time shorter than the halflife, while absence of the isotope points to a longer confinement time. If measured over a wide range of energies (and Lorentz factors $\gamma = E/mc^2$), time dilatation permits the use of the same isotope as a clock over a range of effective decay times. Only nuclei of the isotope Be^{10} have so far been separately observed, but in too small a number to yield a statistically very significant result. An estimate of the cosmic-ray confinement time based on this work is $\tau_0 \approx 3 \times 10^6$ years, within a factor of two.



Cosmic-ray age distributions under the assumptions of simultaneous production (slab), confinement in a leaky box (exponential) and diffusive propagation wth an absorbing boundary. Figure 8

Table 2. Distances and ages of supernova remnants

Galactic source number	Distance (kpc)	Age (10^4 yr)	Name
G 41.9 − 4.1	0.7	3.2	CTB 72
G 74.0 − 8.6	0.6	3.5	Cygnus Loop
G 89.1 + 4.7	0.8	2.3	HB 21
G117.3 + 0.1	0.9	4.7	CTB 1
G156.4 − 1.2	0.6	3.2	CTB 13
G160.5 + 2.8	0.8	2.7	HB 9
G180.0 − 1.7	0.7	4.3	S149
G205.5 + 0.2	0.6	4.6	Monoceros
G263.4 − 3.0	0.4	1.1	Vela X
G330.0 + 15.0	0.4	3.8	Lupus Loop

The evidence of the past two years shows that the cosmic-ray composition changes with energy and that these changes become substantial at energies greater than about 5 GeV/nucleon. The ratio of daughter to parent nuclei decreases with increasing energy, showing clearly that the more energetic nuclei traverse less interstellar matter than those of low energy, and hence are producing fewer spallation products. This evidence is seen in figure 3, which displays the result of measurements of the ratio of daughter nuclei to parent nuclei up to about 100 GeV/nucleon. One can notice that this ratio changes by more than a factor of two over the range of the measurement. It is not possible to explain this evidence by invoking changes of nuclear cross sections with energy, since the cross sections responsible for the production of the daughter elements are known to be essentially energy-independent at the energies of concern.

Among several explanations for this interesting phenomenon, the simplest postulates an energy-dependent escape path, and hence an energy-dependent containment time of the cosmic radiation in the galaxy. Slightly more complex alternative proposals seek to explain the energy-dependent composition through effects of particle propagation while maintaining a model of uniform distributions of sources in space and time throughout the galactic disc. For example, it has been suggested that much of the matter traversed by the cosmic rays is located in the vicinity of the sources, a region from which energetic particles may emerge more readily than those of lower energy. In this model, cosmic rays of low energy travel in paths through interstellar matter the major portion of which are near their sources.

One must raise the question of whether the observed changes in cosmic-ray composition are indeed due to losses during particle propagation or whether they may have as their origin the spatial distribution of the sources. None of the present observations can completely exclude an explanation on the basis of propagation, but this explanation is becoming increasingly difficult. Improved accuracy and measurements at still higher energies will decide whether the changes in composition are not manifestations of features of individual cosmic-ray sources.

The electron–positron component

Turning to the behavior of the electrons, it is convenient to discuss various portions of their energy spectrum as it affects particular astrophysical problems. At energies greater than about 10 GeV, the shape of the electron spectrum should depend on the confinement time of the cosmic rays. At some energy the radiative life due to synchrotron and Compton losses of cosmic-ray electrons in interstellar space must become comparable to or shorter than the residence time of the cosmic rays in the galaxy. A change in the spectral slope should develop around that energy, and the electron intensity should decrease more rapidly with increasing energy.

As seen in figure 6, the electron spectrum in the region 10 GeV $\lesssim E \lesssim 10^3$ GeV is to first approximation a power law; the particle flux per energy interval is proportional to $E^{-\gamma}$, with spectral index $\gamma \approx 2.8$. However, this simple power-law fit is only made possible by the large statistical errors in the data.

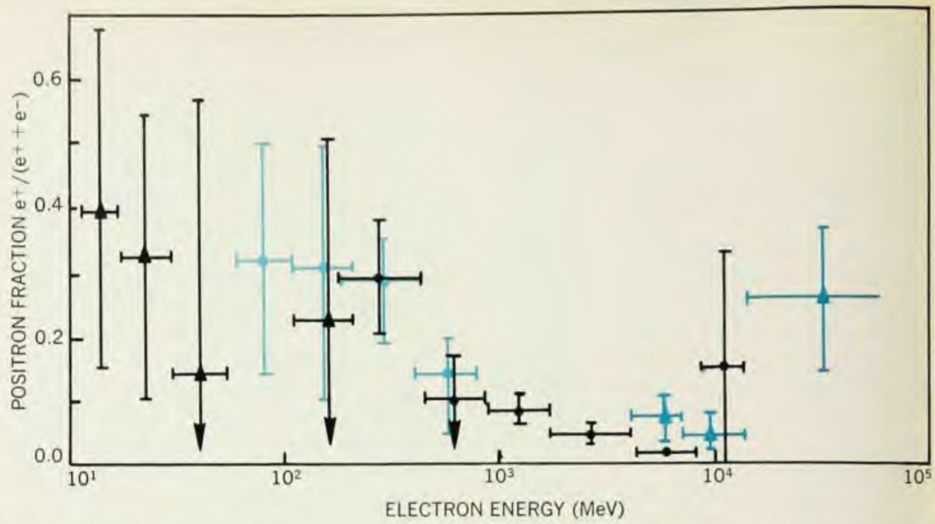
If we accept the evidence indicating no steepening in the electron spectrum up to an energy of about 10^3 GeV, we must conclude one of the following: Either the electron-injection spectrum has a spectral index of about 1.8, and the synchrotron and Compton losses have modified this index to 2.8 already at 3 GeV; or the age of the electrons is less than their radiative life at all observed energies. The first conclusion, although not excluded, is unlikely, since it requires a very long confinement time for the electrons ($\approx 10^8$ years), in conflict with the confinement time observed for most nuclear cosmic rays; it also requires a source spectrum for cosmic-ray electrons that is quite different from the spectra of all other cosmic rays.

The second conclusion is more likely; this alternative could come about in two ways. At about 200 GeV, the lifetime against radiation losses of electrons in typical interstellar fields and in the presence of the 2.7 K blackbody radiation is about 10^6 years, the same as the confinement time determined from the nucleonic component at a few GeV. However, if the confinement time of the cosmic rays decreases with increasing energy, as suggested by the decrease in the daughter-to-parent ratio of the nuclei, it is conceivable that, even at 10^3 GeV, cosmic electrons escape from the galaxy without much energy loss; hence, no steepening would be observed in their spectrum.

On the other hand, the absence of a steepening of the electron spectrum might be due to the spatial distribution of their sources. If the electrons originated in a select set of supernova explosions that occurred at a more recent epoch than the mean cosmic-ray age, their age would be much shorter than their radiative life. Lists of the observable radio remnants of supernovae have been compiled. The ten remnants that are within 1 kpc of the solar system are shown, together with their estimated distance and age, in table 2. All these supernovae could contribute to the electron flux up to approximately 10^3 GeV.

Figure 6 shows both the proton spectrum and the electron spectrum measured near Earth. At energies greater than about 50 MeV, where both the electrons and protons are thought to be of galactic origin, there are fewer electrons than protons, the average electron-to-proton ratio being about 1%. This result does not seem to be an obvious consequence of any of the proposed cosmic-ray acceleration mechanisms. If the cosmic rays are accelerated by a shock wave from a supernova explosion moving in the outermost layers of the presupernova star, electrons and protons should be accelerated to the same velocity. This means that the electron-to-proton ratio of the intensities at the same energy should be $(m_e/m_p)^{\gamma-1}$ where m_e and m_p are the electron and proton rest masses, and γ is the differential spectral index defined above. For $\gamma = 2.8$, the e–p ratio is 1.3×10^{-6}, a value much lower than the observed ratio of about 0.01. If the cosmic rays are accelerated by pulsars, either close to a neutron star or in the supernova remnant in which the pulsar is embedded, about equal amounts of energy should be supplied to the protons and the electrons. Hence, their observed numbers at the same energy should also be about equal, again contrary to observation. Obviously, cosmic-ray acceleration is much more involved than the behavior implied by these two simple models.

The observed fraction of positrons in the electron component is shown in figure 9. A finite flux of positrons exists in the energy range from about 10 MeV to several GeV. The positron component of the cosmic-ray electrons is believed to result from the decay of π^+ mesons that are produced by nuclear collisions of the primary cosmic rays with ambient matter, most probably in the interstellar medium. This assumption is supported by detailed calculations based on accelerator data, which show quite clearly that enough positrons can be produced in the interstellar medium to account for the observed positron flux.



The fraction of positrons in the cosmic-ray electron component as a function of energy. These positrons are produced in high-energy interactions of protons with the nuclei of the interstellar gas, leading to π^+ mesons, which ultimately decay to positrons. Figure 9

Among the astrophysical problems that can best be studied with high-energy positrons is that of cosmic-ray lifetime. While the electron-source spectrum is in principle unknown, the positron source spectrum can be calculated and directly compared with observations in order to deduce the effects of radiative energy losses. Further, because the positrons are of secondary origin, the effect of decreasing fragmentation as a function of increasing energy that was deduced from the daughter–parent ratio of nuclei should become apparent in the high-energy positron data as well. While the prospects are very exciting, detailed studies of these problems cannot yet be carried out because of the lack of good observational data on positrons at sufficiently high energies.

However, a rather straightforward and model-independent result already emerges from the data in figure 9. The observed increase of $e^+/(e^+ + e^-)$ with decreasing energy implies that the total interstellar electron spectrum in the 0.1 to 1 GeV range is flatter than the interstellar positron spectrum. Calculations of the positron-production spectrum via π^+ decay show that the spectral index of the positron spectrum from about 0.2 to 1 GeV is around 2.0, and certainly less than the proton spectral index of 2.6. Therefore, the electron spectrum in this range must have a spectral index flatter than the index γ of about 2.8 measured at higher energies. This is the same conclusion as that obtained from the study of the nonthermal radio background: The observed bend in the electron spectrum at a few GeV is not entirely due to solar modulation, but at least part of it is intrinsic to the interstellar electron spectrum.

Summary and outlook

What are the key directions of cosmic ray research in the immediate future?

Of prime interest is the determination of accurate nuclear and isotopic abundances and their application to the source composition. Major tasks lie ahead in this area, both from the point of view of more detailed reaction network analysis in the nucleosynthesis problem and more detailed abundance information on the cosmic rays—particularly for the isotopes and the heavier elements. The potential to carry out these measurements now exists. The improving cosmic-ray charge and isotopic data appear likely to lead not only to a clearer identification of the types of cosmic-ray sources but also to a detailed understanding of the various thermonuclear processes and temperature regimes in the sources—information that can be obtained in no other way.

Isotope composition data may be utilized to improve our understanding of the spatial distribution and propagation of cosmic rays in the galaxy through the use of radioactive species that serve as "nuclear clocks." These questions can also be attacked by better anisotropy measurements.

Studies of galactic γ rays and eventual identification of x- and γ-ray lines will provide a powerful new tool for the study of the cosmic-ray distribution in space and may ultimately lead to answers on the age-old question of galactic versus extragalactic cosmic rays.

Further studies of the spectra of individual cosmic-ray species at both high and low energies are bound to be extremely fruitful. At high energies, measurements of the compositional changes may lead to a better understanding of how cosmic rays propagate

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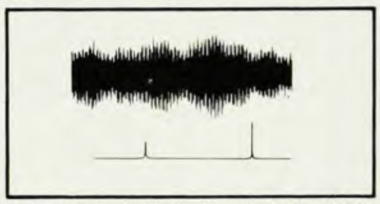

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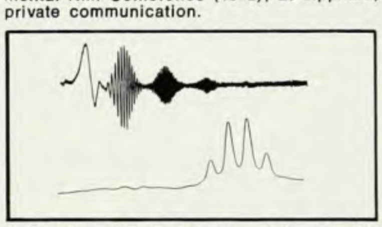
RAPID SCAN NMR — In this technique, a spectral region is swept at a rate much greater than allowed for by slow passage conditions and the resulting ringing spectrum correlated with a spectrum of a single ringing line or of a theoretical line. Its principal advantage lies in the ability to acquire data rapidly even in the presence of strong solvent lines, without requiring that these lines be part of the signal averaged data.



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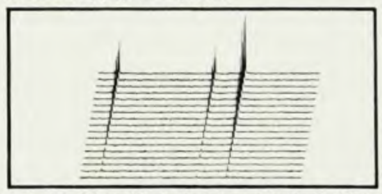

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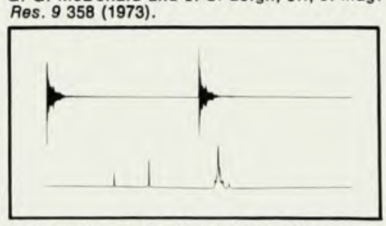
QUADRATURE DETECTION NMR — This technique allows $\sqrt{2}$ enhancement over conventional pulsed nmr since the rf carrier can be placed in the center of the spectral region and dual phase detectors used to receive the response. The two resulting free induction decays are Fourier transformed using a complex transform which results in a single frequency domain spectrum.



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through and escape from the galaxy. This information in turn will affect the interpretation of spectral measurements at the highest energies as obtained from giant air showers. The question of the cosmic-ray spectrum above about 10^{19} eV has most important cosmological implications.

At low energies there is evidence of significant differences in the spectra of different nuclei. It may be that this is already a manifestation of contributions by nearby cosmic-ray sources. The role of cosmic rays in galactic dynamics will be further elucidated as one gains precise knowledge of these spectra.

Antinuclei have been searched for, and this search will undoubtedly continue, because the discovery of a single antinucleus, say oxygen, would prove the synthesis and existence of antimatter in bulk form, an extremely important result about the nature of the universe.

Electrons and positrons play a special role in cosmic-ray astrophysics because of their strong interactions with photons and magnetic fields. Knowledge of the spectrum of these components at both low and high energies needs to be much improved. It is hoped that this work will help to answer the question of whether electrons and nuclei come from the same sources and what role these particles play in both galactic and extragalactic photon dynamics.

The fundamental question of how the cosmic-ray nuclei and electrons are accelerated to their fantastic energies is still wide open. Many diverse approaches must be brought together to obtain an answer to this question. This is characteristic of much of the current cosmic-ray research, which involves many different fields, and it is representative of the exciting challenges that lie ahead.

* * *

We express our thanks and apologies to the many colleagues whose original and review papers we have used in writing this article without referring to their work. Readers interested in more details and in references to the original papers may consult the publications listed below.

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