NASA-CR-196118

NATIONAL RESEARCH COUNCIL

BOARD ON PHYSICS AND ASTRONOMY

COSMIC RAYS: PHYSICS AND ASTROPHYSICS

A Research Briefing

(NASA-CR-196118) COSMIC RAYS: PHYSICS AND ASTROPHYSICS. A RESEARCH BRIEFING (NAS-NRC) 23 p

N94-36921

Unclas

G3/93 0014088

Cosmic Rays: Physics and Astrophysics
A Research Briefing

Committee on Cosmic-Ray Physics

Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

National Academy Press
Washington, D.C. 1994

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an advisor to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce Alberts and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

This project was supported by the National Aeronautics and Space Administration under Grant No. NAGW-3557.

Additional copies of this report are available from:

Board on Physics and Astronomy
HA 562
National Research Council
2101 Constitution Avenue, NW
Washington, DC 20418

Printed in the United States of America

COMMITTEE ON COSMIC-RAY PHYSICS

THOMAS K. GAISSER, University of Delaware, *Chair*
DAVID O. CALDWELL, University of California, Santa Barbara
JAMES CRONIN, University of Chicago
FRANCIS HALZEN, University of Wisconsin, Madison
ALICE K. HARDING, NASA Goddard Space Flight Center
JACK R. JOKIPII, University of Arizona
EUGENE C. LOH, University of Utah
RICHARD MEWALDT, California Institute of Technology
JONATHAN F. ORMES, NASA Goddard Space Flight Center
SIMON SWORDY, University of Chicago
TREVOR C. WEEKES, Whipple Observatory

ROBERT L. RIEMER, Senior Program Officer

BOARD ON PHYSICS AND ASTRONOMY

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND APPLICATIONS

Preface

The Board on Physics and Astronomy of the National Research Council established the Committee on Cosmic-Ray Physics to prepare a review of the field of cosmic-ray physics that addresses both experimental and theoretical aspects of the origin of cosmic radiation from outside the heliosphere. This action was initially motivated by a request from the Space Physics Division of NASA to consider the program of research in this discipline in light of new constraints on the scope of missions at NASA, which make previously planned cosmic-ray missions on a large space station and on the Space Shuttle seem unlikely at present.

At the same time it is apparent that there are several exciting new opportunities in cosmic-ray physics that are ripe for significant progress. Accordingly, the committee has been charged to provide a balanced assessment of the entire field at this point and to consider the experiments needed to take advantage of current scientific opportunities.

Another reason for undertaking a balanced assessment of the field is that cosmic-ray physics is an intrinsically interdisciplinary subject. It is a part both of physics and of astrophysics. Its support, moreover, is drawn from several different sources, including the National Aeronautics and Space Administration, the National Science Foundation, and the Department of Energy. The scientific rationale for the field becomes fully apparent only when all aspects of the subject are seen together. Thus, for example, measurements of positrons and antiprotons are relevant both to models of cosmic-ray propagation (space astrophysics) and to searches for dark matter in the universe (particle physics and cosmology). A direct measurement of the composition of high-energy cosmic rays above the atmosphere (supported by NASA) will not only clear up an important question about the efficiency of supernovas as cosmic accelerators, but also calibrate ground-based experiments (supported by NSF and DOE) that can extend the measurements to still higher energies.

The full report of the committee is to be completed by September 1994. To provide an interim progress report, the committee prepared this research briefing on a short time scale after one meeting of the full committee and several telephone conferences and a series of exchanges of electronic mail within the committee. Opinions of the scientific community are being solicited by electronic mail and in the newsletter of the Division of Astrophysics of the American Physical Society. Because of its interim nature, this document is not a systematic treatment of the field, nor does it attempt to prioritize various proposed lines of investigation or assess their financial implications. Rather, it gives a brief account of selected topics that illustrate the main scientific directions and opportunities of the field.

Contents

PAGE VIII INTENTIONALLY BLANK

1. Overview

Cosmic-ray physics is about Nature's accelerators. The space between the stars in our Milky Way Galaxy is alive with charged particles — ionized atomic nuclei such as protons and He^{++}, electrons, and even a few antiprotons. Most of these form a hot background plasma between denser regions of neutral gas. A few particles find themselves injected into cosmic accelerators and promoted to high energy. These are the particles that we refer to as cosmic rays. They are characterized by a spectral index instead of a temperature, which describes how cosmic-ray particles are distributed among proportionately increasing bands of energy. The number density of relativistic cosmic-ray particles is much less than that of the thermal plasma, but the total energy content of the two groups is comparable. This means that the individual cosmic-ray particles have much higher energy than those of the plasma.

How do cosmic accelerators work? Where does the power to drive them come from? What is their distribution in space? What energetic astrophysical processes are they associated with? Why do a few particles achieve high energies, rather than all of the particles in a given region becoming slightly heated? These are the fundamental questions that drive cosmic-ray physics. Laboratory accelerators produce intense, monoenergetic beams of particles of a single type; cosmic accelerators produce a diffuse spray of particles with a wide distribution of energies — a very few of them with energies orders of magnitude higher than can be achieved in the laboratory.

Each cosmic accelerator is characterized by a total power, a spectral index, and a maximum energy per particle. In addition, it produces a mix of different kinds of particles that reflects its environment. The spectrum observed at a given location in the Galaxy is a composite of the spectra of individual accelerators, with different types of acceleration processes predominant in different ranges of energy.

Much of the power that drives energetic processes in the space between the stars comes from supernovas — explosions of massive stars at the end of the cycle of nuclear fusion. For reasons explained in this report, it is likely that supernovas also power the acceleration of most cosmic rays. But how and where this acceleration happens, what kinds of supernovas are involved, and how to explain the existence of the highest-energy cosmic rays are questions of intense current interest.

This report summarizes some recent results in cosmic-ray physics and describes how they raise new questions of interest both for physics and for astrophysics. An important technical advance — the recently demonstrated capability of long-duration balloon flights of heavy payloads — will offer a great advantage for achieving some of these goals.

Organization of this report.

Figure 1 shows a schematic representation of the cosmic-ray energy spectrum. The figure shows the number of particles per logarithmic interval of energy. The three principal sections

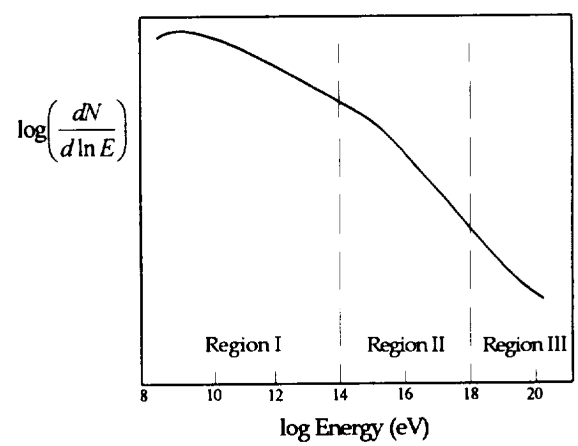

Figure 1. Cosmic-ray energy spectrum.

of this report (Sections 2, 3, and 4) correspond to the three energy regions indicated with Roman numerals (I, II, and III). Although the dividing points are somewhat arbitrary, they correspond approximately to regions where different techniques are applicable and in which different acceleration mechanisms may dominate. The boundaries between the different regions are of particular interest. Section 5 describes important interdisciplinary aspects of cosmic-ray physics. Finally, Section 6 summarizes what we know about the three energy regions and points out what would be necessary to advance our understanding of cosmic rays, their origins, and the astrophysical processes that influence their makeup.

2. Cosmic-Ray Spectroscopy

Cosmic rays provide a direct sample of the matter from their remote sources, and their energy spectra reflect the physics of the acceleration mechanism. Because they are charged, however, scattering in the turbulent magnetized plasma component of the interstellar medium leaves them virtually completely isotropic, except possibly at the very highest energies. Gamma rays give complementary information. Because photons travel in straight lines, they can be used to map the regions in the Galaxy where cosmic-ray interactions with gas produce secondary photons and to identify point sources of cosmic rays if they interact with gas at the source. Thus photons (and neutrinos) are remote probes of the origin of cosmic rays.

Observations of diffuse γ-ray emission from other galaxies also answer fundamental questions about the origin of cosmic rays. For example, the upper limit on γ-ray flux from the Small Magellanic Cloud (SMC), recently found by the Energetic Gamma-Ray Experiment Telescope (EGRET), has now clearly ruled out the possibility that the density of cosmic rays is the same throughout the universe. This fact had been suspected on the basis of other observations but not proved. If the cosmic-ray density were the same everywhere in the universe, then the rate of γ-ray production in the gas of the SMC would be a factor of four higher. In fact, the observed upper limit is even lower than the flux expected if the cosmic-ray density in the SMC were in pressure equilibrium with the gas and magnetic fields there. This observation implies that the SMC, unlike our galaxy, cannot contain its locally produced cosmic rays. EGRET detection of another nearby galaxy, the Large Magellanic Cloud, on the other hand, shows a γ-ray flux that requires a cosmic-ray density comparable to that in the solar neighborhood, and is consistent with that expected for local pressure equilibrium, implying a cosmic-ray source production and interaction in that galaxy similar to the situation in our own.

2.1 Cosmic-ray interactions with the Galaxy

If we are to understand the origin of cosmic rays, it is necessary to relate the observed cosmic-ray spectrum and composition near Earth to those at the sources. This is done by a physical model of cosmic-ray propagation in the interstellar medium. The generally accepted picture has "primary" cosmic rays, produced in sources distributed throughout the galactic disk, which subsequently move in and out of the disk and the nearby more-rarefied galactic halo, guided by the galactic magnetic field. Eventually the cosmic rays diffuse into distant regions of the halo and are lost altogether from the galaxy. The light elements Li, Be, and B are virtually absent in stars and the sources of cosmic rays, yet they are relatively abundant in the cosmic radiation. The light nuclei in cosmic rays are produced in collisions of the primary cosmic rays with the ambient interstellar gas, and are termed "secondary" cosmic rays. From knowledge of the abundances of these secondary cosmic rays relative to "primary" cosmic rays, which are synthesized abundantly in stars, together with a knowledge of the probability of collisions producing light nuclei and of the density in the disk, it has been possible to infer the mean amount of matter traversed by the primary nuclei during their lifetime. The quantity determined in this way is a product of gas density, velocity, and lifetime, $\rho \times \upsilon \times \tau$, which has a maximum of about 10 g/cm^2 at 1 GeV/nucleon and decreases steadily with increasing energy.

A measurement of the unstable isotope ^{10}Be (with a half-life of 1.5×10^6 years) in the cosmic-ray spectrum allows one to determine the mean time between production and observation of the secondary cosmic-ray nuclei. The observed intensity of ^{10}Be is significantly less than that at production, which means that the characteristic lifetime is long enough for most of this isotope to decay, $\tau \sim 10^7$ years. To accumulate the observed amount of matter traversed in this time requires that the matter density encountered by the cosmic rays be only about 1/3 of the density of gas in the galactic disk. This requires that cosmic rays also spend considerable time in the less dense regions of the Galaxy—for example, the galactic halo.

The time spent by a typical cosmic-ray particle in the Galaxy represents several thousand crossings of the gaseous disk—hence the near isotropy of the cosmic-ray flux. Although we learn a great deal from products of the interactions of cosmic rays with gas, such interactions are relatively rare. In fact, what "confines" the cosmic rays is a process of diffusion in the turbulent magnetic fields to which they are coupled.

The distribution of cosmic rays in the disk and halo is still largely uncertain. This uncertainty could be removed by a detailed study of clock "isotopes," such as ^{10}Be and ^{26}Al, as a function of energy. By changing the energy one is tuning the lifetime through relativistic time dilation. Different models of propagation lead to different predictions for the energy dependence of the ratios of stable/unstable isotopes that can be studied in this way.

- *Measurements of clock isotopes can probe the storage of cosmic rays in the galactic halo and may provide evidence for a galactic wind.*

An expectation is that as the energy of a cosmic-ray particle increases, the particle will be less effectively confined to the Galaxy because the magnetic field has less effect on its motion. This means that the cosmic-ray lifetime in the Galaxy decreases with increasing particle energy, which is in accord with the observation, noted above, that the amount of matter traversed is less than for particles with lower energies. Since the observed energy spectrum reflects an equilibrium between sources and escape, the observed energy spectrum is steeper than the energy spectrum at the accelerator. This expectation is in agreement with the fact that the generally accepted shock acceleration mechanism predicts a flatter spectrum (at the source) than is observed (at Earth).

If this picture of cosmic-ray acceleration is correct, then there should be some production of γ rays when accelerated particles mix with the gas of the supernova ejecta. Some recent estimates suggest that the expected flux is tantalizingly close to the measurement capabilities of present detectors, such as EGRET and several of the ground-based γ-ray detectors, which are sensitive to photons with energies in the TeV or 100-TeV range.

2.2 Cosmic-ray source material

Perhaps the most striking difference between the isotopic composition of cosmic rays and that of solar system matter is the excess of ^{22}Ne, which is overabundant relative to ^{20}Ne by a factor of at least four times that found in the solar system. There are several suggested explanations for this difference.

For example, one model proposes that a significant fraction (25 to 30 percent) of the heavy nuclei in cosmic rays originates from the material expelled by Wolf-Rayet (WR) stars (massive stars undergoing significant mass loss) by means of high-velocity stellar winds. As a result, these stars have been stripped of their hydrogen envelopes, and nuclei including ^{12}C, ^{16}O, and ^{22}Ne have been exposed and are being expelled from their surfaces. These high-velocity stellar winds also make WR stars an attractive site for cosmic-ray "pre-acceleration" to modest energies, where they might be further accelerated by supernova shock waves to higher energies. If one mixes some WR material, in which ^{22}Ne is enhanced by a factor of ~ 100, with more normal material, perhaps from the interstellar medium, one can explain both the observed overabundance of ^{22}Ne in cosmic rays, and also the fact that C/O ~ 1 in cosmic rays, compared to C/O ~ 0.4 in the solar system.

Another model takes an entirely different point of view, suggesting that it is not cosmic rays that have an anomalous composition, but rather the solar system itself. In this model the solar system is assumed to have been contaminated by nearby supernova explosions occurring at the time of its formation, which contributed an excess of alpha-particle nuclei (*e.g.*, ^{12}C, ^{16}O, and ^{20}Ne); cosmic rays are taken to be representative of the interstellar medium.

During the next few years, new measurements by instruments on Ulysses, SAMPEX, Geotail, Wind, and especially ACE will extend high-resolution isotope studies to the iron-nickel region, providing new tests of these models, and most likely leading to other possibilities. Beyond ACE, it will be important to extend measurement of the cosmic-ray isotopes to higher energy and to nuclei heavier than iron and nickel.

2.3 Heavy elements in the cosmic rays

Most of the elements in the universe heavier than helium are believed to be produced in stars more massive than the sun, where lighter elements under intense gravitational pressure and high temperature are able to fuse to make heavier nuclei. A very massive star near the end of its lifetime has an onion-like structure, with the heaviest and most stable elements, such as iron, at its core and progressively lighter elements in the outer layers. Once its nuclear fuel is exhausted, the core collapses to a neutron star or black hole, and a supernova explosion ensues. The shock waves from the collapse heat the outer layers of the star, causing a brief, explosive episode during which further nucleosynthesis occurs. Many of the details of this picture of collapse of a massive star were established by the observations of the nearby Supernova 1987A, although a compact remnant has yet to appear. In another class of stars with masses only moderately greater than that of the sun, the entire compact remnant of the progenitor star may be destroyed in a runaway thermonuclear explosion, which also involves synthesis of new elements. In both cases, an amount of material greater than the mass of the sun is injected into the Galaxy and contributes to its evolution.

Synthesis of elements heavier than iron and nickel requires a neutron-rich environment and can occur rapidly during supernova explosions (or perhaps some other violent event) or more slowly, for example, during a certain phase of the evolution of red giant stars. Since different relative abundances of heavy elements characterize the two processes, precise measurements of the rare ultraheavy nuclei could determine what fraction of the cosmic-ray source material was synthesized in supernova explosions. For example, platinum and the actinides are characteristic of the explosive process, whereas lead and bismuth characterize the slow process. In cosmic rays with $Z \geq 60$, there appears to be an overabundance of elements characteristic of rapid synthesis relative to the mix of elements in the solar system. New techniques exist that will offer improved charge and mass resolution as well as better collecting power in the study of ultra-heavy nuclei. More precise measurements of individual heavy elements and isotopes would reveal the contributions of several different processes of nucleosynthesis that are expected to produce ultraheavy nuclei.

A large fraction of the explosively produced nuclei in cosmic rays would not necessarily imply that the material is accelerated immediately by the supernova that produced it. A possible scenario is that the supernova blast wave accelerates material in the surrounding medium. Thus observation of a large fraction of cosmic rays characteristic of rapid nucleosynthesis might, instead, indicate cosmic-ray acceleration in an active star-forming region with a high local supernova rate. Several unstable isotopes of nickel and cobalt are created during supernova explosions that decay by electron capture, with lifetimes ranging from a few days to 10^5 years. They can be used to give information about the delay between synthesis in a supernova explosion and acceleration of the nuclei. If these isotopes were stripped and accelerated before they decay, they would survive indefinitely in the cosmic radiation. Current evidence suggests that the delay between synthesis and acceleration of these nuclei is greater than 3 years. In the thorium-uranium region and just beyond, there are also several radioactive elements whose abundances can be used to measure the age of cosmic rays since nucleosynthesis.

- *Composition studies of elements and isotopes beyond the iron peak can identify the signatures of nucleosynthesis processes in the sample of galactic matter represented by cosmic rays.*

2.4 Electrons, positrons, and antiprotons

High-energy cosmic-ray electrons and positrons are of particular interest because their transport and lifetime in interstellar space are affected by several radiative energy-loss mechanisms that do not affect cosmic-ray nuclei of similar energies—synchrotron losses in the galactic magnetic field, bremsstrahlung losses on interstellar matter, and inverse Compton scattering on visible and 2.73 K blackbody photons. Consequently, they can reveal aspects of the cosmic-ray source distribution and of cosmic-ray transport in the Galaxy that are not evident from studies of nuclei alone.

In the energy range between 10 and 100 GeV the electron spectrum is observed to steepen, a phenomenon that is generally attributed to radiative energy losses. For energies > 10 GeV these losses are faster than leakage from the Galaxy. At energies > 1 TeV the electron "lifetime" against energy loss is so short that such electrons can only have come from sources at distances less than 100 parsecs. Since this distance is less than the thickness of the disk of the Galaxy, it would be particularly interesting to measure both the spectrum and the arrival directions of such energetic electrons. At present, however, measurements of electrons do not extend beyond 1 TeV.

The fraction of positrons is an important diagnostic for the origin of the electron component. For example, if all electrons and positrons were of secondary origin, produced along with the diffuse γ radiation from pion decay ($\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$), then the positron fraction would be 1/2.

Current positron data come from balloon-borne experiments, which are complicated by the background from the residual atmosphere. The measured positron fraction apparently varies from ~ 5 percent around 1 GeV to ~ 20 percent around 30 GeV. A naive interpretation would be that most electrons with energy of several GeV are primary, but that secondaries become more important at high energy. It has also been suggested that there are primary positrons accelerated in some cosmic-ray sources. For example, it is known from observations of 0.511-MeV annihilation radiation that positrons are abundant near the galactic center. Such positrons are expected from the beta decay of radioactive nuclei such as ^{26}Al. More exotic sources of positrons have also been suggested, including electron-positron pair production near black holes (Hawking radiation) and the annihilation of primordial particles that might constitute the dark matter of the halo of the Galaxy.

Clearly, cosmic-ray electrons and positrons have enormous potential for revealing new information about cosmic rays in the Galaxy, but this potential has often been frustrated by a combination of factors, including uncertainties in atmospheric background and in solar modulation as well as the inherent difficulty of the measurements. Most of these difficulties could be overcome by a magnetic spectrometer in space that could separate electrons and protons over a broad energy interval with good statistical accuracy.

Antiprotons are a unique tracer of cosmic-ray origin. Like other secondary species, they are produced by interactions of cosmic rays, either during propagation or in material near their sources. They differ from secondary nuclei in important ways, however: the parent particles are mostly protons rather than nuclei; the energy of the parent particle is much higher than that of the secondary antiproton; and the production cross section for antiprotons is strongly energy dependent because of the large mass that must be produced. Unlike positrons, antiprotons do not suffer significant radiative losses.

One example will suffice to illustrate the use of antiprotons as a probe of cosmic-ray origin. If they were produced in gas at the acceleration site, then one would expect a high flux and a flat spectrum at high energy for two reasons: (1) the primary spectrum at the site of acceleration is flatter than that in the interstellar medium and (2) the production cross section increases with energy. On the other hand, if all production is in the interstellar medium, then the antiproton spectrum will be steeper at high energy than the parent proton spectrum because of energy-dependent loss from the Galaxy. There is some indication of an excess of antiprotons in the energy region around 10 GeV. Measurements at lower energy do not indicate any large excess (as, for example, would be produced if large numbers of antiprotons were being generated by dark-matter annihilation in the galactic halo). Precise measurements of antiprotons over the widest possible energy range are needed to answer these kinds of questions.

- *Electrons, positrons, and antiprotons are important tracers of the source regions, the acceleration mechanisms, and the interactions of cosmic rays with interstellar material and magnetic fields.*

2.5 Advances in experimental technique

During the past decade there have been important advances in the capability to measure the charge, mass, and energy of the various cosmic-ray components, often as a result of the application of detector technologies originally developed for accelerator experiments. Elemental and isotopic composition can now be measured with high precision over a much broader range of energies and masses than was possible previously. Electrons, protons, and their much rarer antiparticles can be resolved up to much higher energies.

The development of long-duration balloon flights of ~ 10 days provides the opportunity to expose new detectors above most of the atmosphere and make important advances in studies of the individual components of cosmic rays. In many cases, however, the lower background levels and factor-of-10-to-100 increase in exposure provided by spaceflight will ultimately be required to make definitive measurements over a sufficiently broad energy range to resolve outstanding questions. Small, low-cost missions such as those envisioned in NASA's Explorer program could address many of these questions.

3. Exploring the Supernova Scale

3.1 The supernova theory of cosmic rays

The kinetic energy of material released in a typical supernova explosion is about 10^{51} ergs. Such explosions occur every few decades somewhere in the disk of the Galaxy. Because the interval between supernovas is short compared to the characteristic time for cosmic-ray diffusion out of the Galaxy, these explosions effectively provide a steady source of power in the galactic disk of approximately 10^{42} ergs/s. This is to be compared with the power required to maintain the observed cosmic rays of approximately 3×10^{40} ergs/s.

The ejecta from collapse of a massive star expand at supersonic velocity and so drive a strong shock into the surrounding medium. The most commonly accepted model for the origin of galactic cosmic rays is diffusive shock acceleration at supernova blast waves. It is a characteristic of diffusive shock acceleration that the resulting energy spectrum of accelerated particles is very much the same for a wide range of parameters or shock properties. This energy spectrum, when corrected for leakage from the Galaxy, yields the observed spectrum of galactic cosmic rays. There is also evidence for similar spectra of accelerated particles elsewhere in the universe where the shocks may be powered by other sources of energy. The combination of an acceleration mechanism that is essentially universal with supernova explosions to drive it is therefore a compelling picture of cosmic-ray origin.

In the diffusive shock acceleration mechanism the random-walking (diffusing) particles pick up a small increment in energy each time they cross the shock. Thus the maximum energy accessible in a given situation depends on the rate at which particles diffuse back and forth across the shock (which depends on the magnetic field) and on how long the acceleration mechanism acts. Shock acceleration is observed to operate at various kinds of shocks inside the heliosphere. In these cases, some of which have been studied from *in situ* measurements from spacecraft, the time and distance scales are relatively small, and so the upper limits on energy that can be reached range from tens or hundreds of keV at planetary bow shocks, to tens of MeV at interplanetary shocks in the solar wind, to hundreds of MeV at the solar termination shock, to several GeV in solar energetic-particle events.

For a supernova blast shock the time and distance scales are much longer, and the corresponding characteristic energy is much larger. The available time is determined by the time taken by the supernova blast wave to propagate outward and weaken to the point that it is no longer an efficient accelerator. The most commonly used version of the theory assumes that the magnetic field near the shock is so turbulent that the particles do not see the average preexisting magnetic field. In this case the characteristic energy is about 10^{14} Z eV, where Z is the particle charge. If this were the case, one would expect that the composition above about 10^{14} eV would begin to change to contain more particles with higher values of Z. Other models basically make other assumptions regarding the magnetic field and suggest that the characteristic energy may be as high as 10^{16} eV even for singly charged particles. The fact that the observed cosmic-ray spectrum extends several orders of magnitude beyond this energy calls attention to the need for a better understanding of this energy region.

It has long been known that the cosmic-ray energy spectrum is somewhat steeper above 10^{16} eV than it is below 10^{14} eV. Whether and how this structure, "the knee of the spectrum," is related to the mechanisms for acceleration, propagation, and confinement is one of the major current questions in cosmic-ray physics. In the examples of acceleration inside the heliosphere, the energy spectra have been observed over the entire range up to the maximum energy. To achieve the same level of understanding on galactic scales, it is essential to measure the spectrum and composition over a much larger range of energies because of the much larger time and distance scales involved. In particular, we need to explore major groups of nuclei such as hydrogen, helium, and carbon, plus oxygen and iron through the region of the knee of the spectrum up to 10^{17} eV in order to determine whether this feature reflects the endpoint of supernova acceleration, a transition to a new mechanism, and/or an effect of transport in the Galaxy. This is an extremely challenging demand because the cosmic-ray intensity decreases by a factor of 50 for every factor-of-10 increase in energy. In the past, the only way to explore the energy region above 10^{14} eV was with ground-based air-shower arrays, which easily satisfied the exposure requirement, but at the expense of sampling only the secondary showers without directly observing the primary particles. The technical ability to achieve direct measurement of the primary composition and spectrum up to 10^{15} eV now exists. The needed exposure can be achieved by several launches of large detectors on long-duration balloon flights.

Such a measurement will do two things: First, it will clarify a hint present in existing data that seems to show the proton spectrum becoming steeper while the spectra of helium and heavier nuclei maintain the same slope. Second, it will provide a significant overlap in energy with air-shower experiments, which have much greater reach in energy. Direct measurements of the primary cosmic rays in the same energy band as air-shower experiments will enable calibration of the results of indirect experiments.

3.2 What will we learn?

Suggested explanations for the origin of cosmic radiation in the knee region fall into two classes: (1) those in which the supernova blast mechanism is somehow extended to higher energy and (2) those in which a new class of sources becomes important at higher energy.

An example of the first category depends on relaxing the assumption that the magnetic field is very turbulent and instead assuming that the shock propagates perpendicular to an organized magnetic field, thus accelerating particles more rapidly. Another idea that has been mentioned is that the higher-energy particles could be accelerated by the collective action of several supernova blast waves in an environment with a group of supernova remnants. In both cases, if all components come from the same class of sources both below and through the knee region, then the relative composition depends on energy in a prescribed way: since the acceleration works through the intermediation of the magnetic field, the spectra of all species should be the same when compared as a function of magnetic rigidity (*i.e.*, gyroradius).

A different view holds that the supernova blast mechanism produces most cosmic rays with energies up to perhaps 10^{18} eV or somewhat higher but postulates two different classes of supernovas. This idea was motivated by observations of the evolution of Supernova 1987A, which showed that its progenitor was a massive star with a strong wind. Thus the environment into which SN1987A exploded was not the general interstellar medium, but rather the astrosphere swept out by the wind of its progenitor. In this situation one would expect the acceleration rate to be determined at first by the magnetic field of the progenitor star's wind. If the magnetic field were significantly higher than that in the interstellar medium, then the acceleration rate would be higher and the accelerator could achieve higher energy than can be achieved when a supernova explodes into the interstellar medium.

The more massive stars, such as Wolf-Rayet stars, indeed have strong winds. In addition they have a characteristic composition, different from that of some of the less massive progenitors of type-II supernovas. One characteristic is a relative excess of helium near the surface that would be accelerated. As noted in Section 2.2, it is also possible that the Wolf-Rayet and related stars contribute to the cosmic radiation at much lower energy.

Compact objects, especially neutron stars in various environments, have been suggested as a possible new class of accelerators to supply particles in the knee region. One possible mechanism invokes the spin-down power of rapidly rotating neutron stars to accelerate particles in pulsar magnetospheres. Another possible mechanism involves the accretion power in contact binary stars in which matter from a companion star is falling onto the surface of its compact partner.

Two of the three well-established galactic sources of TeV γ rays, SN1054 (the Crab Nebula) and PSR1706-44, are pulsar-driven supernova remnants. Since photons of TeV energy are almost inevitably the product of the interaction of a progenitor particle of even greater energy, these observations constitute direct evidence of particle acceleration to energies beyond the TeV region. Favored theoretical explanations of γ

radiation from the Crab Nebula imply the acceleration of electrons to energies of the order of 10^{15} eV or possibly even higher.

But what about still higher energies? Several acceleration mechanisms have been suggested that might operate in the vicinity of compact objects to produce cosmic rays with energies up to 10^{17} eV or even higher. These include the unipolar inductor mechanism in a rotating, magnetized neutron star, shock acceleration in an accretion flow, magnetic reconnection, and plasma turbulence. Establishing any of these would require a combination of γ-ray astronomy and demonstration that the composition in the knee region changes in a way that corresponds to what is expected for a particular type of point source. Current results of searches for ultrahigh-energy γ rays from candidate objects do not favor these models, although they are still a possibility.

A summary of current data suggests that the energy spectrum of protons differs from that of heavier nuclei, becoming steeper around 4×10^{13} eV while the heavier nuclei remain relatively flat. It is impossible to be certain of this behavior with present limited data. If such behavior is confirmed by experiments with greater collecting power, it would be a clear sign that at least two classes of cosmic accelerator are at work.

- *Direct measurements of the major components of the cosmic radiation up to 10^{15} eV would present a real opportunity for a qualitative advance of the field by providing the collecting power needed to establish whether the major components indeed have different spectra.*

3.3 An experimental program

From the preceding discussion it is clear that detailed data on composition are crucial for a better understanding of cosmic rays in the range of the knee and above. Some methods have evolved recently that make collection of these data possible with relatively modest resources. The capability to fly large, high-altitude balloons for 10 days or more around the South Pole has provided a new observational opportunity. Payloads of many square meters weighing about 4,000 pounds can be carried to altitudes above most of the atmosphere. These flights provide an ideal platform for direct measurements of composition, giving the possibility of reaching energies of ~10^{15} eV, an order of magnitude beyond the existing data.

To extend the measurements beyond the knee requires the use of ground-based air-shower arrays. There are several new, large air-shower arrays in the world that have the capability of measuring separately the muonic and electromagnetic part of the shower. In the range from 10^{14} to 10^{16} eV, the ratio of muon number to electron number at fixed energy varies as $A^{\sim 0.4}$, where A is the atomic weight of the cosmic ray particle. Fluctuations as well as systematic errors in determination of the ratio add uncertainties. Detectors that provide an image of the Cherenkov light emitted by showers can provide an additional constraint by making possible a measurement of the shower maximum. From the combined measurements of these three components (electrons, muons, and Cherenkov light), it will be possible to determine at least the variation of the average value of A with energy, if not its absolute value. Extending the direct measurements of the composition to 10^{15} eV will allow a calibration of the air-shower measurement because it will provide a factor-of-10 increase in energy for which overlapping measurements can be made.

Other types of hybrid arrays follow a similar strategy and will be normalized by the direct measurements. These include several detectors located deep below the Earth's surface that can detect high-energy muons in coincidence with shower detectors at the surface. Another approach is to measure the energy of the air-shower core with a calorimeter in coincidence with measurements of electrons and muons in the shower front.

Simulation techniques are also improving as a consequence of the possibility of running shower simulations without approximations or shortcuts on inexpensive, powerful computers that have recently become available. By direct comparison of air-shower data to simulations, the spectrum can be determined up to uncertainties due to composition. This aspect of the interpretation will also be calibrated by overlapping direct measurements.

4. The Highest Energies

The Fly's Eye detector opened a new era in cosmic-ray physics above 10^{17} eV by realizing a technique by which individual showers can be followed as they pass through the atmosphere. The detector works by observing air showers at distances of several kilometers. It consists of a mosaic (somewhat like the eye of an insect) of mirrors and photodetectors that segment the sky into small regions for observation. Rather than sampling the shower at one depth only, this technique follows the shower development through the atmosphere. It does so by tracking the atmospheric fluorescence light generated by a shower as it crosses over the detector, allowing practically the whole shower profile to be reconstructed. In this way, the atmosphere is being used as a calorimeter. A high-energy nucleus enters the atmosphere and initiates a shower that multiplies, reaches maximum size, and dies away. The amount of nitrogen fluorescence generated is proportional to the energy deposited by the ionizing particles (mostly electrons and positrons) along the shower trajectory. The energy of each shower is inferred by integrating the energy deposition. Depth of maximum (X_{max}) depends both on energy and on primary mass—for a given mass the average value of X_{max} is proportional to the logarithm of the primary energy, and for a given energy it is proportional to the logarithm of $1/A$.

4.1 Composition

The Fly's Eye has been operating for about a decade, but recently the first statistically significant results obtained with the stereo version (*i.e.*, two Fly's Eye detectors viewing the same event) have been presented. Events seen in stereo are more precisely defined. Comparison of the measured distributions of X_{max} with simulations leads to the conclusion that cosmic rays with energies between 10^{17} and 10^{18} eV consist mostly of heavy nuclei. At 10^{19} eV most of the primary cosmic rays appear to be protons. It is noted that the gyroradius of a 10^{19}-eV proton in the 3×10^{-6} gauss interstellar magnetic field is some 10,000 light-years, comparable to the size of the galactic disk. Confinement and acceleration of such particles in the Galaxy are therefore very difficult.

The conclusions about composition depend on simulations, which involve extrapolation of models of particle interactions several orders of magnitude beyond the reach of accelerator experiments. It is particularly noteworthy, therefore, that the stereo measurements show a steepening followed by a flattening of the energy spectrum around 3×10^{18} eV, just in the region where the apparent transition from heavy to light composition occurs. The correlation of these two effects is circumstantial evidence for a transition from one population to another. A natural conjecture is that up to this transition energy, most particles are accelerated within the Galaxy, and that the higher-energy particles ($E > 3 \times 10^{18}$ eV) are extragalactic. Whether the source of the extragalactic particles is nearby (*e.g.*, from acceleration at a shock in the galactic wind) or from more distant objects (such as active galactic nuclei) is an important question that is ripe for exploration.

4.2 Spectrum

Four giant air-shower experiments have measured the spectrum above 10^{17} eV: the Haverah Park detector in the United Kingdom, the Yakutsk array in the former Soviet Union, the Akeno array in Japan, and the Fly's Eye array in Utah. All are consistent with the shape described above. Because of its superior spatial resolution, the stereo Fly's Eye yields data that give a clear picture of the shape of the high-energy spectrum. But, within a reasonable observing time, there is not sufficient sensitivity to gather enough of the rare events that occur beyond 3×10^{19} eV to make meaningful measurements, since in this energy region, cosmic-ray intensity is only ~ 0.1 $(km^2 sr\ yr)^{-1}$. The data obtained with a single Eye are used to extend the spectrum to somewhat higher energy. Even so, the Fly's Eye, as well as other arrays up to now, are not able to collect data above 3×10^{19} eV with significant statistics.

Cosmic rays with energies > 10^{20} eV interact strongly with the 2.73 K microwave background through the processes of photoproduction and pair production. A cosmic ray proton cannot have an energy that exceeds 10^{20} eV after it has traveled for more than 10^8 years, no matter how high its initial energy. A measurement of the shape of the spectrum in this energy region therefore reflects the distances to the sources. Extrapolating current data to higher energy, one would expect to have seen six monocular events at Fly's Eye and six events at Akeno above 10^{20} eV, whereas only one event above this energy has been seen with both detectors. This result may be due to energy losses resulting from propagation over cosmological distances through the microwave background radiation. Such a cutoff would be expected, for example, if the component of the cosmic radiation above 3×10^{18} eV were accelerated in distant, powerful radio galaxies, quasars, or active galactic nuclei. A measurement of the shape of the spectrum in this energy region would give information about the spectrum of particles accelerated at such sources (*e.g.*, spectral shape and maximum energy, E_{max}) and the distribution of source distances.

On the other hand, a single event has been observed with an energy of approximately 3×10^{20} eV. Such an event must have had a path length of less than about 10^8 light-years, which corresponds to a cosmological redshift of $z < 0.01$, much closer than typical quasars and active galaxies.

For a cosmic-ray nucleus in a magnetic field B (μgauss), the Larmor radius in kiloparsecs (kpc) is $R = E_{18}/(Z\ B)$, where E_{18} is total energy of the nucleus in units of 10^{18} eV and Z its charge. Since the disk of the Galaxy is significantly thinner than 1 kpc, if all cosmic rays are from sources in the disk they must begin to show a tendency to come from the galactic plane as the energy increases. At present there is no statistically significant evidence of large-scale anisotropy at all.

- *The origin of the highest-energy cosmic radiation is a question of great scientific interest. Major advances in understanding can be made if the spectrum above 10^{19} eV can be measured with much better statistical accuracy to determine the origin of these particles.*

The Akeno 100-km^2 array (AGASA) and the planned high-resolution Fly's Eye will collect about 300 events per year with energy above 10^{19} eV and a few events per year above 10^{20} eV if the spectrum continues. The idea of constructing two giant arrays with 5,000-km^2 area, one in the Northern Hemisphere and the other in the Southern Hemisphere, is being discussed. If it were realized, such a project would yield 5,000 events per year above 10^{19} eV and ~ 50 per year above 10^{20} eV, depending on the spectrum.

4.3 Gamma-ray and neutrino astronomy at very high energy

The discovery of high-energy γ rays from active galactic nuclei raises the prospect of a direct connection between the origin of the highest-energy cosmic rays and γ-ray and neutrino astronomy. One of the major successes of the Compton Gamma-Ray Observatory has been the detection of nearly 40 active galactic nuclei (AGNs). Many of them give off more energy in the γ-ray bands than at any other frequency, implying that particle acceleration must be accommodated in any source model. AGNs that are detected by EGRET up to energies of 10 GeV have several characteristics in common: they have flat spectra, are timevariable, and are of that AGN subclass known as blazars. Most AGNs are observed to emit jets of relativistic particles; in blazars it is believed that the jet happens to be pointed toward Earth.

The detection of TeV γ rays (up to energies of 4 TeV) by a ground-based telescope from one of these blazars, Markarian 421, is direct evidence of particle acceleration within these AGNs to energies of 10 TeV or greater. As yet TeV γ rays have not been detected from any other AGNs. Although Markarian 421 is the closest of these AGNs (at a distance of 400 million light-years), it is one of the weakest. The reason that it is detected—whereas the other, more distant, but more powerful, AGNs are not—must be that the TeV γ rays suffer absorption in intergalactic space through the interaction with background infrared photons. This implies that all of the AGNs may have significant very high energy components but that only Markarian 421 is close enough to be detectable in TeV γ radiation.

One class of theoretical ideas being used to account for these observations involves the acceleration of protons to ultrahigh energies in the jets as well as the cores of active galaxies. In these models high-energy neutrinos are also produced at levels sufficiently high that they may be detectable with planned neutrino detectors. In another class of models the photons are produced by accelerated electrons through inverse Compton scattering. Since production of neutrinos requires a hadronic origin, the observation of neutrinos would confirm the class of models in which the active galactic nuclei would also be potential sources of the most energetic cosmic rays.

5. *Interdisciplinary Aspects*

5.1 Cosmic rays in the heliosphere

The heliosphere is the region swept out by the magnetized plasma emitted by the sun, the so-called solar wind. The importance of particle acceleration at shocks inside the heliosphere as a laboratory for understanding the origin of galactic cosmic rays has already been mentioned in section 3.1. Indeed, the fundamental transport theory that governs propagation and acceleration of charged particles in cosmic plasmas was developed in response to detailed, *in situ* observations in the heliosphere. Conversely, galactic cosmic rays serve as a probe of the heliosphere as they come under the influence of the solar wind. For example, there are some indications that electrons and positrons are modulated differently. Proposed studies of charge-sign-dependent effects of modulation are expected to lead to a new understanding of the dynamical magnetic structure of the heliosphere as it evolves during the solar cycle.

The "anomalous" cosmic rays (a singly charged component with energies in the few-hundred-MeV range) represent the acceleration of newly ionized interstellar neutral atoms at the termination shock of the solar wind. This is by far the largest and strongest shock in the heliosphere, and its study will have a significant impact on our understanding of shock acceleration elsewhere in the universe. For example, accelerated particles may be sufficiently numerous near this shock that it is a "cosmic-ray" shock, that is, one in which cosmic rays influence the nature of the gas dynamics. Recent observations of radio waves from the heliopause, possibly related to the passage of a shock propagating out of the heliosphere, suggest the possibility of similar phenomena in other astrophysical shocks. It also may be, for example, that our galaxy has a wind flowing outward from its disk, driven by the accumulated effects of galactic cosmic-ray activity, which could be a site for acceleration of high-energy cosmic rays.

At present, major aspects of our understanding of cosmic rays, both in the heliosphere and outside, are being subjected to unique and essential observational tests by data obtained from spacecraft in the outer heliosphere. For this reason, continued progress depends crucially on operating the existing fleet of heliospheric exploration spacecraft – Pioneers, Voyagers, and Ulysses – until the ends of their useful lives. It is likely that one or more of these probes will pass through the termination shock. It is even possible that one will penetrate beyond the heliosphere altogether and be able to transmit data about unmodulated cosmic rays in the interstellar medium. For the same reason, the proposed Interstellar Probe, designed to optimize the return on scientific measurements in the region of the termination shock, the heliopause, and the interstellar medium beyond, represents an important opportunity for future progress.

5.2 Particle physics

The ability to observe particle interactions at the highest energies has always been one of the primary goals of high-energy physics. Several topics are suitable for exploration with a detector that can measure the development of large air showers with energies in the range of 10^{18} eV and above (center of mass energy $\sqrt{s} \sim 40$ TeV). This energy is beyond that of any accelerator planned for the next 20 or 30 years.

The distribution of the depth of shower penetration or attenuation in the atmosphere gives an indication of the inelastic cross section in air as well as the inelasticity of hadronic interactions at high energy. Because shower penetration also depends on primary composition, it is essential to be able to measure properties of individual showers with the highest possible resolution to disentangle the two effects. Careful simulations using models of hadronic interactions to extrapolate beyond accelerator energies are needed to extract the quantities of primary astrophysical interest (composition) and to assess the extent to which the results depend on uncertainties in the models of interactions.

Since the profiles of individual showers reflect how and where the energy of the shower is dissipated in the atmosphere, the observation of extreme shower profiles would signal the presence of new physics. For example, showers that reach maximum before penetrating through a column density of a few hundred gm/cm^2 of the atmosphere could indicate very large interaction cross sections or possible coherent nuclear effects such as a quark-gluon phase transition. Nearly horizontal showers with maxima at depths equivalent to more than twice the vertical thickness of the atmosphere could be evidence for neutrinos at unexpectedly high intensities or diffractive production of hadrons that contain more massive quarks than found in ordinary hadrons, such as the proton.

5.3 Antimatter and dark matter

If antinuclei with $\overline{Z} \leq -2$ were found in the cosmic radiation, the consequences both for cosmology and for particle physics would be profound. One naturally assumes that in a big-bang universe, equal amounts of matter and antimatter are produced. However, no mechanism for separating matter from antimatter has been found. The preferred solution now is Sakharov's suggestion of a combination of charge-parity (CP) violation and non-conservation of baryon number occurring during an epoch when particle interactions were out of thermal equilibrium. This solution allows the observable universe to be entirely matter or entirely antimatter.

If CP violation arises from spontaneous symmetry breaking (rather than being built into the Lagrangian function that describes the fundamental particle interactions), then it is possible (perhaps inevitable) to form domains of antimatter and domains of matter. If inflation (exponential expansion of the universe) occurred after the domains appeared, the entire observable universe would likely be a single domain of one sign, *i.e.*, completely made of matter or of antimatter. The discovery of large-scale domains of antimatter would show that somehow domains with both signs occur in our universe. There are strong limits on the separation of matter and antimatter domains to avoid production of an extragalactic background γ-ray flux greater than what is observed.

It is extremely unlikely that any antinucleus heavier than antideuterium could have been produced by collisions of cosmic rays in the interstellar medium. Detection of such antinuclei would imply the existence of antimatter domains within 100 Mpc from which antimatter cosmic rays are able to escape, as well as a sufficiently weak wind from our galaxy so that they can get in. Estimates suggest that a sensitivity of 1 part in 10^7 for $\bar{Z} / Z$ would open an interesting window on this question. Balloon-borne payloads on long-duration flights could reach this level of sensitivity.

Another cosmic-ray window on cosmology relates to dark matter. One form of cold dark matter that has been suggested is a new kind of elementary particle—massive, but weakly interacting, generically called a WIMP (weakly interacting massive particle). Annihilation of these exotic particles in the halo of the Galaxy could produce antiprotons, positrons, and photons. One signal of such a process could be an excess of antiprotons at low energy in the region where the background of secondary antiprotons from interactions of cosmic rays in the interstellar gas is suppressed by kinematics. Another could be the apparently large ratio of positrons to electrons above 10 GeV, if the line spectrum from annihilation into positrons and electrons were broadened by energy losses of the positrons during propagation in galactic magnetic fields. The signature of such an effect would be a sharp upper cutoff at the mass of the dark-matter particle. Planned measurements of electrons and positrons should clarify this possibility.

The difficulty with searches for products of dark-matter annihilation in the halo is that there are large uncertainties, particularly in the estimates of confinement of the WIMPs in the halo. The uncertainty makes it difficult to use the observations mentioned above to set limits if no signal is seen. Underground detectors that search for an excess of neutrino-induced muons from the direction of the sun or Earth's core are in a much better position in this respect because the event rates are much more predictable for capture and annihilation in the sun or at Earth. Thus underground detectors are now providing limits on these dark-matter candidates.

It is also possible that the cosmological dark matter is in the form of neutrinos with a mass of several electron volts. This is sometimes known as "hot dark matter." A possible probe of most models with hot (or mixed) dark matter is the redshift at which the initial large galaxies formed, which is contained in the spectrum of redshifted starlight. Gamma rays from AGNs can be used as a probe of the spectrum of starlight by measuring the energy above which the photons from the AGNs are absorbed by starlight to create electron-positron pairs, $\gamma + \gamma_{starlight} \rightarrow e^+ + e^-$, as a function of distance to the AGNs. To observe the dip in energy due to absorption by starlight requires the ability to measure photons over a range of energies from 10 to 1,000 GeV.

There are already possible hints of neutrino masses and mixings from astrophysical neutrinos. The most familiar is the potential of neutrino oscillations as an explanation of the solar neutrino problem. The favored scenario for explaining the deficit of ν_e from the sun in this way leads to the conjecture that the ν_τ has a mass in the range needed to provide some 30 percent of the closure mass as desired for the mixed-dark-matter scenario. This explanation ignores another cosmic-ray result, namely that several independent experiments find a ratio of ν_e/ν_μ significantly in excess of that produced by cosmic-ray interactions in the atmosphere. This would require a more complicated pattern of neutrino masses to provide also a solution to the solar neutrino and dark-matter problems. These problems are being studied intensively at present, and it is not clear what the outcome will be. The point is that the pattern of neutrino masses can provide crucial clues to the more general theory beyond the standard model and that precise measurements of astrophysical neutrinos can play an important part in understanding this pattern.

The possibility of topological defects left over from phase transitions in the early universe is also of great importance for cosmology and particle physics. Cosmic strings, for example, would possess remarkable amounts of energy, and it has been proposed that they might be the source of acceleration for the highest-energy cosmic rays. Of special interest in this regard is the highest-energy particle observed by Fly's Eye and discussed in Section 4.2. Since it had to come from relatively close by, it is difficult to imagine a suitable acceleration mechanism—cosmic strings could provide the explanation. This possibility is a further motivation to pursue the study of the highest-energy cosmic rays.

6. Summary and Conclusions

In summary, there are recent results in each of the three regions of the cosmic-ray energy spectrum shown in Figure 1 that suggest ways to make further progress in advancing our understanding of the origin of cosmic rays and the astrophysical processes that create and accelerate them.

Region I

The cosmic-ray particles in the lowest-energy region are the most abundant. Collectively, they carry most of the energy content of cosmic rays, even though the energy per particle is relatively low. Recent measurements in γ-ray astronomy confirm that most of these cosmic rays originate inside our own galaxy. Comparison of the isotopic and elemental composition of these cosmic rays with solar system material shows significant differences that reflect their sources. A clear understanding of the origin of the bulk of cosmic rays would require:

- *Sensitive measurements of elemental and isotopic composition at higher energy and including ultraheavy elements to identify the source of the material that gets accelerated;*
- *Measurements of cosmic-ray "clock" isotopes with lifetimes suitable to trace the time history of cosmic-ray synthesis, acceleration, and propagation; and*
- *Measurements of positrons and antiprotons to explore cosmic-ray transport in the Galaxy and to search for possible exotic sources of cosmic rays.*

Region II

The intermediate-energy region of the cosmic-ray spectrum is of particular interest because there appears to be some structure in the spectrum here ("the knee," as in Figure 1). Moreover, this is where the supernova-driven shock acceleration mechanism must begin to fail. Thus we can learn here about the characteristic maximum energies of cosmic accelerators in the Galaxy. The very low intensity of particles in this region has limited progress in the past, but there is now an opportunity to make great progress here. To do so would require:

- *Direct measurements of the primary composition and spectrum to significantly higher energy than that in existing measurements in order to explore and understand the knee region.*

Region III

The highest-energy cosmic rays may come from distant regions far outside our galaxy. To determine the origin of the highest-energy cosmic rays would require:

- *Measurements of the spectrum and composition to the highest possible energies to identify the sources, whether galactic or extragalactic, of the highest-energy particles; and*
- *A complementary program of measurements of high-energy γ rays and neutrinos.*

These highlights illustrate some of the principal opportunities in the field of cosmic-ray physics and their linkage to problems in other areas, including heliospheric physics, the interstellar medium, particle physics, astronomy, and cosmology.

Glossary

ν_e – The electron neutrino, which is associated with the electron and radioactive decay and interacts with matter through the weak force.
ν_μ – The muon neutrino, which is associated with the muon and interacts with matter through the weak force.
ν_τ – The tau neutrino, which is associated with the tau particle and interacts with matter through the weak force.
ACE – NASA's Advanced Composition Explorer mission, an advanced successor to SAMPEX, scheduled for launch in 1997 to perform a comprehensive analysis of isotopic composition of the solar wind and cosmic rays.
AGASA – A 100-km^2 air-shower detector array exploring energies above 10^{17} electron-volts, located in Japan.
AGN – Active galactic nuclei, a class of energetic centers of galaxies.
Akeno array – See AGASA.
EGRET – The Energetic Gamma-Ray Experiment Telescope, a gamma-ray detector on NASA's Compton Gamma-Ray Observatory.
Fly's Eye detector – A giant air-shower detector array that uses a unique optical technique to explore energies above 10^{17} electron-volts, located in Utah.
Geotail – An international mission to study the Earth's magnetotail--part of the International Solar-Terrestrial Program (ISTP).
Haverah Park array – A giant air-shower detector array that was used to explore energies above 10^{17} electron-volts, located in the United Kingdom.
SAMPEX – NASA's Solar, Anomalous, and Magnetospheric Particle Explorer, which was a successful small explorer-class mission to study solar flares, energetic solar-wind particles, anomalous cosmic rays, and magnetospheric electrons.
Ulysses – An international mission with a trajectory that takes the spacecraft out of the ecliptic plane over the sun's poles.
Wind – An international mission to study the solar wind (part of ISTP).
WR – Wolf-Rayet stars: very luminous, very hot, massive stars, which undergo significant mass loss.
Yakutsk array – A giant air-shower detector array exploring energies above 10^{17} electron-volts, located in the former Soviet Union.