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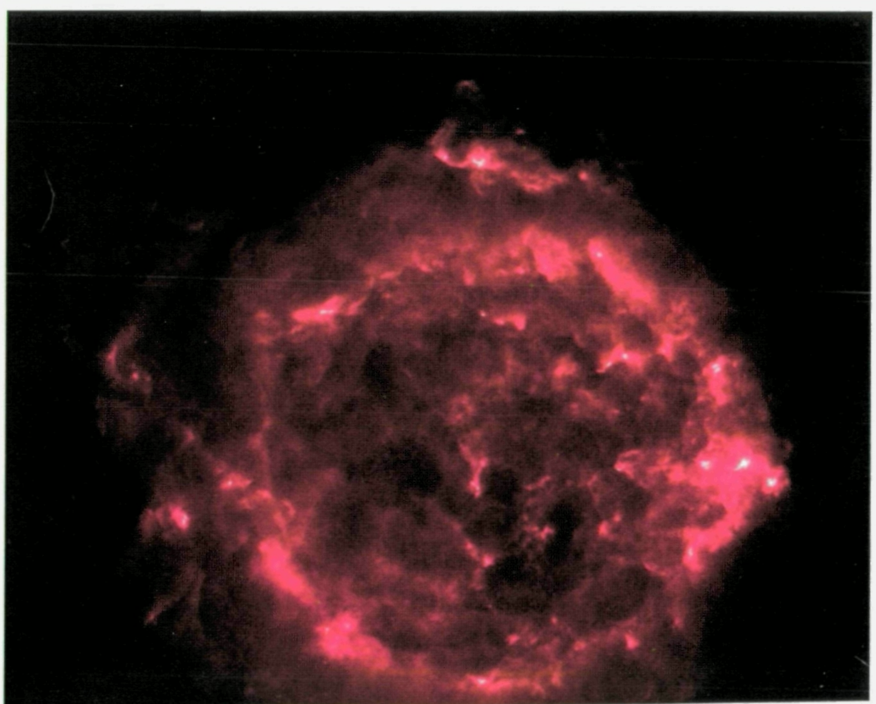
Opportunities in Cosmic-Ray Physics and Astrophysics



Opportunities in Cosmic-Ray Physics and Astrophysics

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. 1995

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

Front Cover: Radio map of the supernova remnant Cassiopeia A made with the National Radio Astronomy Observatory's (NRAO) Very Large Array. The bright ring of radio emission marks the interface between the rapidly expanding sphere of ejecta from the supernova and the shock-heated interstellar medium outside. This supernova occurred about 300 years ago, and the sphere is now about 10 light-years across. Acceleration of cosmic rays is thought to occur at shocks driven by expanding supernova remnants. (Courtesy of NRAO.)

Back Cover: Interactions of cosmic-ray protons and nuclei with the gas in the interstellar medium create all kinds of secondary particles. Among these are neutral π-mesons, which in turn produce high-energy γ rays from the decay $\pi^0 \rightarrow \gamma\gamma$. The back cover shows a map in galactic coordinates of the diffuse γ-ray flux seen by the EGRET instrument on the Compton Gamma-Ray Observatory. Interpretation of these observations confirms that the cosmic-ray sources must supply about 3×10^{40} ergs/s. (Courtesy of NASA.)

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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 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 the National Aeronautics and Space Administration (NASA) to consider the program of research in this discipline in light of new constraints on the scope of missions at NASA, which made previously planned cosmic-ray missions on a large space station and on the Space Shuttle seem difficult to realize at that time. In the meantime, it has become apparent that exciting new opportunities in cosmic-ray physics are ripe for significant progress with ground-based detectors as well as with observations from spacecraft or balloons. Accordingly, the committee was 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 NASA, the National Science Foundation (NSF), and the Department of Energy (DOE). 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 work of the committee began in late 1993, at which time there was a call for comments from the community by electronic mail and through the Division of Astrophysics of the American Physical Society. An interim report entitled *Cosmic Rays: Physics and Astrophysics, A Research Briefing* (National Academy Press, Washington, D.C.) was issued in mid-1994. The committee met again during the Snowmass Summer Study, "Particle and Nuclear Astrophysics and Cosmology in the Next Millennium." The present report reflects interactions of the individual committee members with many working groups and individual scientists during the summer study and afterward, as well as earlier discussions.

Thomas K. Gaisser, *Chair*
Committee on Cosmic-Ray Physics

Contents

Executive Summary

Studies of energetic particles from distant regions of the galaxy and the universe bring us information about the processes in which the particles are accelerated to relativistic energies, about the role of the particles and their accelerators in driving dynamical processes in our galaxy and beyond, and about the distribution of matter and fields in interstellar space. This information is complementary to astronomy with photons in various wavelength bands.

The field of cosmic-ray physics has evolved sufficiently so that the general outlines of a theory of the origin of cosmic rays are visible, but as the field has evolved, important questions have been raised. What is the physical origin of the similarities between galactic cosmic rays and solar flare particles? What is the maximum energy to which supernova blast waves can accelerate particles? Can we find specific point sources of high-energy cosmic rays? Is there a high-energy component of protons or nuclei from distant, extragalactic sources, and how does it interact with microwave background radiation on cosmological time scales? What new sources may be responsible for the few highest-energy particles observed recently with the largest ground-based detectors? Are there signals among cosmic-ray positrons or antiprotons of the existence of dark matter? Are there cosmic-ray antinuclei?

There is much new activity aimed at answering these questions, including efforts by scientists previously working in other fields who have been attracted by the scientific interest of some of the problems. The committee's recommendations reflect this new activity and interest. Cosmic-ray physics is an interdisciplinary field, both in the nature of the scientific problems it addresses and in the techniques it uses. Thus, this report emphasizes the need for the granting agencies to be aware of and responsive to initiatives that sometimes cross the boundaries of traditional scientific disciplines.

Summary Recommendations

- *NASA should provide the opportunity to measure cosmic-ray electrons, positrons, ultraheavy nuclei, isotopes, and antiparticles in space.*

These measurements are needed to identify the sources of the material that gets accelerated; to understand the time scales for injection, acceleration, and propagation; and to search for possible exotic sources of cosmic rays. They will also lead to greater understanding of the structure and dynamics of the plasma surrounding the Sun. Small, low-cost missions, such as those carried out in NASA's Explorer program, can address each of these issues. Because of the long lead time needed for space experiments, it is essential that there be strong support for balloon payloads. In some cases, significant scientific results can be achieved with such suborbital exposures; in addition, this activity is of great benefit in the development of future payloads for space and in training students to work in a variety of fields that require advanced technical skills.

- *NASA, NSF, and DOE should facilitate direct and indirect measurement of the* *elemental composition to as high an energy as possible. Support of long-duration ballooning and support of hybrid ground arrays will be needed to accomplish this end.*

The goal here is to look for a maximum energy associated with acceleration by supernova-driven shocks, which is expected to occur around 10^{14} eV. Since the cosmic-ray spectrum continues to higher energy, a cutoff in one type of source would imply a transition to a new source capable of accelerating particles to higher energy. Understanding whether and how such a transition occurs is an important objective. There is already an indication for some structure in the energy spectrum near 10^{14} eV. Because of the low intensity of cosmic rays at such high energy, however, present direct measurements with detectors flown above the atmosphere have not accumulated enough data to clarify its significance. Long-duration balloon flights of detectors will extend direct measurements by an order of magnitude in energy. Hybrid ground arrays, overlapping with direct measurements at the low-energy end of their range, will extend the study of composition beyond the "knee" of the spectrum to much higher energy.

- *NSF and DOE should support the new Fly's Eye and provide for U.S. participation in the big projects on the horizon, which include giant arrays, ground-based γ-ray astronomy, and neutrino telescopes.*

In the energy range above 10^{18} eV there is possible evidence from large air-shower experiments for a transition to a different, high-energy component of the cosmic radiation. This component may originate far outside our galaxy, or at least from its outermost reaches. The High-Resolution Fly's Eye will be able to explore this region with unprecedented energy resolution. Giant arrays spread over thousands of square kilometers are needed to accumulate sufficient statistics to study the very highest-energy particles, which probe cosmological distances and may lead to the discovery of new, energetic astrophysical sources.

The main thrust of ground-based γ-ray astronomy is to extend present measurements to lower energy and to greater levels of sensitivity in order to study the variety of galactic and extragalactic sources that are being discovered at lower energy with detectors on the Compton Gamma-Ray Observatory. Objects such as active galactic nuclei may be high-energy particle accelerators producing secondary photons and neutrinos at the source. It is desirable to extend measurements of spectra of γ rays from these and other point sources beyond the energies of present space experiments to understand these sources better. If sufficiently large neutrino telescopes can be built, a comparison between neutrino and photon fluxes from the same objects or classes of objects could be made that will be very helpful in understanding physical processes within the source. Because of their great penetrating power, neutrinos probe activity deep within sources where the corresponding photons would be reabsorbed.

- *NASA, NSF, and DOE should support a strong program of relevant theoretical investigations.*

Examples of key problems are sources and propagation of the highest-energy particles; how the details of the source and the magnetic field geometry determine the maximum energy of a particular accelerator; and the relation between acceleration of electrons and acceleration of ions.

These recommendations cover a broad range of topics and techniques, yet the underlying astrophysical processes that we seek to understand, taken together, form a coherent whole. One unifying theme is particle acceleration on a variety of scales; another is the role of energetic particles in the dynamics of the universe, again on many scales, from the heliosphere to supernova remnants, to the galactic disk and halo, and beyond to clusters of galaxies and distant active galaxies. Ultimately, cosmic rays are tracers of the processes by which the elements, synthesized in stars, are dispersed and reprocessed by energetic processes such as stellar winds, supernova explosions, and jets driven by accretion onto compact objects. The committee concludes that carrying out the recommendations of this report will lead to significant advances in our understanding of these processes from which important new insights and discoveries are likely.

1

Overview—The Energetic Universe

> Some Fundamental Questions of Cosmic-Ray Physics
>
> - How do cosmic accelerators work?
> - Where does the power to drive them come from?
> - What is the distribution of cosmic accelerators in space?
> - What energetic astrophysical processes are they associated with?
> - What are is the origin and the history of the matter that is accelerated to become cosmic rays?
> - Why do a few particles achieve high energies, rather than all of the particles in a given region becoming slightly heated?
> - How do cosmic- ray particles propagate through space and how do they reach us?

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^{2+}, electrons, positrons, 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 referred to as cosmic rays. Cosmic rays hit the top of the Earth's atmosphere at a rate of roughly 1,000 particles per square meter per second, where they generate cascades of lower-energy particles in the atmosphere. The average person standing on the ground at sea level will be struck by about 20 cosmic-ray shower particles every second. Cosmic rays are important for astrophysics because they play an essential role in the energy budget of the diffuse regions of our Milky Way Galaxy and in distant galaxies throughout the universe.

Cosmic-ray particles appear over many decades in energy, unlike a thermal spectrum in which most particles have energies concentrated around a value characterized by a temperature. In contrast, the cosmic-ray energy spectrum is approximately an inverse power characterized by a spectral index instead of a temperature. The number density of relativistic cosmic-ray particles is much lower than that of the thermal plasma, but the total energy content of the two groups is comparable. This means that individual cosmic rays have much higher energies than those of the plasma. The most energetic cosmic rays have energies billions of times higher than would be released by converting a particle's entire rest mass into kinetic energy.

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. 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, which are explosions of massive stars at the end of the cycle of nuclear burning. For reasons explained in this report, it is likely that supernovas also power the acceleration of most cosmic rays, perhaps in association with a shock wave driven into space by debris from the supernova explosion. Exactly how and where this acceleration happens and what kinds of supernovas are involved, are questions of intense current interest.

The highest-energy cosmic rays, those from 10^{18} eV up to a few times 10^{20} eV, are particularly intriguing. The highest-energy particle that has been detected has the kinetic energy of a 1-kg object moving at a velocity of 10 m/s. It is very unlikely that they come from supernovas, and they may even originate in other galaxies, requiring the power generated by supermassive black holes to accelerate them.

The cosmic rays that we observe directly at Earth probe only a small fraction of the population of accelerated particles in the universe, since most do not survive the trip from their sources of acceleration without attenuation or energy losses. Measurements of other types of particles, such as high-energy γ rays and neutrinos, can provide valuable information about cosmic-ray particles at their sources by detecting their radiations. This report therefore also discusses high-energy (ground-based) γ-ray and neutrino observations and how they can be used in conjunction with direct detection of cosmic rays to tell us about particle acceleration at the cosmic-ray sources and the distribution of cosmic rays in our galaxy.

Cosmic-ray physics has many important connections to other fields of physics and astrophysics. Measurements of galactic cosmic rays address important questions in solar and heliospheric physics such as the structure of the magnetic field in the heliosphere, through which all Earth-bound cosmic rays must pass, and the nature of the solar wind termination shock, which may accelerate some of the lower-energy cosmic rays. Measurements of high-energy cosmic rays are of some interest also for particle physics because they can study particle interactions at higher center-of-mass energies than current Earth-bound accelerators, although with very limited statistics. Study of the propagation and distribution of cosmic rays in our galaxy addresses fundamental questions about the distribution of matter and magnetic fields, and about the birth and death of stars. Observations with radio telescopes map regions of electrons radiating in magnetic fields, and γ rays are produced when electrons and ions interact with interstellar gas. Study of the sources of the highest-energy cosmic rays, which may have their origin in active galaxies or quasars, will have strong ties to the study of galaxy formation and cosmology. Finally, cosmic-ray physics has the potential to answer some of the most fundamental questions of cosmology, for example, Does antimatter exist in the universe? What is the nature of the dark matter?

1.1 Scope of this report

This report summarizes some recent results in high-energy cosmic-ray physics, describes how they raise new questions of interest both for physics and for astrophysics, and gives recommendations for the future studies that may best be able to provide the answers to these questions. The committee is charged to report on cosmic rays from outside the solar system and the region of influence of the Sun. The heliosphere itself, cosmic rays of local origin, and the influence of the Sun on galactic cosmic rays are all considered in *A Science Strategy for Space Physics*, Committee on Solar and Space Physics/Committee on Solar-Terrestrial Physics (National Academy of Sciences, Washington, D.C., 1995, in press). However, some of the connections between these two closely related fields are mentioned in Section 8 of this report. This report also briefly addresses the topic of high-energy neutrino astrophysics because of its close relationship to high-energy cosmic rays. The topic is dealt with more fully in *Neutrino Astrophysics: A Research Briefing*, Panel on

Neutrino Astrophysics (National Academy Press, Washington, D.C., 1995).

1.2 Organization of this report

Figure 1.1 shows a schematic representation of the cosmic-ray energy spectrum. The figure shows the number of particles per factor of ten interval of energy. Section 2 reviews the low-energy region (Region I in the figure) where we have the most detailed information about the elemental and isotopic composition of the cosmic rays and the energy spectra of the various components. This is followed by a description of the current picture of the origin of cosmic rays that emerges from a study of these data and the questions that arise, in particular about the properties of cosmic radiation at higher energy.

Sections 4 and 5 are concerned with regions II and III, respectively. Although the dividing points between the regions in Figure 1.1 are somewhat arbitrary, they correspond approximately to regions in which different techniques are applicable and in which different acceleration mechanisms may dominate. The boundaries between the different regions are of particular interest.

To a large extent, the techniques needed to study each of these energy regions are

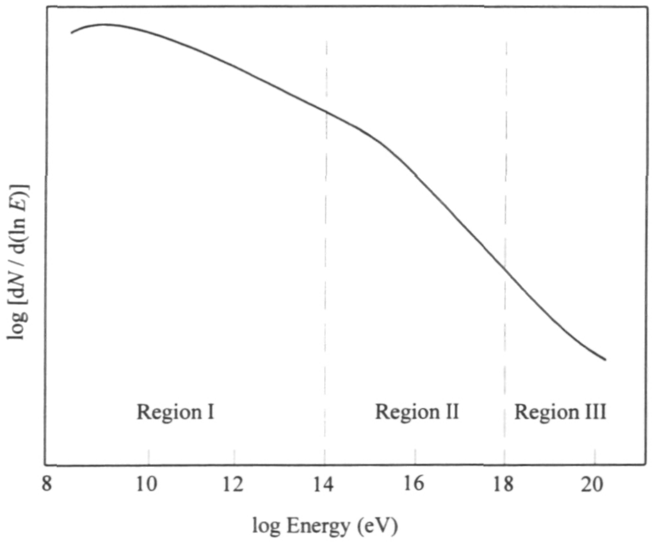


Figure 1.1 The cosmic-ray energy spectrum.

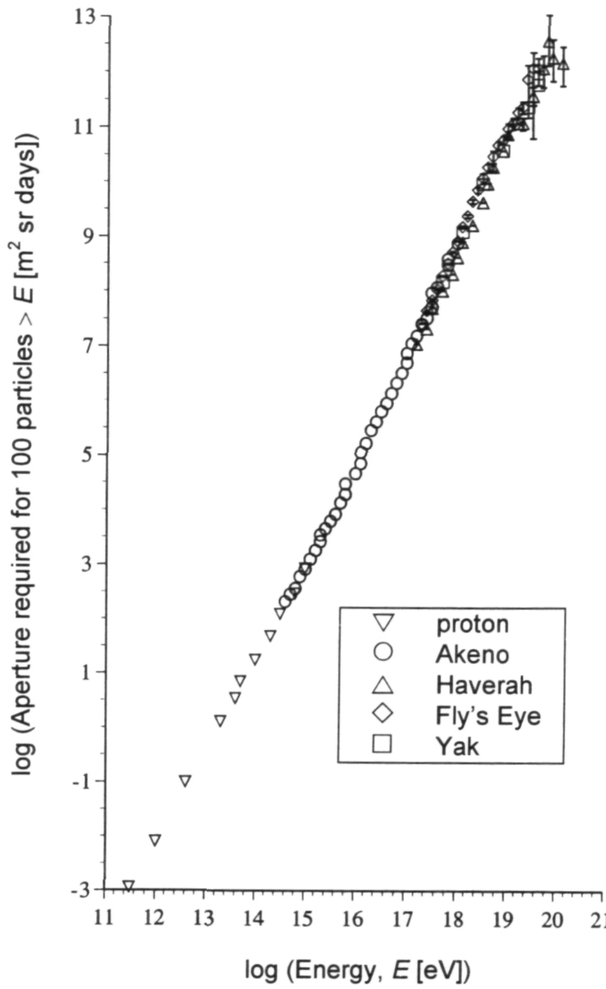


Figure 1.2 The aperture needed to obtain 100 particles above energy *E*. The plot is essentially the inverse of the measured cosmic-ray spectrum.

determined by the exposure required to obtain a sufficiently large sample of data in the face of the steep energy spectrum of cosmic rays. This is illustrated for high-energy particles in Figure 1.2, which shows the exposure needed to detect 100 particles above a given energy for $E > 10^{14}$ eV. This graph is essentially the inverse of the cosmic-ray spectrum, and it demonstrates the fact that large, ground-based detectors are needed to explore energies much beyond 10^{15} eV. In the lower-energy region (I in Figure 1.1), cosmic rays become increasingly abundant and the required exposure depends on the level of detail desired. For example, to study cosmic rays heavier than iron, which are extremely rare, requires exposures at the limit of what is possible with balloon-borne detectors, and for some purposes, long-term exposures in space are required.

Section 6 reviews the related subjects of very-high-energy γ-ray and neutrino astronomy. Because they are neutral, photons and neutrinos produced by cosmic-ray interactions with gas, either near the sources or in interstellar space, point directly back to their origin and so can be used to map regions of cosmic-ray activity. The charged cosmic rays themselves follow complicated paths through magnetic fields in the galaxy and are therefore nearly isotropic. Measurements of secondary γ rays and neutrinos are thus complementary to measurements of the charged particles.

Section 7 is a discussion of the present status and plans for long-duration ballooning at high altitude, a facility that is crucial for advancement of the subject of cosmic-ray physics. Section 8 describes several important interdisciplinary aspects of cosmic-ray physics. Finally, the report concludes with some projections and recommendations for the field.

2

Cosmic-Ray Composition from Direct Observations

> **Production of Galactic Cosmic Rays**
>
> It is generally thought that galactic cosmic rays are produced in sources distributed throughout the disk of our galaxy associated with supernova remnants or other energetic regions. After their initial injection and acceleration, they subsequently move in and out of the disk and the nearby more rarefied galactic halo, guided by the galactic magnetic field. During this time the cosmic rays are likely to undergo further acceleration as they move through the turbulent interstellar plasma, and they are likely to interact with the interstellar gas. Eventually, the cosmic rays diffuse into distant regions of the halo and are lost altogether from the galaxy.

Cosmic rays provide the only direct sample of matter from distant regions of space. To understand the origin of these particles it is necessary to relate the cosmic-ray energy spectrum and composition observed near Earth to those at the sources. The relative abundances of the elements in the cosmic radiation and their energy spectra contain a record of the nucleosynthetic processes that forged this material in stars, of the processes that accelerated some nuclei to cosmic-ray energies, and of their subsequent interactions with matter and fields in interstellar space.

The energy spectra of the major components of the cosmic radiation are similar to each other, as shown in Figure 2.1. At high energies the spectra approach a power law with a slope of about –2.7. Deviations from this slope at high energy are significant and are discussed in later sections of this report. In general, the shape of the spectra observed at Earth reflects the processes of acceleration as modified by cosmic-ray interactions with the interstellar medium and (at low energies) with the interplanetary magnetic field carried out by the expanding solar wind. Thus, below ~1 GeV/nucleon the spectra of all species flatten and then decrease. This is a consequence of the difficulty that cosmic rays have in diffusing through the interplanetary field to reach the inner solar system. These effects are greatest at low energies, and the intensity of cosmic rays below ~1 GeV/nucleon varies by a factor of as much as 5 to 10 over the course of the 11-year solar cycle, in anticorrelation with solar activity. Similar processes on larger scales in distant regions of space may be expected to affect cosmic-ray transport in the galaxy, as well as the entry and exit of cosmic rays from the galaxy.

In the energy region below ~1 TeV/nucleon, spectra and abundances of individual elements have been measured with enough accuracy to establish some general features of their history. As Figure 2.2 indicates, cosmic rays comprise essentially all of the stable elements of the solar system, from hydrogen ($Z = 1$) to uranium ($Z = 92$), with relative abundances that differ by more than 10 orders of magnitude. It is instructive to compare the relative abundances of elements in the cosmic radiation with the average abundance of elements in the solar system, as derived from meteorites and spectroscopic studies of the solar photosphere. This comparison is the subject of Figure 2.3.

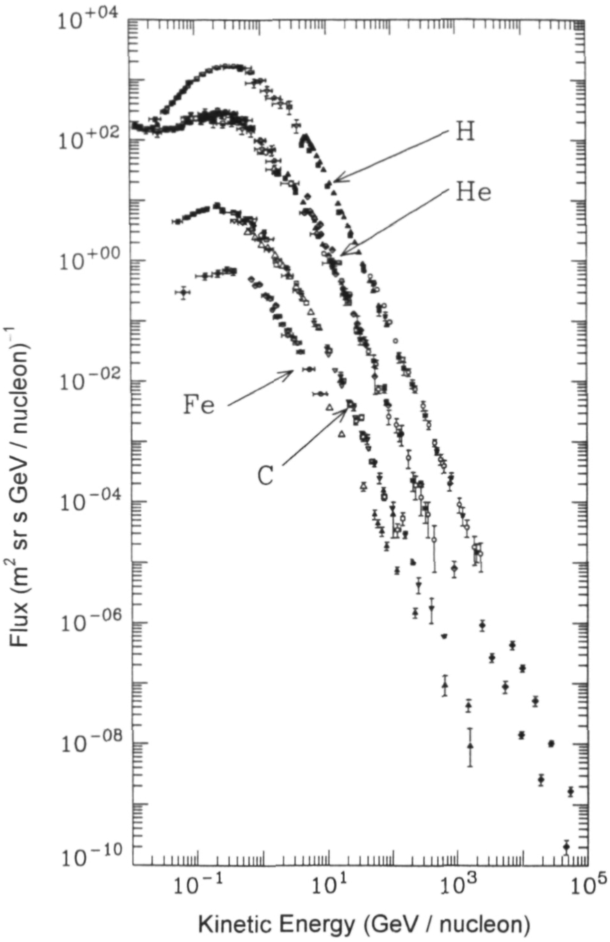


Figure 2.1 Energy spectra of some typical cosmic-ray species, including the elements H, C, He, and Fe. Note that when plotted as a function of kinetic energy per nucleon (in which comparison is made at the same particle velocity), all cosmic-ray elements have a similar spectral shape, which can be represented as a power law over the energy range from several GeV/nucleon to more than 10^3 GeV/nucleon. The slopes of these power laws differ somewhat from species to species, reflecting the effects of their transport through the interstellar medium. At low energies (<1 GeV/nucleon) cosmic rays experience more difficulty diffusing into the inner heliosphere, and the spectra of all species flatten and "roll over."

Many aspects of the two kinds of material are quite similar, for example, the excess of elements of even charge over odd charge and the extreme scarcity of elements much heavier than iron, the most tightly bound nucleus.

One striking difference is the vast overabundance of the elements lithium, beryllium, and boron (those with nuclear charge $Z = 3$, 4, and 5, respectively) in the cosmic radiation. These elements are virtually absent as endproducts of the processes of nucleosynthesis in stars, in which most complex nuclei are built up by fusion. When the abundant nuclei such as carbon and oxygen ($Z = 6$ and 8) collide with interstellar gas as they move through the galaxy, lithium, beryllium, and boron are among the spallation products. Indeed, this is the principal mechanism for producing some of the isotopes of these "secondary" nuclei in the universe. A similar excess of secondary nuclei is evident in the element region from $Z = 21$ to $Z = 25$ produced by the breakup of primary Fe ($Z = 26$) nuclei. From knowledge of the abundances of these secondary cosmic rays relative to the "primary" cosmic rays that are accelerated at the cosmic-ray sources, together with a knowledge of the

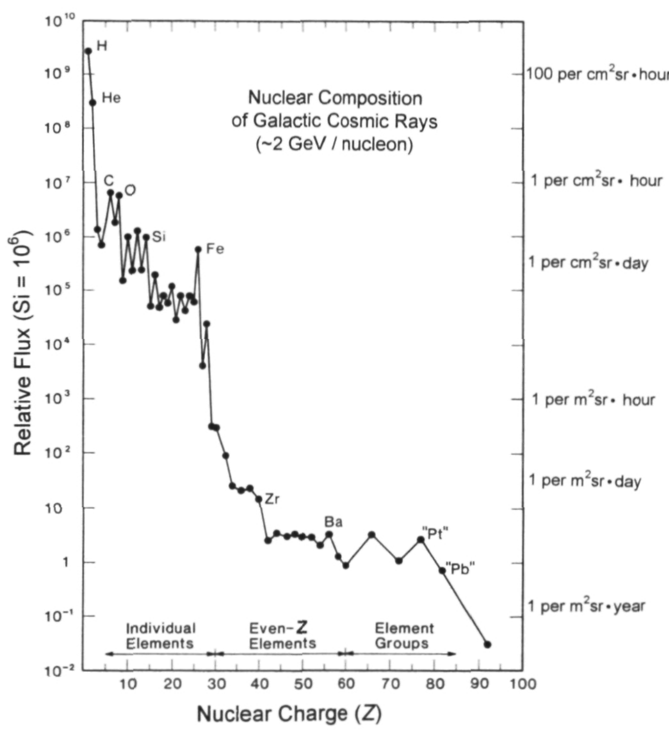


Figure 2.2 Measured abundances of cosmic-ray elements from H ($Z = 1$) to U ($Z = 92$), based on data from a variety of spacecraft and balloon experiments. For elements with $Z > 30$, measurements are available only for pairs of adjacent elements or for element groups. Indicated on the right-hand scale is the collecting power required to observe 100 events of a given species.

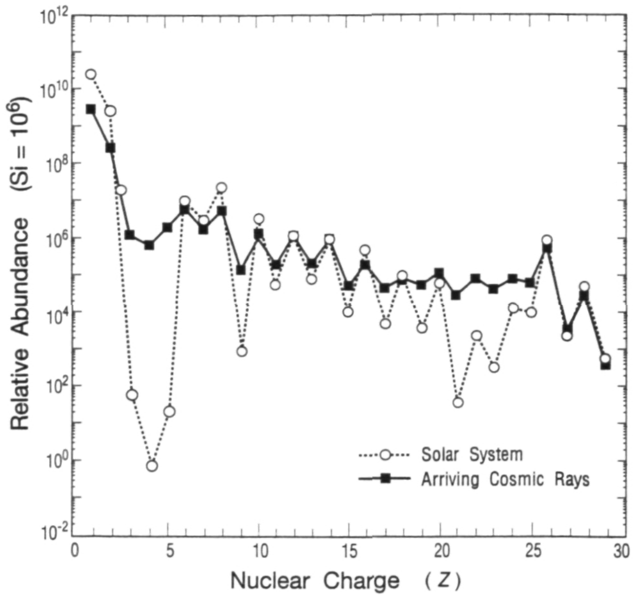


Figure 2.3 Comparison of the elemental composition of cosmic-ray nuclei (as measured at ~1 GeV/nucleon) with the abundances of the elements measured in solar system material, as derived from meteorites and from spectroscopic studies of the solar photosphere. The abundances are normalized on a scale where the abundance of Si = 10^6.

probabilities of fragmentation and of the density in the disk, it has been possible to learn something about the history of typical cosmic-ray nuclei.

By comparing the abundances of secondary and primary cosmic-ray species, and taking into account the probability of producing the secondary species in collisions with the interstellar gas, it has been possible to infer the mean amount of matter traversed by primary cosmic rays during their lifetime. The quantity determined in this way is a product of the mean gas density and the cosmic-ray velocity and lifetime, $\rho \times v \times t$, which has a maximum at about 10 g/cm^2 at 1 GeV/nucleon. The fact that the secondary/primary ratio decreases as energy increases, as shown in Figure 2.4, tells us that higher-energy particles have traversed less matter than lower-energy particles, which in turn implies that higher-energy particles have spent less time in the galaxy than lower-energy particles.

A measurement of the unstable isotope ^{10}Be (with a half-life of 1.5×10^6 years) in the cosmic-ray spectrum has provided a determination of 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, but not all, of this isotope to have decayed (approximately 10 million years). If, as expected, the primary nuclei also spend at least this much time in the galaxy and if most of it were spent in the disk, where the mean gas density is about one hydrogen atom per cubic centimeter, then even more secondary

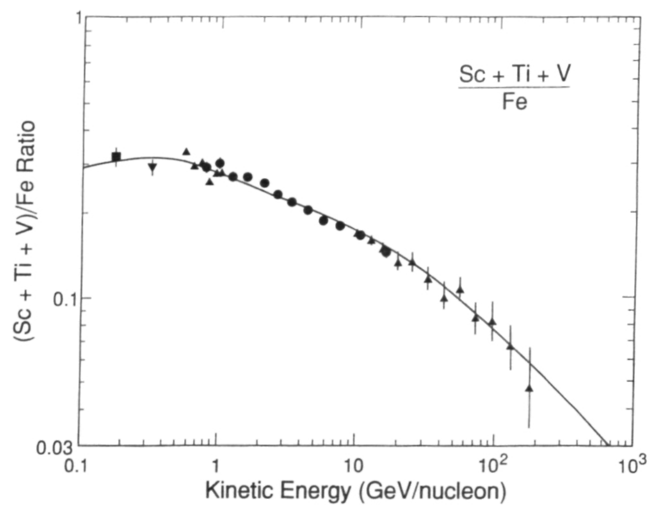


Figure 2.4 The abundance of secondary nuclei from scandium to vanadium ($21 \le Z \le 23$), measured by the HEAO, IMP-8, and ISEE-3 satellites is compared to that of iron nuclei (Z = 26) over the energy range from ~0.2 to 200 GeV/nucleon. These secondary nuclei are relatively rare in the solar system (see Figure 2.3), and are produced in cosmic rays by the fragmentation of Fe nuclei as they collide with interstellar gas. The decrease in this secondary/primary ratio with increasing energy implies that higher-energy cosmic rays have passed through less material and therefore have a shorter lifetime in the galaxy. The measurements can be fit by a model in which the mean path length for escape from the galaxy decreases from ~10 g/cm^2 at 1 GeV/nucleon to ~1 g/cm^2 at 150 GeV/nucleon.

nuclei than observed would have been produced. To fit the data it is necessary to assume that cosmic rays spend a considerable fraction of their lifetime in the less dense regions of the galaxy, for example, in the galactic halo.

The transport of cosmic rays from the disk to the halo may be largely controlled by a "galactic wind" (analogous to the solar wind) that convects gas, embedded magnetic fields, and cosmic rays out from the disk. The existence of such a wind would have significant effects on the age distribution and composition of cosmic rays, as diffusion and convection compete. For stable nuclides, the age distribution is determined entirely by the properties of this diffusing and convecting medium, including the probabilities for escape and for catastrophic nuclear collisions with the ambient gas. However, the cosmic-ray lifetimes of radioactive isotopes such as ^{10}Be, ^{26}Al (half-life = 740,000 years), and ^{36}Cl (half-life = 310,000 years) are also limited by radioactive decay. At higher energies, relativistic time dilation can extend the lifetime of these "clock" isotopes, and a greater fraction will survive radioactive decay. Thus, by studying the surviving fraction of these isotopes as a function of energy, it will be possible to map the age distribution of cosmic rays in the galaxy.

As an example, Figure 2.5 illustrates the energy dependence of the surviving fraction of ^{10}Be expected in three different models of cosmic-ray propagation in the galaxy. Measurements of ^{10}Be extending to energies of several GeV/nucleon should distinguish among these possibilities. Such measurements are planned to be made in long-duration balloon flights of the ISOMAX payload, now under development. While accurate studies of heavier radioactive clocks such as ^{26}Al and ^{36}Cl will be provided at low energies by the Advanced Composition Explorer (ACE) mission, to be launched in 1997, to extend these over a broad energy range will most likely require exposure of suitable new instrumentation above the atmosphere.

An interesting clue to the details of the mechanism of cosmic-ray production is given by another difference between the composition of the cosmic radiation and that of the general abundances of the elements in the solar system as deduced from meteorites and spectroscopic studies of the solar photosphere. It is observed that elements with high first-ionization potential (FIP > 10 eV) are systematically depleted in cosmic rays. This is likely to be a clue to the way in which nature selects the material from which particles are accelerated to become cosmic rays.

It is remarkable that a very similar first-ionization potential correlation is also observed

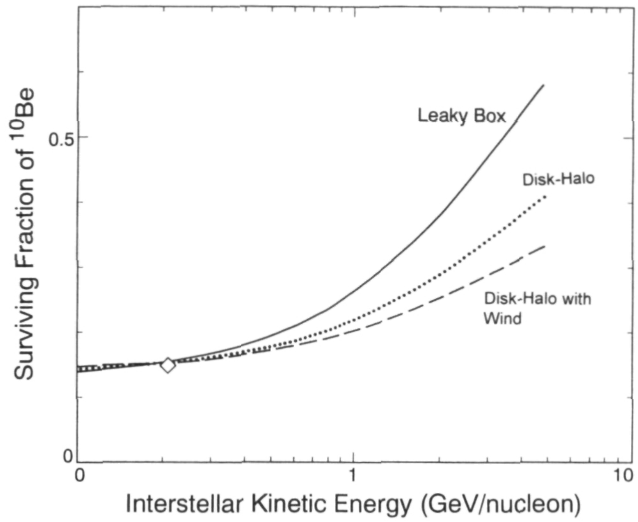


Figure 2.5 The predicted surviving fraction of ^{10}Be is shown as a function of kinetic energy per nucleon for three models of cosmic-ray propagation in the galaxy. In the leaky box model, cosmic rays are assumed to be confined to the galactic disk and to leak out into intergalactic space at an energy-dependent rate (consistent with, e.g., Figure 2.3). In the more realistic disk/halo model it is assumed that cosmic rays can diffuse from the disk into a lower-density halo, with a finite probability of returning to the disk. Finally, the last model includes a galactic wind that convects cosmic rays from the disk and impedes their return from the halo to the disk. The models are normalized to the average of several low-energy measurements of ^{10}Be available at ~0.2 GeV/nucleon from spacecraft experiments, where only ~15 percent of ^{10}Be survives. Measurements of ^{10}Be and/or other cosmic-ray clocks at higher energies (>1 GeV/nucleon) can distinguish among these models.

among particles accelerated in association with large solar flares on the Sun. In this latter case, it appears that solar energetic particles reflect the composition of material of the solar corona and that the corona is systematically depleted in elements with FIP > 10 eV relative to the photosphere of the Sun. Thus one might speculate that cosmic-ray particles originate in stellar winds and flares from pre-supernova stars and are subsequently swept up and accelerated by supernova shocks. However, the conditions that differentiate among elements on the basis of their first-ionization potential might also occur in some other environment such as the interstellar medium.

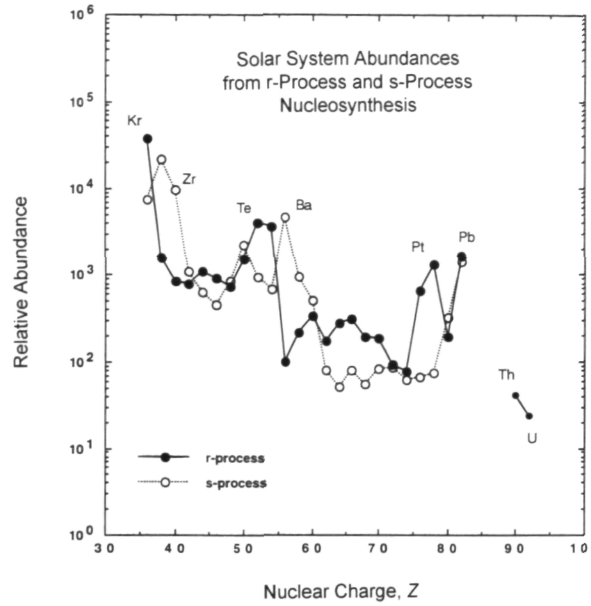


Figure 2.6 Contributions of the rapid (r) and slow (s) processes of neutron-capture nucleosynthesis to the solar system abundances of elements with $30 \leq Z \leq 92$ (shown for even-Z elements only for the sake of clarity). Note that the slow neutron capture process (s-process) results in abundance peaks at $Z = 56$ (Ba) and $Z = 82$ (Pb), whereas the rapid neutron capture process (r-process) peaks occur about four charge units lower, at $Z = 52$ (Te) and $Z = 78$ (Pt). Only the r-process can produce elements with $Z > 83$.

2.1 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 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 progenitor star may be destroyed in a runaway thermonuclear explosion, which also involves the 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 chemical evolution.

Synthesis of elements heavier than iron and nickel requires a neutron-rich environment and can occur rapidly (r-process) during supernova explosions (or perhaps some other violent event) or more slowly (s-process), for example, during a certain phase of the evolution of red giant stars. Since different relative abundances of heavy elements characterize the two processes (see Figure 2.6), precise measurements of the rare ultraheavy nuclei could determine what fraction of the cosmic-ray source material was synthesized under explosive conditions. For example, platinum ($Z = 78$) and the actinides are characteristic of the r-process, whereas lead and bismuth ($Z = 82$ and 83) characterize the s-process. In the late 1970s the HEAO and Ariel-6 missions surveyed the composition of ultraheavy cosmic rays with charge resolution sufficient to resolve adjacent pairs of elements up to $Z = 60$ and element groups beyond (see, e.g., Figure 2.2). In cosmic rays with $Z \geq 60$, there appears to be an overabundance of elements characteristic of rapid synthesis (those with $76 \leq Z \leq 78$ in Figure 2.6) relative to the mix of elements in the solar system. New results from the long-duration exposure facility (LDEF), and the TREK experiment now on MIR, should provide improved statistical accuracy for cosmic-ray nuclei with $Z > 60$.

In future experiments with individual element resolution it will be important to determine whether the general depletion of elements with high first-ionization potential that occurs among the cosmic-ray elements with $Z < 30$ also applies to those cosmic-ray elements synthesized by the r-process. If these nuclei are accelerated immediately following their production in supernovas, one would not expect that the necessary conditions to distinguish elements on the basis of first-ionization potential would apply, since this corresponds to a temperature of ~10,000 K.

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. If a depletion of elements with FIP > 10 eV is found among the elements produced in rapid nucleosynthesis, it would favor a scenario such as this over one in which freshly synthesized products of a supernova were accelerated immediately. If such a depletion is not found, it would point to contributions from freshly synthesized material.

New techniques exist that offer improved charge and mass resolution, as well as better collecting power, in the study of ultraheavy nuclei. During the next few years the TIGER balloon payload should provide studies of individual ultraheavy elements with $30 \leq Z \leq 40$. If similar instrumentation were exposed above the atmosphere on a medium-class Explorer mission the collecting power could be improved by about 2 orders of magnitude, extending studies of individual cosmic-ray elements over the entire range $30 \leq Z \leq 83$. Such measurements would reveal the contributions of several different processes of nucleosynthesis that are expected to produce ultraheavy nuclei.

In the thorium and uranium region and just beyond, there are several radioactive elements whose abundances can be used to measure the total time elapsed since nucleosynthesis. It is expected that observations to be reported from LDEF will indicate how the overall abundance of these radioactive elements, which can be produced only during rapid neutron capture, compares to the corresponding abundance of such elements in the solar system. However, to identify the individual elements with $Z > 90$ in cosmic rays (e.g., thorium, uranium, neptunium, plutonium, and curium) and use their relative abundances to determine the time delay between nucleosynthesis and cosmic-ray acceleration, may require a new experiment with a collecting power greater than 100 m^2 sr years combined with the capability of resolving individual elements. Although detection techniques to resolve these heavy elements in cosmic rays are now developed, it will be a challenge to identify low-cost space platforms with the required area.

2.2 Cosmic-ray isotopes

The most detailed and precise information obtained from studies of the composition of the nuclear component of galactic cosmic rays has come from measurements of isotopic composition at low energies (less than 1 GeV/nucleon). In addition to providing a determination of the lifetime of cosmic rays through the measurement of ^{10}Be, cosmic-ray isotope studies have provided evidence that cosmic-ray material has had a different history of nucleosynthesis than typical material in our solar system.

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 when compared to solar system samples of Ne. 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. 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 the fact that C/O ~ 1 in cosmic rays, compared to C/O ~ 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 α-particle nuclei (e.g., ^{12}C, ^{16}O, and ^{20}Ne); cosmic rays are taken to be representative of the interstellar medium.

Finally, it has been suggested that cosmic rays originate in supernovas or in regions of the galaxy that are "metal"-rich compared to the solar system. (Astronomers use the term "metals" to represent all of the elements heavier than He.) Such metal-rich regions might result either from inhomogeneities in the galactic metal distribution or from evolutionary effects, if cosmic rays are indeed a younger sample of matter than that which condensed to form the solar system some 4.5×10^9 years ago. A basic question that arises in distinguishing these models is whether cosmic rays represent freshly synthesized material ejected from a supernova, which is then accelerated immediately, or whether they include contributions from element synthesis integrated over the age of the galaxy. This fundamental question can be addressed by measuring radioactive isotopes created during supernova explosions that decay only by electron capture, including ^{56}Ni, ^{57}Co, and ^{59}Ni, with lifetimes ranging from a few days to 10^5 years. Once accelerated and stripped of their electrons, these nuclei can no longer decay. Their abundances (together with the abundances of their daughter nuclei, ^{56}Fe, ^{57}Fe, and ^{59}Co) therefore preserve a record of the time delay between synthesis in a supernova explosion and acceleration of the nuclei. Current evidence suggests that the delay between synthesis and acceleration of these nuclei is at least 3 years.

During the next few years, new measurements by instruments on Ulysses, SAMPEX, Geotail, Wind, and especially ACE are expected to measure the abundances of essentially all of the stable and long-lived nuclides up through the iron group ($Z \leq 30$) in the energy region below ~0.5 GeV/nucleon. This will provide new tests of these models and most likely lead 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.

To extend isotope studies to the rare "ultraheavy" elements (those with $Z > 30$) will be particularly challenging because of the requirement to combine the high resolution needed to separate isotopes with the very large collecting areas needed to obtain adequate statistical accuracy. There is, however, great scientific benefit that can be realized from successfully carrying out such a program. The endothermic nuclear reactions that are responsible for producing the ultraheavies are fundamentally different from the exothermic fusion reactions that make the lighter nuclei. By establishing the isotopic abundance patterns among the ultraheavies, one should be able to explore contributions from a wide range of possible nucleosynthesis environments (temperature, density, neutron flux), since certain nuclides are thought to be produced only by a slow neutron capture chain (s-process) while others are produced only by rapid neutron captures (r-process).

To extract such detailed information about the nucleosynthesis of the primary cosmic rays, one must rely on species that are not greatly contaminated by secondaries produced by spallation during passage through the interstellar medium. Ultraheavy isotopes are particularly favorable from this point of view since the rapid fall-off of abundances with increasing atomic number also means that there are few parent nuclei from which spallation products can be made (see Figure 2.2). Typically, for elements with $30 < Z \leq 50$ there are three or more isotopes that have significant primary contributions and are suitable for use in nucleosynthesis studies. This same range of elements is also a rich source of radioactive clock nuclei, which can be used to probe the history of cosmic rays. Just in the narrow range of elements from $34 \leq Z \leq 43$ one has a suitable set of seven clock isotopes with half-lives ranging from 2×10^4 to 5×10^8 years.

The survival of secondary nuclides, which can decay only by electron capture, is sensitive to the density of the medium through which the cosmic rays propagate because when a bare nucleus attaches an electron from the interstellar gas its survival or decay depends on the competition between electron capture and collisions that will strip off the electron. The electron attachment cross section is a strong function both of the particle's atomic number and of its velocity. At the typical interstellar energies for which isotope identification is possible with current techniques, electron attachment becomes significant only for ultraheavy elements. Over the charge range $30 \leq Z \leq 50$, pure electron capture nuclides are available for probing interstellar densities ranging from less than 10^{-2} to greater than 10^6 atoms/cm^3. By using measurements of the abundances of these isotopes it should be possible, for example, to determine whether a significant fraction of the material traversed by cosmic rays during their propagation is contained in high-density regions such as one might find surrounding some types of sources.

Meeting the experimental challenge of measuring isotopic abundances of ultraheavy elements will require a concerted effort to develop suitable sensor systems. An evolutionary approach is possible, starting with small prototypes that can be tested with accelerator beams of heavy ions to meet the stringent resolution requirements for separating ultraheavy isotopes. Exposure of larger detector systems (~1 m^2 sr), possibly involving mosaics of small, high-resolution devices, can be carried out with long-duration balloon payloads and MIDEX-class satellites to study isotopes in the charge range up to $Z \sim 40$ as well as to further investigate the iron group with unprecedented precision. Comprehensive studies of ultraheavy isotopes over a broad range of elements could become a reality in the early part of the next century with the exposure of very large detector arrays (10 to 100 m^2 sr) on suitable platforms in space.

- 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.

2.3 Electrons, positrons, and antiprotons

Production of Antimatter

Although there is almost complete symmetry between the properties of matter and antimatter, the universe is apparently dominated by one variety only. Antiparticles can be created in collisions between particles in laboratory accelerators and in interstellar collisions of cosmic-ray protons. The existence of even a small excess of antiparticles over what is expected from such collisions would be remarkable in the light of cosmological theories that provide a total dominance of matter over antimatter during the moments after the Big Bang. Both antiprotons and positrons have in the past been reported in cosmic rays at levels higher than predicted for production by interstellar collisions. The present generation of balloon-borne experiments is breaking new ground in improving these measurements to ask the question: Are these simply antiparticles produced in collisions or are there so many that they must have come from a more exotic source? A primary aim of the experiments is to use the antiparticles as tracers of the processes and locations in which they originate.

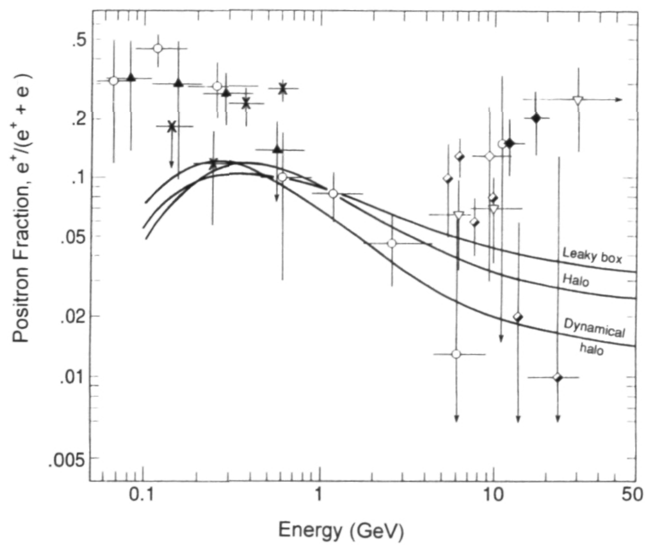


Figure 2.7 Observations of the fraction of cosmic-ray electrons that are positively charged are compared with the predictions of three cosmic-ray transport models. In the leaky box model positrons and electrons are produced in roughly equal numbers by the decay of pions resulting from collisions of cosmic-ray nuclei with the interstellar gas. Because this process accounts for less than one-half of the observed flux of negative cosmic-ray electrons, additional negative electrons are assumed to be accelerated in cosmic-ray sources, subject to loss mechanisms that include synchrotron losses, inverse Compton scattering, and leakage from the galaxy. The halo model includes the storage of cosmic rays in a low-density halo, while in the halo-with-wind model there is also a convective component at energies <1 GeV and >10 GeV.

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. These include 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 cosmic-ray source distribution and cosmic-ray transport in the galaxy that are not evident from studies of nuclei alone.

About 1 percent of cosmic rays by number are electrons, including both negatrons and positrons. It is unclear just why cosmic rays include approximately 100 times more nuclei than electrons. The energy spectrum of $(e^+ + e^-)$ from the galaxy has now been studied by a combination of balloon and spacecraft instruments over the energy range from ~0.1 GeV to ~1 TeV. It bears an overall similarity to that of cosmic-ray nuclei, with some significant differences. In the energy range $\sim 0.1 \leq E \leq 10$ GeV, the electron lifetime is probably dominated by diffusive escape from the galaxy, possibly into a galactic halo. In the range $10 \leq E \leq 100$ 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. Estimates of the electron "lifetime" on the basis of this steepening are consistent with the ~10^7-year lifetime derived for nuclei.

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 (pc). 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 and thereby attempt to establish their connection with specific source regions. 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 magnetic spectrometers; these studies are complicated by the background of positrons produced by cosmic-ray interactions in the upper atmosphere. Figure 2.7 compares the measured positron fraction with the predictions of three cosmic-ray propagation models. It is expected that new measurements to be reported from the recently flown AESOP and CAPRICE balloon instruments will reduce the experimental uncertainty below 10 GeV, while the HEAT instrument is providing improved high-energy measurements extending up to ~50 GeV.

Note in Figure 2.7 that the typical ratio expected from the models is ~5 to 10 percent, if all primary electrons have negative charge. The measured ratio indicates an apparent positron excess at both low energies (<1 GeV), and high energies (>10 GeV) (although recent data from the HEAT experiment, which indicate little or no high-energy excess, are not shown in Figure 2.7). The low-energy excess may reflect atmospheric background effects that have not been properly accounted for, or the effects of transport in the interplanetary medium, which may depend on the sign of the particle charge. Any excess at high energy would require another explanation. A naive interpretation of a high-energy positron excess 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 from the galaxy that positrons are abundant near the galactic center. Such positrons are expected from the beta decay of radioactive nuclei such as ^{26}Al. Pulsars could also be a source of primary positrons. 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 (see Section 8.4).

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 possible heliospheric effects, as well as the inherent difficulty of the measurements. Most of these difficulties would be overcome by a magnetic spectrometer in space that could separate electrons and positrons 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. The basic reaction for producing antiprotons in high-energy collisions,

$$p + p \rightarrow p + p + p + \bar{p}, \qquad (1)$$

first demonstrated at the Lawrence Berkeley Laboratory Bevatron in 1955, requires an incident proton with a kinetic energy of ~6 GeV or more. Cosmic-ray antiprotons differ from other secondary nuclei in several important ways: they are produced mainly by collision of

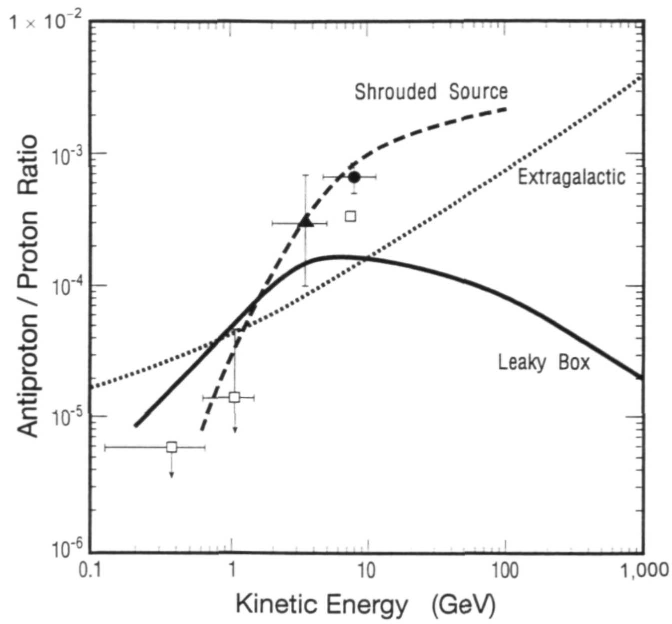


Figure 2.8 Observations of the antiproton/proton ratio in cosmic rays, based on a combination of several balloon-borne instruments, are compared with the predictions of models for the origin of cosmic-ray antiprotons. In the standard leaky box model, secondary antiprotons are produced in collisions between high-energy (>10 GeV) cosmic-ray protons (and heavier nuclei) with the interstellar gas. The protons are assumed to have the same lifetime in the galaxy as heavier species. The predicted ratio decreases below several GeV because it is difficult kinematically to produce low-energy antiprotons in high-energy collisions. At high energies the ratio decreases because of the decreasing lifetime of cosmic rays in the galaxy. There is an uncertainty in the predicted ratio of approximately a factor of two due to uncertainties in the models, especially at low energy where solar modulation becomes a significant effect. Even so, there is an indication of an overabundance of cosmic-ray antiprotons with ~10 GeV. The curve labeled "extragalactic" shows the spectral shape that would be expected for antiprotons that leak out of antigalaxies and cross intergalactic space to enter our own galaxy, if the energy-dependent leakage rate is the same for antigalaxies as for our own. The normalization of this curve is arbitrary; the antimatter-to-matter fraction in heavier cosmic rays is known to be less than $\sim 10^{-5}$. In the shrouded source model it is assumed that about one-fourth of cosmic-ray sources are surrounded by a shell of material with a column density of ~30 g/cm^2. Antiprotons produced in this shell must be added to those from interactions in the interstellar medium.

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.

The following example illustrates 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 relatively flat spectrum of antiprotons 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 energy-dependent escape from the galaxy should more than offset the energy-dependent cross section, with the result that the antiproton spectrum will be steeper at high energy than the parent proton spectrum.

Figure 2.8 summarizes present measurements of the antiproton/proton ratio, compared with the predicted ratio based on secondary production, with the assumption that cosmic-ray protons have the same origin and lifetime as heavier cosmic-ray nuclei. 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 (which, for example, would be produced if large numbers of antiprotons were being generated by dark-matter annihilation in the galactic halo).

If the flux of cosmic-ray antiprotons is confirmed to be greater than expected from secondary production by cosmic rays colliding with the interstellar gas, it may provide evidence for one of several possibilities. It may be that many cosmic-ray protons have traversed more material than heavier elements such as C, N, and O because there are additional sources of cosmic-ray protons such as supernova remnants surrounded by shells of matter. There may also be more exotic sources of antiprotons such as the decay of massive particles left over from the big bang (see discussion in Section 7.4).

Finally, there is the possibility of "primary" cosmic-ray antiprotons originating in condensed regions of antimatter beyond our galaxy. Precise measurements of antiprotons over the widest possible energy range are needed to address these possibilities.

Balloon-borne magnetic spectrometers are now capable of unambiguously resolving cosmic-ray antiprotons with energies in the range $\sim 0.1 \leq E \leq \sim 50$ GeV, with sufficient statistical accuracy to identify unexpected flux levels or spectral features. Over the next few years new antiproton measurements are expected from the MASS, IMAX, CAPRICE, BESS, and HEAT payloads. If the results of these studies provide a compelling rationale for improving this accuracy or for tracing the antiproton spectrum to energies >50 GeV (where some existing models are better tested, but where atmospheric background radiation is expected to be more important), then an orbiting magnetic spectrometer with sufficient resolving power will probably be required.

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

2.4 Future programs

During the past decade there have been a number of important advances in the capability to measure the charge, mass, and energy of the various cosmic-ray components, often as the result of detector technologies originally developed for accelerator experiments in the fields of high-energy and nuclear physics. For example, a number of balloon payloads now employ magnetic spectroscopy techniques based on both superconducting and permanent magnets. In such experiments, particle trajectories are now measured to an accuracy of ~100 μm with multiwire proportional counters, drift chambers, silicon strip detectors, and scintillating optical fibers, while particle velocities are measured to high accuracy with time-of-flight techniques, and by measuring the Cherenkov and transition radiation emitted by relativistic particles. As a result of these advances, elemental and isotopic composition can now be measured with high precision over a much broader range of energies and masses than was previously possible, and electrons, positrons, and antiprotons can be resolved up to much higher energies.

Table 2.1 summarizes balloon payloads that are currently in use or under development to study cosmic-ray composition. Other proposals are under consideration at present. Included are studies of electrons, positrons, antiprotons, and the elemental and isotopic composition of nuclei that can now be carried out with unprecedented precision and will extend to unexplored energy ranges. Experiments designed to measure composition beyond 1 TeV are discussed further in Section 4. The recent development of long-duration balloon flights of about 10 days provides the opportunity to gain an order-of-magnitude exposure factor for these new detectors above most of the atmosphere.

Tables 2.2 and 2.3 include examples of the additional studies that can be addressed with long-duration payloads, both on balloons and in space. The improved statistical precision that results is particularly important for studies of rare species such as ultraheavy nuclei, ^{10}Be, and antiprotons, and for extending composition studies to very high energies. Thus, the continued development and flight of these long-duration payloads will lead to major advances in several key areas of cosmic-ray composition studies within the next few years. Many of the scientific goals can be accomplished with long-duration balloon flights, which also allow for the development of payloads for spaceflight and provide realistic tests for new detector technologies that may ultimately fly in space and often have other applications.

For certain goals, 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 (see Table 2.2). Small, low-cost missions such as those developed in NASA's Explorer program could address many of these questions. Studies of cosmic-ray positrons and ultraheavy nuclei would appear to be particularly well suited for such an opportunity; in both cases there are proven instrumentation approaches that can provide greatly improved measurements if exposed above the atmosphere for a period of 2 years or more.

From time to time there are also opportunities to fly cosmic-ray experiments on space missions developed by other countries or by government agencies other than NASA. Such "missions of opportunity" can provide a very cost-effective means of addressing many of the scientific goals discussed above. It is important that NASA have a means of evaluating these opportunities and funding those that are appropriate.

In addition, the cargo bay of the Space Shuttle can, in principle, provide the opportunity for exposing larger, heavier payloads in low-Earth orbit for periods of up to 2 weeks. The exposure of such payloads could be increased by as much as two orders of magnitude by using the International Space Station Alpha (ISSA) for a period of up to several years. Although the availability of ISSA for scientific payloads will be limited, it could be especially useful for payloads that require servicing or that require extended exposure in space to measure very rare species such as ultraheavy nuclei, very-high-energy cosmic rays, or antinuclei.

Table 2.1 Balloon Payloads to Measure Cosmic-Ray Composition

Payload Name	Measured Species	Energy Range	Past/Planned 1-Day Flights	Past/Planned Long-Duration Flights
LEE/AESOP	Electrons/positrons	0.5 GeV - 5 GeV	1994/1996	Not required
HEAT	Electrons/positrons and antiprotons	5 GeV - 50 GeV 0.2 GeV - 30 GeV	1994/1995 1996	
MASS/ CAPRICE	Electrons/positrons and antiprotons	1 GeV - 8 GeV	1994	1996, midlatitudes
JACEE	$1 \leq Z \leq 26$ interactions and spectra	1 TeV - 100 TeV	1979-1987	1987-1994, continuing
Super-JACEE	$1 \leq Z \leq 26$ interactions and spectra	1 TeV - 10 TeV		1995
RICH	H and He spectra	20 GeV/nucleon - 200 GeV/nucleon	1991/1995	
ISOMAX	^{10}Be; $2 \leq Z \leq 8$ isotopes	0.2 GeV/nucleon - 3 GeV/nucleon	1995	1997
THISTLE	Fe group isotopes	0.45 GeV/nucleon - 0.5 GeV/nucleon	1992	?
TIGER	$30 \leq Z \leq 40$ elements	>0.5 GeV/nucleon	1995	1997

Table 2.2 Future Cosmic-Ray Composition Studies Accessible to Balloon-borne Instrumentation

Duration	Species	Energy Range	Scientific Objectives
1-day flights	Positrons/electrons	0.5 GeV to 50 GeV	Origin of cosmic-ray electrons Evidence for primary positrons
	Antiprotons	0.1 GeV to 20 GeV	Test predicted spectrum of interstellar secondaries
	Anti-helium search to 1 ppm	<10 GeV/nucleon	Search for evidence of primordial antimatter
	^{10}Be clock isotope	>1 GeV/nucleon	Test predictions of leaky box and diffusion models
10-day flights	Antiprotons	To 50 GeV	Test predicted spectrum of interstellar secondaries
	Anti-helium search to 0.1 ppm	<10 GeV/nucleon	Search for evidence of primordial antimatter
	^{10}Be clock isotope	To ~3 GeV/nucleon	Search for evidence of galactic halo/wind effects
	Composition $1 < Z < 26$	$\geq 10^{14}$ eV	Search for evidence of spectral differences
	Composition $30 < Z < 40$	>0.5 GeV/nucleon	Identify nucleosynthesis contributions

Table 2.3 Future Cosmic-Ray Composition Satellite Studies That Require Access to Space

Species	Energy Range	Scientific Objectives
Positrons	< 0.5 GeV and >50 GeV	Search for additional positron sources
Antiprotons	50 GeV - 300 GeV	Evidence of additional antiproton sources
Anti-helium search to 1 in 10^9 or 10^{10}	<10 GeV/nucleon	Search for evidence of primordial antimatter
^{26}Al, ^{36}Cl, and other clock isotopes	≥1 GeV/nucleon	Measure cosmic-ray age distribution
Isotopic composition $Z \geq 30$	<0.5 GeV/nucleon	Identify nucleosynthesis contributions; measure additional clock isotopes
Elemental composition $40 \leq Z \leq 96$	>0.5 GeV/nucleon	Identify r- and s-process contributions
Secondary/primary ratios	>300 GeV/nucleon	Path length of high-energy cosmic rays in galaxy
Definitive composition	$>3 \times 10^{15}$ eV	Measure composition “at the knee”

3

A Model of Cosmic-Ray Origin

Observations about the composition and spectra of the various components of the cosmic radiation, as described in the previous section, have led to an attractive, though tentative and incomplete, picture of cosmic-ray origin. This section summarizes the picture and focuses on the questions that it raises, especially about the origin of cosmic rays with ultrahigh energy.

3.1 Spectrum of the sources

The basic picture is that cosmic rays are accelerated in sources distributed in the disk of the galaxy. The accelerated particles subsequently diffuse in the disk and halo, with a characteristic lifetime of 10 million years before they are lost from the galaxy altogether. The time spent by a typical cosmic-ray particle in the galaxy represents a path length equivalent to 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.

It is perhaps not surprising, therefore (as mentioned above in connection with Figure 2.4) that the higher-energy particles appear to escape from the galaxy faster than the lower-energy particles. An important implication of this energy dependence of the cosmic-ray lifetime is that the source spectrum must be "harder" (involving more energetic radiation) than the observed spectrum, because the cosmic rays are in equilibrium between acceleration and escape. Since the higher-energy particles spend less time in the galaxy, they must be relatively more abundant at the sources. The mathematical expression of this idea is

$$\rho(E) = \frac{Q(E)\,\tau(E)}{V} \qquad (2)$$

where $\rho(E) \sim E^{-2.7}$ is the density of cosmic rays of energy E, $Q(E) \sim E^{-\alpha}$ is the spectrum produced by a typical accelerator, and $\tau(E) \sim E^{-\delta}$. The denominator V is the volume over which the sources and the cosmic rays are averaged.

Fits of this simple picture to the data give $\delta \sim 0.6$, which requires a source spectral index $\alpha \sim 2.1$. The integral, $\int Q(E)\,dE$, gives the total power required of cosmic-ray sources in the disk to maintain the cosmic radiation in a steady state. If the cosmic-ray density we measure is assumed to be typical of other regions of the disk of the galaxy, then the measured lifetime, $\tau(E)$, can be used to estimate the total power required of galactic cosmic-ray sources: $\sim 3 \times 10^{40}$ ergs/s.

Supernovas can provide this power if a few percent of their kinetic energy on average goes into acceleration of relativistic protons and nuclei. 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, which leads to an estimate of $\sim 10^{42}$ ergs/s for the average rate at which energy supernovas pump energy into the interstellar medium (excluding the energy carried away by neutrinos). Because the interval of time between supernovas is short compared to the

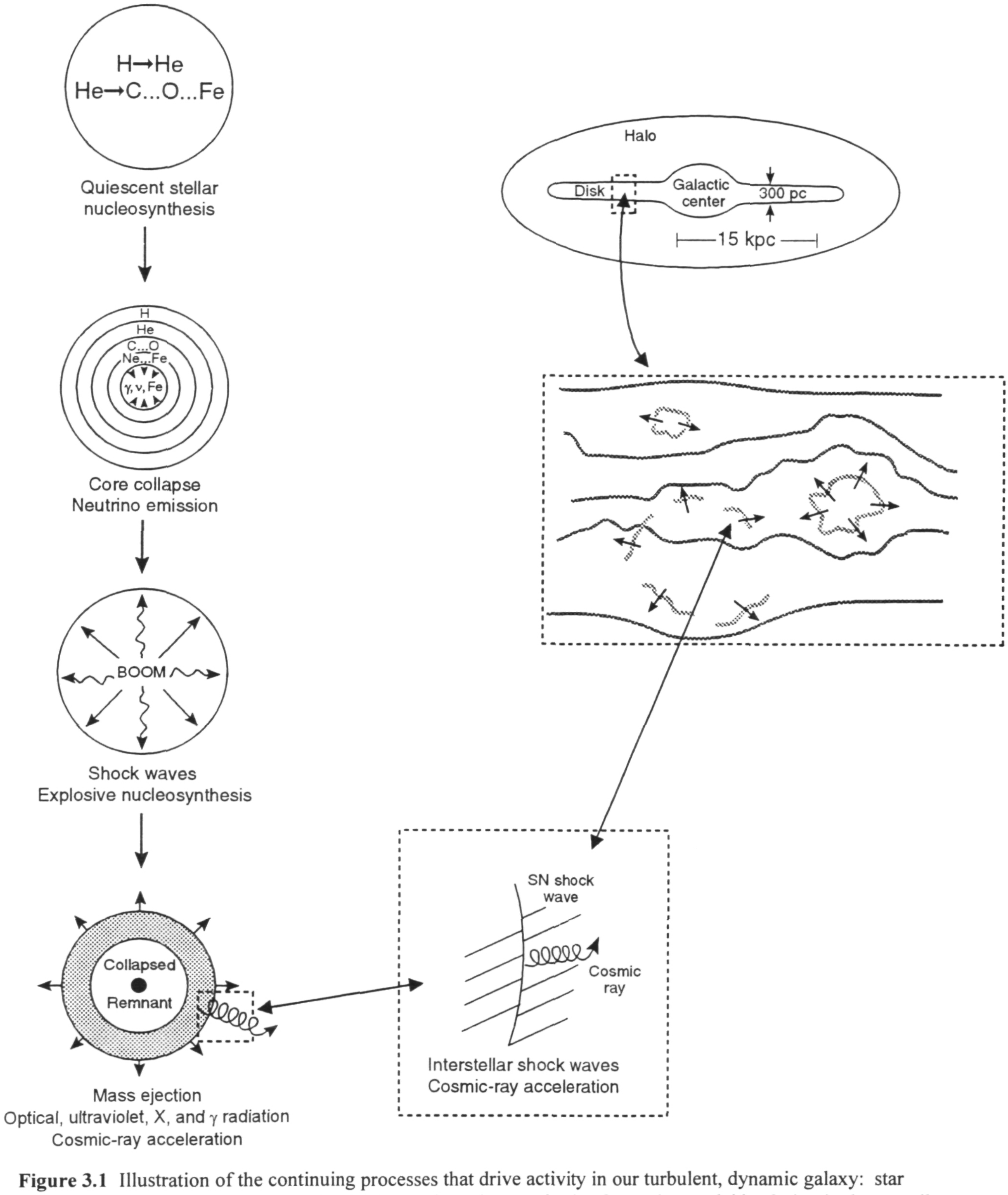


Figure 3.1 Illustration of the continuing processes that drive activity in our turbulent, dynamic galaxy: star formation as gas clouds contract under the force of gravity; synthesis of complex nuclei by fusion in dense stellar interiors; generation of strong winds by active, massive stars that, together with supernova explosions, generate turbulence in the interstellar medium; stellar collapse of massive stars that leads to supernova explosions; and acceleration of cosmic rays by shocks driven by the explosions.

characteristic time for cosmic-ray diffusion out of the galaxy, these explosions effectively provide a steady source of power.

Ejecta from the collapse of a massive star expand at supersonic velocity and so drive a strong shock into the surrounding medium. Particle acceleration occurs at shocks propagating in turbulent plasmas. As particles diffuse back and forth across the shock front, they are effectively trapped in a converging flow because of the discontinuity of velocity across the shock front. This provides a mechanism for transferring some of the macroscopic energy associated with the shock to the acceleration of individual, microscopic particles, thus promoting them to extremely high energies.

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. For strong shocks (Mach number >>1) the natural spectrum is a power law with spectral indices $\alpha = -2$, close to the inferred spectral index of galactic cosmic-ray sources. 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. Some aspects of this picture are illustrated in Figure 3.1.

3.2 The evidence from gamma-ray and radio astronomy

The diffuse γ-radiation component in our galaxy that originates from interactions of cosmic rays with interstellar gas and photons provides important information about the density, distribution, and spectrum of the cosmic rays that pervade the interstellar medium. The galactic diffuse γ-ray flux is currently observed at energies up to around 20 GeV but is expected to extend into the TeV range. The most prominent feature of the γ-ray sky at these energies is the bright emission along the plane of our galaxy, showing that energetic cosmic-ray particles are present throughout the interstellar medium. The primary processes thought to be responsible for the diffuse γ-ray production are (1) the decay of neutral pions produced in interactions of cosmic-ray protons with nuclei of atomic, molecular, and ionized hydrogen; (2) bremsstrahlung from scattering of cosmic-ray electrons with nuclei of interstellar gas; and (3) inverse Compton scattering of cosmic-ray electrons with optical, infrared, and microwave background photons. Combining the observed diffuse γ-ray flux distribution with the known distributions of the various interstellar gas components and photon fields to derive the galactic cosmic-ray density distribution indicates that a radial cosmic-ray gradient in the galaxy is required to produce the center-to-anticenter variation in the observed γ-ray flux. This gradient is weaker than that of the main tracers of population I stars such as H_2, HII, and pulsars, which is expected as diffusion tends to smear out the source distribution of cosmic rays. There is also indication of a coupling between cosmic rays and interstellar material (i.e., a proportionality between the cosmic-ray density and the matter density), possibly on the scale of spiral arms. The total luminosity in galactic cosmic rays deduced from these models is $L_{CR} \sim 3 \times 10^{40}$ ergs/s, which compares to the estimated total rate of energy output from supernovas, $L_{SN} \sim 10^{42}$ ergs/s.

It is also possible to obtain information about the galactic interstellar spectra of cosmic-ray protons and electrons from measurement of the diffuse γ-ray spectrum. This spectrum is generally in good agreement with the shape one would expect from a combination of π^0-decay, bremsstrahlung, and inverse Compton radiation using the inferred interstellar cosmic-ray spectra of protons and electrons. A bump at 70 MeV, the expected signature of π^0-decay, has now been clearly seen in spectra of the diffuse emission from the galactic plane observed by EGRET. The galactic γ-ray spectrum at energies below 10 MeV, due primarily to bremsstrahlung, can constrain the cosmic-ray interstellar electron spectrum below a few GeV where direct measurements are severely affected by solar modulation. They can also constrain the path length by comparing the electron spectrum with the proton spectrum needed to produce the γ rays above 100 MeV. Already, early galactic plane survey results from COMPTEL have placed constraints on the path length for electron energies less than 4 GeV at 4 to 6 g/cm^2, somewhat lower than the value from data on cosmic-ray secondary nuclei.

Diffuse γ rays observed from molecular clouds have revealed important information about the cosmic-ray density inside potential sources of energetic particles and the ability of cosmic rays to penetrate the clouds. Since several of these clouds are resolved as extended sources, it is assumed that the γ-ray emission originates from interactions between cosmic rays and the gas and photons in the cloud. EGRET observations of the Ophiuchus cloud complex have shown that the measured γ-ray flux is consistent with a cosmic-ray density equal to that in nearby regions of the galactic plane. Therefore, interstellar cosmic rays can fully penetrate molecular clouds and there is no evidence for an enhancement of cosmic rays inside the cloud. The COMPTEL instrument on Compton Observatory has detected a surprisingly high flux of γ rays from the Orion molecular cloud complex in the energy range 3 to 7 MeV. This emission most likely originates from nuclear de-excitation lines of ^{12}C and ^{16}O at 4.44 and 6 MeV, due either to collisional excitation of these elements in the ambient medium by a high flux of cosmic-ray protons and α-particles or to ambient H and He bombarded by accelerated cosmic-ray C and O nuclei in enhanced abundances. This important measurement has potential implications for cosmic-ray acceleration by stellar winds and supernovas in sources where active star formation is taking place.

Observations of diffuse γ-ray emission from other galaxies can answer fundamental questions about the origin of cosmic rays. One of these is whether the cosmic rays we detect are galactic or universal. It was realized some time ago that at least the bulk of the electron cosmic rays cannot be universal because they would produce an X-ray and γ-ray background from inverse Compton boosting of microwave background photons far in excess of what is observed. The recent EGRET upper limit on γ-ray flux from the Small Magellanic Cloud (SMC) has now clearly ruled out a universal proton component below 10 GeV, since the flux predicted by assuming the local cosmic-ray density in our galaxy 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, implying that the SMC cannot contain its locally produced cosmic rays and is in a state of disruption. EGRET detection of the Large Magellanic Cloud gives 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 similar to our galaxy.

Energetic electrons moving through interstellar magnetic fields generally emit synchrotron radiation in the radio band. Studies of the diffuse galactic nonthermal radio emission make it possible to map regions where electrons are being accelerated in supernova remnants, both within our galaxy and in external galaxies. In addition, the prompt radio emission seen just following a supernova explosion indicates that we are witnessing the acceleration of electrons by the blast wave shock. Although the supernova origin of the galactic cosmic-ray electrons is generally supported by these radio observations, the relation between acceleration of electrons and acceleration of ions is not understood. For example, are shocks as effective at accelerating electrons as ions? Do electrons and/or positrons come from a different distribution of sources from ions? Because of their much smaller mass, electrons at low energies will encounter more difficulties in shock acceleration that ions, with both injection and radiative losses, but it is believed that once the particles achieve the same momentum per charge ("rigidity"), their acceleration will be identical. Further theoretical work is needed to study these problems.

3.3 Limitations of the supernova model

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; thus, 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 greater. 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, for acceleration in a region where the average magnetic field is about 3 microgauss. 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.

4

Exploring the Supernova Scale

The Cosmic-Ray Knee

Since the supernova mechanism is expected to have an upper limit to the particle energies that can be achieved, the next question is what the spectrum and composition look like in the range where the termination is expected to occur (i.e., around 100 TeV and above). Figure 4.1 shows a summary of measurements of the total spectrum of particles extending to high energy. There is certainly no evidence of a sharp cutoff, although the spectrum steepens significantly above about 3,000 TeV. This feature is called the knee of the cosmic-ray spectrum.

The knee may reflect the upper limiting energy of some types of cosmic accelerators, or it may arise from an energy-dependent change in the way cosmic rays propagate in the magnetized galactic medium. Such a plot of the "all-particle" spectrum gives a global view of the cosmic-ray energy spectrum as a function of total energy per particle, without attempting to distinguish among different kinds of nuclei. At the low-energy end, spectra of individual elements are summed to obtain the total number of cosmic rays in each energy bin. At higher energies ($>>10^{14}$ eV), only indirect air-shower measurements are available, in which the primary nuclei cannot be identified on an event-by-event basis. The only measurement that bridges the gap between direct measurements below $\sim10^{14}$ eV and indirect air-shower measurements above that energy is the series of measurements carried out by the heavy calorimeters on Russian satellites launched by the Proton rocket. Learning more about the relative abundances of different kinds of nuclei in the knee region will be of great significance for understanding the origin of high-energy cosmic rays.

4.1 Cosmic-ray spectrum above 100 TeV

Whether and how the *knee* of the spectrum (see Figure 4.1) is related to the mechanisms for acceleration, propagation, and confinement is one of the major current questions in cosmic-ray physics. In examples of acceleration inside the heliosphere, 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 greater 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 end point 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 (see Figure 1.2). 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 (see Table 4.1). The exposure required 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 seem to show the proton spectrum becoming steeper while the spectra of helium and heavier nuclei maintain the same slope (see Figure 4.2). 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.

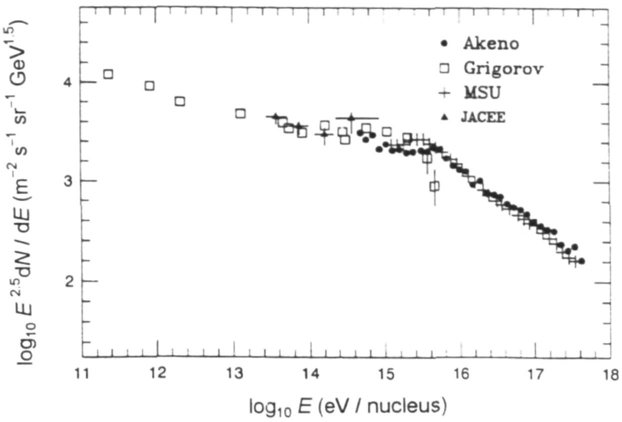


Figure 4.1 Summary of measurement of the "all-particle" cosmic-ray energy spectrum. The particles are classified by total energy per nucleus. Note that in this plot the differential energy spectrum is multiplied by $E^{2.5}$ to display the steep spectrum on an expanded scale.

4.2 What will we learn?

> Cosmic Accelerators
>
> Acceleration and propagation of charged particles in turbulent plasmas depend only on magnetic rigidity (gyroradius). Therefore, if all elements come from the same distribution of sources and have similar propagation histories, then all would have the same rigidity spectrum. There is a suggestion common to several measurements of the proton spectrum that this is not the case. This is seen as an apparent steepening of the proton spectrum in the energy region above 10 TeV (see Figure 4.2). 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.

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 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

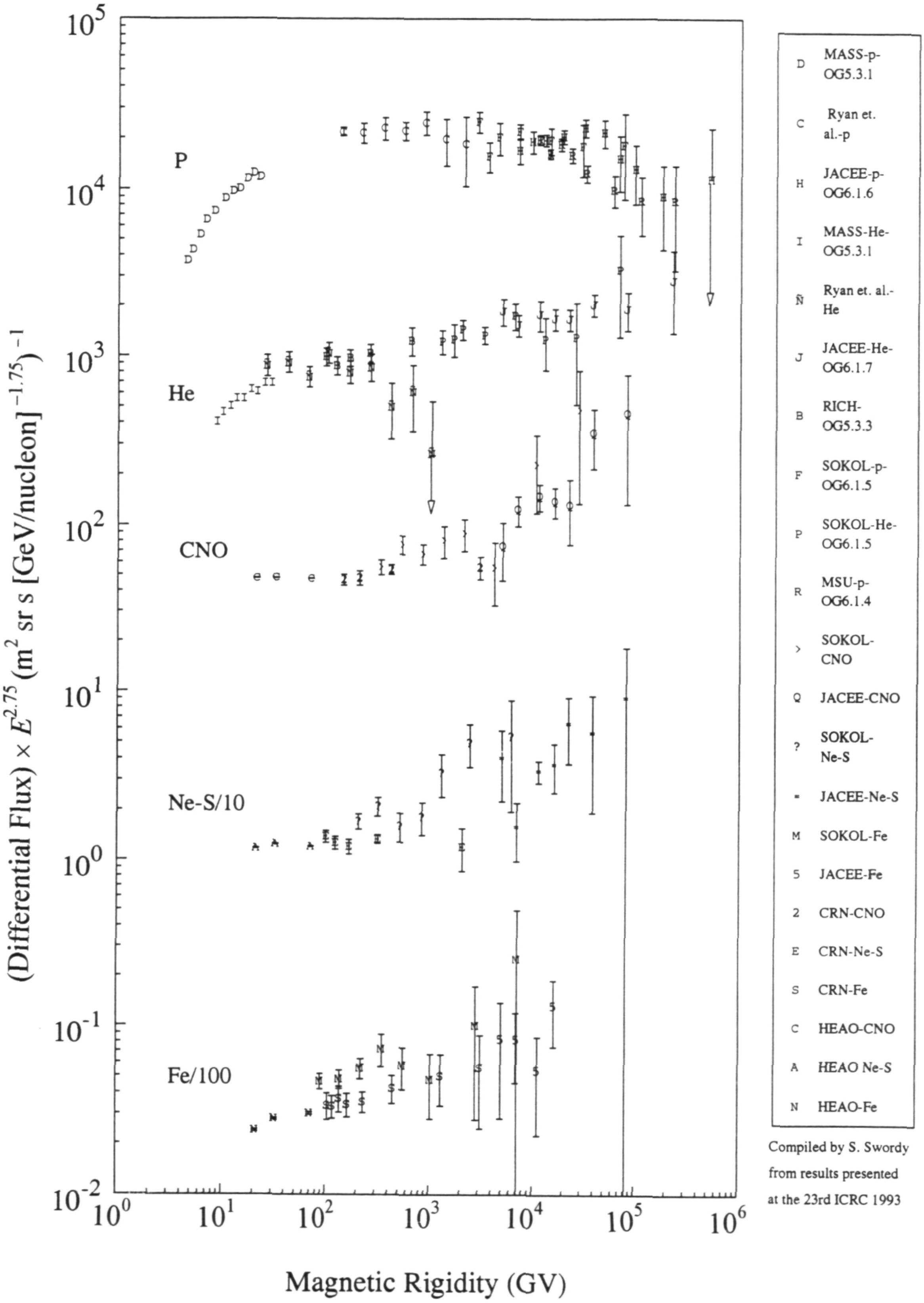


Figure 4.2 Summary of direct measurements of the major groups of elements at high energy as a function of magnetic rigidity (which is proportional to gyroradius in a magnetic field). If all species had the same distribution of sources and propagation history, all would have rigidity spectra of the same shape at high energy (> 100 GeV).

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 greater 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 and surrounding the star 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.

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.

- 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 establishing whether the major components indeed have different spectra, reflecting a different distribution of sources.

4.3 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. 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. The limited objectives of present detectors are shown in Table 4.1. The capability to fly large, high- altitude balloons for 10 days or more around the South Pole provides a new observational opportunity that will allow experimenters to achieve the exposure of 300 m^2 sr days necessary to extend direct measurements of composition to 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, which can achieve much greater exposure factors, but at the price of not observing the primary nucleus directly. Both kinds of experiments are needed.

Table 4.1 Some Direct-Measurement Techniques

Name	Technique	Objective	Status
CRN	Transition radiation detector	$Z \geq 5$, abundant nuclei to 1 TeV/A	Completed
JACEE	Thin passive calorimeter	All nuclei to >10 TeV/Z	Ongoing
Sokol	Thin passive calorimeter	All nuclei to >10 TeV/Z	Ongoing
MSU	Thin passive calorimeter	All nuclei to >10 TeV/Z	Ongoing
RICH	Ring Imaging Cherenkov	Helium to 1 TeV	Ongoing

4.3.1 Extending direct measurements to 10^{15} eV

The required exposure (see Figure 1.2) to reach 10^{15} eV requires detectors of 30 m^2 sr exposed for 10 days or smaller detectors with repeated exposures on long-duration balloon flights or extended exposure in space. As discussed in Section 7, payloads of ≈ 2 tons can be carried on long-duration balloon flights at present. These requirements place severe constraints on the design of detectors. Total absorption calorimeters with such large apertures are out of the question for balloon flights because one interaction length because one interaction length in iron corresponds to a mass of 1.3 tons per square meter of area.

Three alternatives have been developed, each of which has its own strengths and limitations.

Thin calorimeters The incident particles usually interact only once inside the detector, but sometimes more often. The charge is measured as the particle enters the detector (e.g., from the signal in a thin scintillator, which is proportional to Z^2). The energy is estimated either by a totally absorbing electromagnetic calorimeter, which measures the total energy in neutral pions, or by measuring the angular spread of the charged particles produced in the initial interactions. The electromagnetic calorimeter can in principle be either a passive detector (emulsion chamber) or an electronic calorimeter similar to a lead-glass calorimeter in a high-energy physics experiment. In the case of passive calorimeters, extraction of the data is slow and somewhat painstaking. In all cases with a thin calorimeter, extensive simulation studies are needed to relate the fraction of the energy measured to the total energy carried by the incident nucleus. An advantage is that particles of all charges can be detected.

Nondestructive measurements A nondestructive technique, first used in the Cosmic-Ray Nuclei experiment (CRN) flown on the Space Shuttle, involves the measurement of the Lorentz factor of the primary particle with a transition radiation detector. Such a detector has a small mass per unit area so that large exposures can be achieved. The energy range that can be measured is limited, however, and the technique is sensitive only to nuclei with a charge of five or higher. Other possible nondestructive techniques are being discussed. These include detection of Cherenkov light produced high in the atmosphere by iron nuclei before they interact in the atmosphere and the use of passive track detectors to identify directly produced electron pairs when a particle traverses the detector.

Satellite measurements The use of massive total-absorption calorimeters has been suggested from time to time. This is a straightforward way to extend the spectrum to higher energy, limited only by the ability to lift the weight into space. The Russian Proton Launcher can put payloads of 16 tons into orbit. After several years of operation, a well-instrumented detector of this weight could extend the measurement of all major groups of nuclei up to beyond $\sim 10^{15}$ eV.

4.3.2 Composition at the knee from air-shower experiments

The only way at present to extend measurements of the cosmic ray spectrum and composition beyond the knee is with large air-shower detectors on the ground (see Table 4.2). Traditionally, arrays such as those at Akeno in Japan, Moscow State University and Tien Shan in the former Soviet Union, Durham and Haverah Park in the United Kingdom, Buckland Park in Australia, the Kolar Gold Fields in India, and Mt. Chacaltaya in Bolivia, have measured the ratio of low-energy (~GeV) muons to electrons in the shower front. The combination of the Chicago Air Shower Array (CASA) and the Michigan Array (MIA) at Dugway, Utah, is the most extensive and technologically advanced example of such a measurement. In the energy range from 10^{14} to 10^{16} eV, the ratio of muon number to electron number at fixed energy varies as $A^{0.4}$, where A is the atomic weight of the cosmic-ray particle. Fluctuations as well as systematic errors in determination of the ratio lead to large uncertainties and limit estimates of the primary mass to a very crude level.

Another traditional approach is to measure as many properties of the same shower as possible. The object is to provide redundancy to overcome ambiguities due to the large fluctuations combined with uncertainties in the simulations needed to interpret the measured properties of the showers. The EASTOP array above the Gran Sasso Underground Laboratory in Italy, with its central hadron-muon calorimeter is one contemporary example of such an experiment. Another is the KASCADE array being constructed at Karlsruhe. Some detectors combine a surface array with a deep detector of large area to measure simultaneously the shower size at the surface (mostly the dominant electron/positron component) and the signal from high-energy muons in the shower core. Because these muons are produced high in the atmosphere, they carry information from closer to the primary particle. Two detectors currently doing this kind of experiment are EASTOP/MACRO at Gran Sasso (~3-TeV muons) and SPASE/AMANDA at the South Pole (~0.3-TeV muons).

In all air-shower experiments, fluctuations in development of the secondary cascades present a fundamental difficulty for making an inference about the primary particle. Problems of fluctuations are particularly severe for small showers with energies characteristic of the knee region of the spectrum (10^{14} to 10^{17} eV). This is because the showers are past maximum development, so fluctuations in early stages of development (e.g., point of first interaction) lead to large fluctuations in what is observed at the ground, which samples the tail of the shower. Detectors that provide an image of the Cherenkov light emitted by showers can give an additional constraint by making possible a measurement of the shower maximum. A new example of such a detector is DICE (Dual Imaging Cherenkov Experiment). Another new experiment is HEGRA, which combines measurements of electrons and low-energy muons in the shower front with a measurement of the Cherenkov light. Characteristics of some ground-based detectors are listed in Table 4.2.

4.4 Simulations

Techniques for the simulations that are necessary to interpret air-shower experiments 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. Several computer codes designed for this purpose have been developed recently. It has been demonstrated

Table 4.2 Air-Shower Experiments for Study of Composition at the Knee

Name	Technique	Energy Range (eV)	Running Since
DICE/CASA-MIA	Imaging Cherenkov plus muon/electron	10^{14}-10^{16}	1994
HEGRA	Imaging Cherenkov plus muon/electron	10^{14}-10^{16}	1994
EASTOP/MACRO	TeV muon/electron	10^{14}-10^{16}	1990
SPASE/AMANDA	0.3 TeV muon/electron	10^{14}-10^{16}	1994
KASCADE	Multiparameter Extensive Air-Shower (EAS) array	10^{14}-10^{17}	1996 (?)

that air-shower measurements of the type described above have the sensitivity to determine the energy dependence of the gross features of composition, certainly the ratio of light nuclei (the primordial elements hydrogen and helium) to heavy nuclei (carbon and heavier elements). There is, however, significant uncertainty in the particle physics input needed to carry out these simulations, especially the behavior of fast secondary particles. Such particles are outside the acceptance of the highest-energy colliding beam detectors, but they have the dominant impact on the development of atmospheric cascades. This uncertainty leads to ambiguities in the interpretation of measurements.

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. Achieving this large overlap between direct and indirect measurements will remove ambiguities in the interpretation of indirect experiments that arise from uncertainties in the input to the simulations. Extending direct measurements in energy to 10^{15} eV thus not only will resolve the uncertainty surrounding a proton cutoff below 10^{14} eV, but also will normalize the interpretation of the measurements needed to determine the energy dependence of the major groups of nuclei past the region of the knee of the spectrum (i.e., up to $>10^{16}$ eV).

5

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 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 total absorption calorimeter (apart from a negligible fraction of energy lost to neutrinos and a small fraction remaining in the shower at the ground). The fact that the whole shower is detected greatly reduces ambiguities due to fluctuations in development.

A high-energy nucleus enters the atmosphere and initiates a shower of particles 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. The energy spectrum is formed by plotting the number of showers as a function of energy, after correcting for the energy-dependent acceptance of the detector.

Depth of maximum (X_{max}) depends both on energy and on primary mass. For a given mass the average value of X_{max} increases at a rate proportional to the logarithm of the primary energy, and for a given energy it changes in proportion to the logarithm of $1/A$. The distribution of depth of maximum for showers with similar energies is therefore sensitive to the composition of the primary cosmic radiation. The mass resolution is, however, extremely crude. This is a consequence of large fluctuations and dependence on Monte Carlo simulations in an energy region several orders of magnitude higher than the energies for which the relevant cross sections can be measured at accelerators. For these reasons, in this energy range the composition is generally classified into two groups: protons and helium on the one hand and all heavier elements on the other. Note, however, that this division corresponds to primordial elements from the Big Bang (p and He) and to elements synthesized during stellar burning. Thus it is still of great astrophysical significance.

- Continued study of the hadronic physics input to the cascade simulations is essential for proper understanding of the results obtained with large air-shower detectors.

5.1 Spectrum

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.

Air-Shower Detection of Populations with Different Energies

Four large, ground-based air-shower experiments have measured the spectrum above 10^{17} eV: the Fly's Eye, the 10-km^2 Haverah Park detector in the United Kingdom, the 18-km^2 Yakutsk array in the former Soviet Union, and the 100-km^2 AGASA array in Japan. All the arrays except for the Haverah Park Array are still in operation. A consistent picture is emerging that may indicate two populations, one dominant below $\sim 3 \times 10^{18}$ eV and the other (possibly extragalactic) dominant above that energy. The signature for a new, higher-energy population is the flattening of the spectrum, which can be seen as the spectrum of the higher-energy population emerging from the background of lower-energy particles (see Figure 5.1).

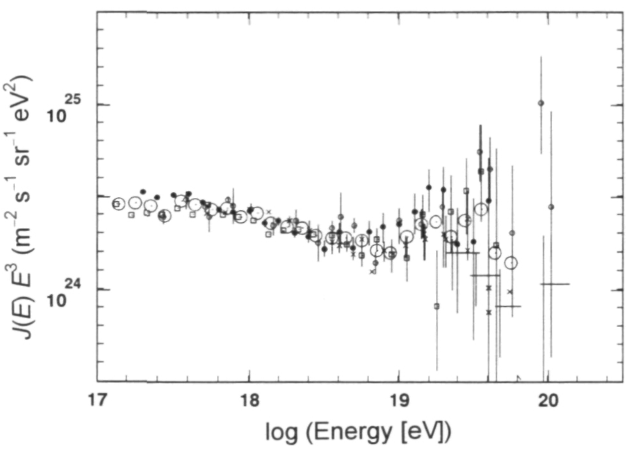


Figure 5.1 Summary of measurements of the cosmic-ray spectrum above 10^{17} eV from the Haverah Park, the Yakutsk, the stereo Fly's Eye, and the Akeno experiment. All spectra are normalized to the stereo Fly's Eye, result at around 10^{18} eV (Akeno Collaboration, *Astroparticle Physics*, Vol. 3, p. 105, 1995).

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: The measured spectrum (see

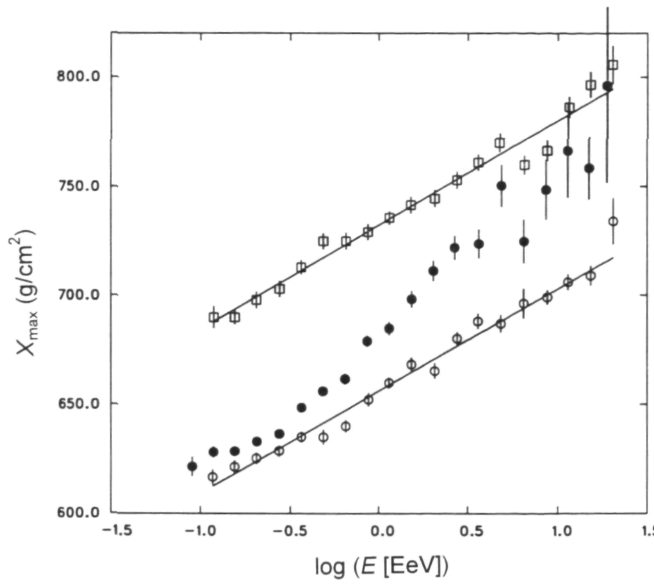


Figure 5.2 The Fly's Eye measurement of the depth of shower maximum as a function of shower energy (filled circles). The open boxes show a simulation based on the assumption that all primaries are protons. The open circles represent another extreme assumption, that all primary nuclei are iron. Note the apparent transition from a large fraction of heavy nuclei at 3×10^{17} eV to a dominance of protons at 10^{19} eV. The transition may correspond to the flattening of the spectrum below 10^{19} eV in Figure 5.1.

Figure 5.1) can be described by two power laws, with a change in spectral slope around 3×10^{18} eV. Given the low cosmic-ray flux of ~ 0.1 (km^2 sr years)$^{-1}$, there is not sufficient sensitivity to gather enough of the rare events that occur around 3×10^{19} eV within a reasonable period of time to study the spectrum with precision. For this reason, data obtained with a single Fly's Eye are used to extend the spectrum to somewhat higher energy.

5.2 Composition

Comparison of distributions of X_{max} measured in stereo with simulations (see Figure 5.2) 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 therefore particularly important 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, as illustrated in Figure 5.1. 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. Indeed, the presence of two populations of particles is not the only possible interpretation of the data in this region, and the problem requires further study.

The Greisen-Zatsepin Energy Cutoff

Cosmic rays with energies $>5 \times 10^{19}$ eV interact with the 2.7 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^{9} years (300 Mpc), no matter how high its initial energy. A cosmic ray of large mass would be reduced to protons in about the same time through photodisintegration. If the highest-energy cosmic rays come from a distribution of sources at cosmological distances, then the spectrum should not extend beyond a maximum energy. This is the behavior predicted by Greisen and Zatsepin soon after the discovery of the background radiation by Penzias and Wilson. The recent observation of two events with energy in excess of 10^{20} eV becomes especially interesting in this context because the events must be from sources that are close to Earth by cosmological standards.

5.3 The highest-energy events

A straight-line extrapolation of currently measured energy spectra (Figure 5.1) to higher energy predicts that there should have been six monocular events at Fly's Eye and a similar number at AGASA above 10^{20} eV, whereas only two events above this energy have been seen with both detectors. Could this be the first evidence for the Greisen-Zatsepin cutoff (which specifies that particles from very distant regions of the universe should not be able to arrive at Earth with energies greater than 5×10^{19} eV)? The cutoff would, for example, be expected to apply if the highest-energy particles were accelerated in distant, powerful radio galaxies, quasars, or active galactic nuclei. A measurement of the shape of the cosmic-ray spectrum and mass composition in this energy region would give information about the spectrum of particles accelerated at such sources (e.g., spectral shape and maximum energy) and the distribution of source distances.

For a cosmic-ray nucleus in a magnetic field B (in microgauss), the Larmor radius in kiloparsecs is

$$R = E_{18}/(Z\,B) \qquad (3)$$

where E_{18} is the total energy of the nucleus in units of 10^{18} eV and Z is 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.

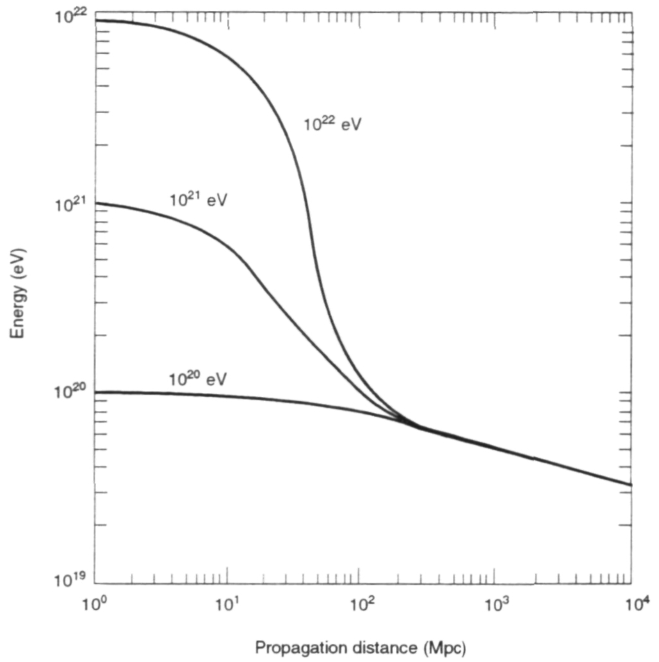


Figure 5.3 Energy of a proton as a function of the distance it propagates through the microwave background radiation that fills space. Ten megaparsecs (Mpc) is approximately 30 million light-years. The three curves correspond three different initial values of the proton energy, as shown.

In view of the evidence for a cutoff mentioned above, it is intriguing that two events of extremely high energy have been seen, one at Akeno and one at Fly's Eye. These both have energies above the microwave cutoff. If they have an extragalactic origin, they must come from relatively nearby, as illustrated in the curves in Figure 5.3. In particular, the highest-energy event (3×10^{20} eV), observed by the monocular Fly's Eye detector, must have had a path length of about 10^8 light-years or less, which corresponds to a cosmological redshift of $z < 0.01$, much closer than typical quasars and active galaxies. The profile of the highest-energy event is most like that of a shower initiated by a nucleus, but the shower could also have been generated by a proton or photon. Its incident direction points toward the antigalactic center. This is more than 90 degrees away from known nearby active objects such as M87 (an active galactic nucleus), Centaurus A (a galaxy with evidence of violent explosions), or M82 (a star-burst galaxy). Previously unseen sources or unexpectedly high intergalactic magnetic fields may be required to account for the fact that these events do not point back to the most likely sources of such high-energy events.

The highest-energy cosmic ray has about 50 joules of kinetic energy, a macroscopic energy in a microscopic particle. The process by which acceleration to such an energy can occur is completely unknown. These cosmic rays most likely come from outside our galaxy. Their radius of curvature in the extragalactic magnetic field is probably large compared to the proximity of the possible sources so that they should point to their origin. An astronomy with charged particles is now possible. By using modern technology, detectors can be built that can collect a significant sample of cosmic rays with energy greater than 10^{20} eV. It will then be possible to identify the sources with previously known astrophysical objects or to establish the existence of new sources that are not visible in other forms of radiation.

5.4 Future prospects

The high-resolution data on composition obtained with the stereo Fly's Eye cover the energy range from about 10^{17} to 10^{19} eV. Further studies are needed at both ends of this range. There are proposals to bridge the energy range between 10^{16} and 10^{18} eV, including both large ground arrays and extension of the air fluorescence technique to lower energy. One possibility is a coincidence experiment with CASA-MIA and the High-Resolution Fly's Eye.

There is also intense exploration of the possibility of how best to extend measurements up to 10^{20} eV and beyond with good statistics, which is international in scope. Because of the variety of experiments already in place at Dugway proving ground, including both the Fly's Eye and the Chicago-Michigan experiment, this site is a focal point for such activity.

Several large-aperture detectors are being considered. The High-Resolution Fly's Eye detector that is currently under construction, will, when fully instrumented, collect about 400 events per year above 10^{19} eV. The planned Japanese Telescope Array (a prototype version is under construction) is designed to collect between 1,500 and 2,000 well-measured events per year in the same energy region. Efforts are under way to develop the next-generation detector, which combines detection of air fluorescence with electron and muon arrays. Simulations show that such a hybrid giant array will have the collection power and superior energy and mass resolutions to detect and measure the parameters of the highest-energy cosmic rays. The idea of constructing two giant arrays, each with 5,000-km^2 area, one in the Northern Hemisphere and the other in the Southern Hemisphere, is being discussed. If realized, such a project would yield a total of 10,000 events per year above 10^{19} eV and perhaps 100 per year above 10^{20} eV, depending on the spectrum.

A full-scale design study for giant air-shower arrays was conducted at Fermilab during the first half of 1995. This study examined all aspects of giant arrays, scientific as well as technical and calculational.

- 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 and mass composition above 10^{19} eV can be measured with much better statistical accuracy and precision to determine the origin of these particles. Construction of the High-Resolution Fly's Eye and, beyond that, a next-generation giant detector to study cosmic rays of the highest energy, is needed to achieve these goals.

6

Very-High-Energy Gamma-Ray and Neutrino Astronomy

Wherever cosmic accelerators generate high-energy protons and nuclei, there is the potential for production of secondary pions, which produce both photons (from π^0) and neutrinos (from $\pi^{\pm}$) when they decay. Accelerated electrons will radiate only γ rays, most often through synchrotron or inverse Compton emission. Because photons and neutrinos travel in straight lines, undeflected by magnetic fields, they can be used to map the regions in which cosmic rays are produced and interact. Thus, photons and neutrinos are remote probes of cosmic-ray origin.

Whether specific cosmic acceleration processes can be traced in this way depends on the distance and power of the particular accelerators and on the distribution and density of matter in the acceleration regions. Photons are also produced by radiative processes from electrons, whereas neutrinos are not. Thus, the neutrino-to-photon ratio is in principle sensitive to the relative intensity of electrons and ions. Neutrinos and photons are also complementary probes of the source region, since photons can easily be absorbed by matter or radiation within the source or by the intergalactic infrared photon background, whereas neutrinos cannot. Table 6.1 illustrates these relations.

For the purposes of this report, *very-high-energy* (VHE) is defined as greater than 30 GeV, the effective upper limit of space γ-ray telescopes. The discussion here is limited to ground-based γ-ray and neutrino astronomy in the VHE region. Whereas γ-ray astronomy has achieved observational status, neutrino astronomy at these energies is still largely in the future. The reason is that the cross section for neutrino interaction in matter is very weak. Thus, very large detectors at great depths are required to detect neutrinos while filtering out background radiations.

Table 6.1 TeV Observations

Gamma Rays	Neutrinos	Conclusion
Yes	Yes	Hadron progenitor; low γ–ray absorption
Yes	No	Electron progenitor
No	Yes	Hadron progenitor; high γ–ray absorption
No	No	Not a high-energy accelerator (or source too transparent)

6.1 Scientific potential

6.1.1 Galactic sources

Since photons of energy 1 TeV or greater are almost inevitably the product of the interaction of a progenitor particle of even greater energy, the observation of sources of TeV γ rays is proof that charged particles (ions or electrons) are being accelerated to higher energies in these same sources. The extent to which these charged particles escape from the source regions to become cosmic rays needs to be investigated for each type of γ-ray source.

Of the three well-established sources of TeV γ rays, two (the Crab Nebula and PSR1706-44) are pulsar-driven supernova remnants. The γ rays from such supernova remnants with filled synchrotron shells most probably originate in the inverse Compton interactions of relativistic electrons with their own synchrotron photons or with other sources of soft photons, which include the 2.7 K microwave background and infrared radiation from dust (Figure 6.1).

Observation of TeV photons from a small number of supernova remnants is confirmation that electrons are efficiently accelerated by a mechanism that is somehow powered by the spin-down of a young pulsar. Since the acceleration site for the relativistic electrons in these cases is located deep within the supernova remnant, it is not clear what fraction will escape into interstellar space without severe energy losses.

The observation of γ rays from shell-type supernova remnants, those without synchrotron nebulas, would be a direct test of theories of shock acceleration of nucleonic cosmic rays. In contrast to electron acceleration in supernova remnants with filled synchrotron shells, acceleration of cosmic rays in shell-type remnants is expected to occur at the outer blast-wave shock. When the supernova ejecta have swept up a comparable amount of interstellar gas (the so-called Sedov phase), γ rays will result from the decay of π^0-particles produced in the interaction of the accelerated cosmic rays and the swept-up gas. This will occur at radii of a few parsecs and within a few hundred years after the outburst, depending on the density of the local interstellar medium. The hard spectrum of accelerated charged particles in the supernova remnant will result in a correspondingly hard spectrum of cosmic rays, which may turn over at energies beyond a few TeV. The observed galactic cosmic-ray spectrum will be softer since the cosmic rays will have selectively lost their more energetic particles because of their shorter trapping time in the galaxy.

The observation of extended γ-ray sources, such as supernova remnants, at MeV to GeV energies is limited by the background of diffuse, galactic plane radiation. At TeV energies, the most serious background radiation comes from the cosmic electron flux; however, the signal-to-noise ratio is more favorable because of the relative flatness of the predicted γ-ray flux. Such a hard spectrum is expected because the production occurs in the vicinity of the accelerator where the cosmic rays presumably have the E^{-2} spectrum characteristic of shock acceleration.

At energies greater than 1 TeV, the γ-ray fluxes are predicted to be of order 10^{-11} to 10^{-12} photons cm^{-2} s^{-1} for distances of 1 kpc; such remnants might have angular diameters of 0.5 degree. The Tycho supernova remnant, for example, is predicted to have a flux at about the level of 0.1 that of the Crab Nebula. These predicted fluxes are well within the sensitivity ranges of existing and planned ground-based detectors. A similar flux of neutrinos would be expected, but a detector of 10^6-m^2 effective area would be needed to detect it.

6.1.2 Extragalactic sources

One of the major successes of the Compton Gamma-Ray Observatory (CGRO) has been the detection of MeV-GeV γ-rays from more than 40 active galactic nuclei (AGN). Many of them give off more energy in the γ-ray bands than at any other frequency, emphasizing that particle acceleration must be accommodated in any model of these sources. Indeed, AGNs have been suggested as sources of an extragalactic

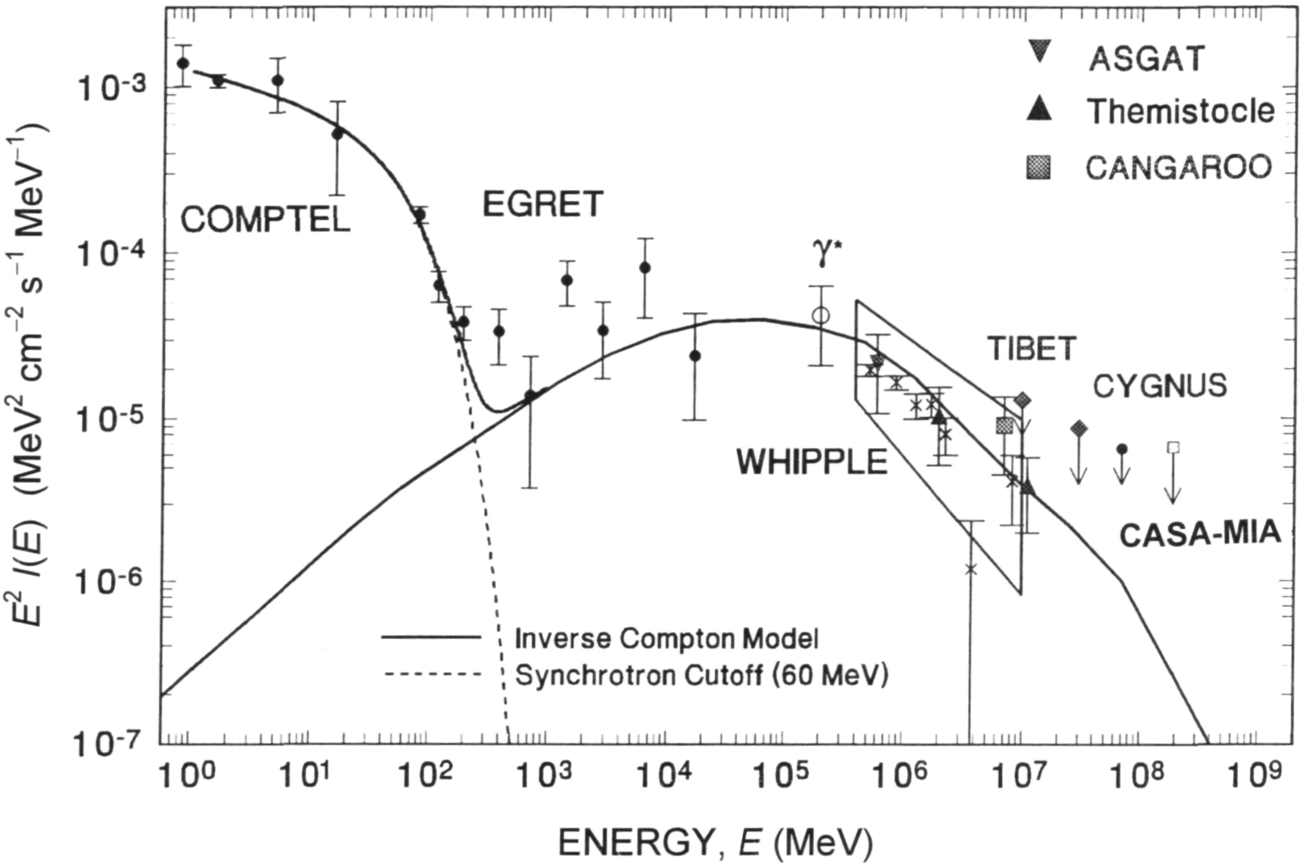


Figure 6.1 The high-energy γ-ray spectrum of the Crab Nebula. The observations in the left half of the figure come from the COMPTEL and EGRET experiments on the Compton Gamma-Ray Observatory. The points and upper limits on the right are a composite of observations from ground-based γ-ray experiments. The lines are predictions of the Compton synchrotron model of De Jager and Harding.

component of the observed cosmic radiation in the energy region around 10^{19} eV and above.

The AGNs detected by EGRET up to energies of 10 GeV all have flat spectra and are variable on short time scales. They all belong to an AGN subclass called blazars. Most AGNs are observed to emit relativistic jets of particles extending vast distances into intergalactic space. Blazars are believed to be AGNs with a jet pointed in our direction.

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; it is also clear that this AGN is the source of ongoing violent activity on short time scales (Figure 6.2). TeV γ rays from another nearby AGN have also been reported very recently. Although Markarian 421 is an unusually nearby AGN (at a distance of 400 million light-years), it is one of the weakest; the reason that it is detected, whereas other, more distant, more powerful AGNs are not, may well be that the TeV γ rays suffer absorption in intergalactic space through interaction with background infrared photons. If so, this would imply that all of the AGNs may have significant very-high-energy components but that only Markarian 421 is close enough to be detectable with currently available γ-ray telescopes.

It is an open question whether the progenitors of γ rays in AGNs are electrons or protons. If they are protons, then neutrinos from

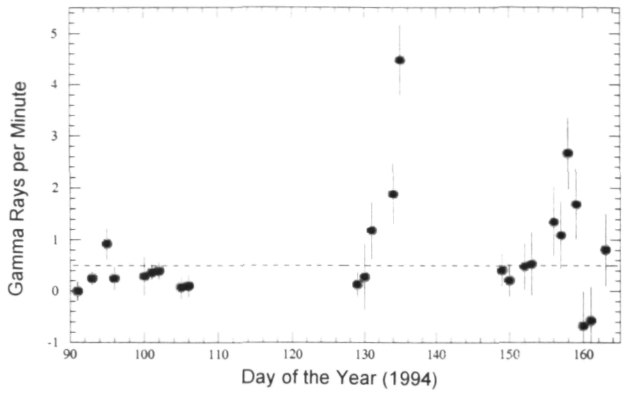


Figure 6.2 Observations at the Whipple Observatory of the 300-GeV γ-ray flux from the blazar Markarian 421 in April through June 1994. The dotted line is the extrapolation of the mean flux recorded in the previous 2 years. The gaps in the data taking correspond to bright Moon periods. One day after the highest flux recorded here (May 15), the ASCA X-ray satellite recorded a flux 20 times the quiescent level of Markarian 421.

the decay of charged pions would be detectable in a sufficiently large detector.

A particularly interesting situation for neutrino astronomy arises if AGNs accelerate particles in their inner regions near the central black hole that may provide the ultimate source of power for these objects. In this case, γ rays would probably not escape from the central regions, but would be degraded by interactions with the ambient electromagnetic radiation to the X-ray band and below. Neutrinos, on the other hand, would emerge directly from the central region because of their weak cross section for interaction. In some models of AGNs, the intensity of the neutrinos from the accumulation of all such sources would be detectable in the neutrino telescopes currently under construction.

Thus, astronomy at TeV energies offers a unique probe of the physical processes in the strong field limit of general relativity (i.e., near the Schwarzschild radius). The latest Hubble Observatory measurements give a strong indication of a massive black hole at the center of M87, an object that may be similar to Markarian 421 in many ways but differs in that the jet is not pointing directly toward us. In addition, M87 is only 50 million light-years away, some eight times closer than Markarian 421. This will be an interesting object to study with a combination of γ-ray and neutrino detectors. If there is significant particle acceleration near the central black hole with reabsorption of produced photons, then one would see high-energy neutrinos, but little or no high-energy γ radiation.

6.2 Detection techniques

The motivation for ground-based γ-ray astronomy is the need to overcome the very low intensity of signals at high energy with detectors having larger effective areas than can be deployed in space. This is similar to the use of large arrays on the ground to study cosmic-ray cascades in the atmosphere. Indeed, one way to search for γ rays is to use air-shower arrays. The γ ray interacts in the upper atmosphere to produce an electron pair and subsequently an electromagnetic cascade. Arrays designed for γ–ray astronomy emphasize good angular resolution, so point sources will stand out more readily above the isotropic background of cosmic-ray showers. They also should have the ability to reject showers with large numbers of muons to reject hadronic background.

The confirmed VHE γ-ray sources mentioned above have been observed with atmospheric Cherenkov telescopes. The concept is to detect the Cherenkov light emitted by the numerous relativistic particles near shower maximum. This allows small showers with energies in the TeV range and below to be studied even though such small showers are highly attenuated at the surface.

Large, relatively crude optical detectors on the ground can focus this light to photomultipliers which permit the signature of the event to be recorded. Arrays of such detectors can be used to distinguish the signature of the electromagnetic cascade from the large background of air showers from cosmic rays.

Table 6.2 Major Ground-Based γ-Ray Experiments

Group	Location	Technique	Equivalent Aperture (m)	Threshold Energy (GeV)	Status
Whipple	Arizona, United States	Imaging, stereo	14	200	Operational
CANGAROO	Australia	Imaging, stereo	7	500	Operational
HEGRA	La Palma, Spain	Imaging, multiple	7	500	Coming on-line
Durham	Australia	Imaging plus	14	50?	Coming on-line

Neutrinos interact weakly, so very large effective detector volumes are needed for neutrino astronomy in a regime of low flux at high energy. Neutrinos are detected via the reaction in which the muon neutrino (or antineutrino) exchanges a charge with a quark and becomes a charged muon. Once produced, a muon with multi-TeV energy will travel distances of several kilometers in earth or water. The neutrino target volume is thus the area of the muon detector times the range of the muon. If the muon is detected via the Cherenkov light given off in the transparent water or ice, the target volume can then be billions of tons. The detectors are optimized for high energies where (1) neutrino cross sections are large and the muon range is increased, (2) the angle between the muon and parent neutrino is less than 1 degree, and (3) the atmospheric neutrino background is low.

6.3 Existing detectors

6.3.1 Gamma-ray telescopes (TeV energies)

There are currently more than 10 second-generation TeV atmospheric-Cherenkov γ-ray telescopes in operation (or about to come into operation); a second-generation telescope is defined as one that provides effective discrimination against the cosmic-ray background. Some of these are listed in Table 6.2. Telescopes of this genre have collection areas determined by the size of the Cherenkov light pool, generally about 30,000-50,000 m^2. Operation is possible only on clear, dark nights, and the best locations are mountain observatories in desert climates.

6.3.2 Air-shower detectors

At higher energies (>50 TeV) there have been significant advances in γ-ray detector sensitivity. There are now more than a dozen major air-shower γ-ray arrays in operation worldwide including the Cygnus experiment at Los Alamos, the CASA-MIA array at Utah, and the SPASE effort at the South Pole. The results at these high energies have been somewhat disappointing; despite the increased sensitivity of these experiments, early reports of the detection of 100-TeV signals from the X-ray binaries (Cygnus X-3, Hercules X-1, etc.) have not been confirmed. Emphasis in the operation of these arrays is now shifting to investigation of the composition of cosmic rays in the region of the knee of the spectrum.

A completely different experimental approach is provided by the MILAGRO experiment now under construction at Fenton Hill, near Los Alamos, New Mexico. The water-Cherenkov technology developed for the IMB experiment is combined with a conventional particle array to give a γ-ray experiment; the telescope is built around a large (existing) water reservoir with elements of the disassembled Cygnus array surrounding it. Because the water detector samples a large fraction of the surviving particles in the shower, the energy threshold for γ rays is low (<1 TeV) compared with conventional air-shower arrays, which have thresholds in the 50-TeV range. Some discrimination against hadron showers is provided by the deep-water detectors, which respond primarily to penetrating muons; however this is not useful near the threshold where only a few particles are detected.

The principal advantage of this kind of detector is that it can operate 24 hours a day, viewing the entire overhead sky in all weather; hence it is well suited for surveying the sky for both constant and transient sources around 1 TeV. It has also strong sensitivity to γ-ray bursts to energies as low as 100 GeV.

MILAGRO is being built by a consortium of U.S. institutions with funding from NSF and DOE; funding was approved in 1994 with completion expected in 1998.

6.3.3 Neutrino detectors

The direction of a muon-type neutrino can be inferred from the muon track produced when it interacts. For neutrino energy above ~3 TeV the angle between the muon and the parent neutrino is typically less than 1 degree. If, as in all proposed detectors for VHE neutrino astronomy, the muon is detected by its Cherenkov radiation in water or ice, then the muon track is reconstructed by mapping the Cherenkov cone as it passes through the detector. The arrival times and amplitudes of the Cherenkov photons, recorded by a grid of optical detectors, are used to reconstruct the direction of the radiating muon. The optical detectors are deployed like beads on long strings that carry the signals (see Table 6.3). It is necessary to record the muon direction with sufficient precision (i.e., sufficient to reject the much more numerous down-going cosmic-ray muons from the up-coming muons of neutrino origin) by using a minimum number of optical modules. Critical parameters are detector depth (which determines the level of the cosmic-ray muon background) and the noise rate in the optical modules (which will sprinkle a muon trigger with false signals). Sources of such noise include radioactive decays such as potassium decay in water, bioluminescence, and inevitably, the dark current of the photomultiplier tube. The experimental advantages and challenges are different for each experiment, and in this sense, they complement one another nicely. Each has its own approach to achieve neutrino detection with a minimum number of optical modules.

Table 6.3 Large Neutrino Detectors

Group	Location	Radiating Medium	Status [Planned]
DUMAND	Hawaii	Ocean	[3 strings 1995]
AMANDA	South Pole	Ice	4 strings, 1994 [plus 6 in 1995]
Baikal	Russia	Lake	Partial 1993 [complete 1995]
NESTOR	Greece	Ocean	[1 tower (168 sensors) in 1997]

6.4 Future Prospects

6.4.1 Gamma-ray astronomy

Ground-based γ-ray astronomy is now an established channel of astronomical investigation that effectively complements and extends observations from γ-ray telescopes in space. Only a small fraction of the sky has been surveyed by existing telescopes with high sensitivity. Advances can, and should, be made in the following areas:

1. The imaging telescopes that operate in the 100- to 1,000-GeV energy range must be extended so as to build on the successes achieved to date. The angular resolution, energy resolution and field of view of imaging telescopes can be improved by the use of more sophisticated electronic cameras.

2. With a major investment (by the standards of non-accelerator physics) the atmospheric-Cherenkov technique can be extended to energies as low as 20 GeV, where the sources detected by the EGRET experiment on the Compton GRO can easily be studied. The design of a new generation of telescopes is still a matter of debate, but the concepts that have been considered include arrays of optical reflectors of 10-m aperture, arrays of "heliostats" focused to a common detector as used in large solar arrays, a large fixed "Arecibo"-type optical dish, and so on. It is expected that space telescopes (e.g., GLAST, AGATE), will eventually extend into the 10- to 100-GeV decade of energy. It is unlikely that these missions will be launched before the end of the century, whereas it will be possible to build a Large Atmospheric Cherenkov Telescope in stages to overlap in energy with future space experiments.

3. Only a small portion of the southern sky can be seen from observatories in the Northern Hemisphere. The galactic center is a particularity interesting source with a possible potential to accumulate dark matter (hypothetical particles such as weakly interacting massive particles (WIMPs), neutralinos, and so on). The galactic plane can be best studied from a southern site.

4. In the energy range above 1 TeV the MILAGRO experiment will provide an "all-sky" monitor for transient sources and will extend the energy spectrum of steady sources detected by the atmospheric-Cherenkov telescopes. It should be completed as planned.

6.4.2 Neutrino astronomy: Kilometer-scale high-energy neutrino telescope

Several independent neutrino experiments with effective collection areas greater than 10^4 m^2 are in various stages of construction. In the optimum case, one or more of them could be taking data by 1996. It is important that both the DUMAND and the AMANDA experiments be completed so that a reliable estimate can be made of their relative sensitivities. Although these will be major telescopes, even the most optimistic predictions indicate that for TeV neutrino astronomy to be a truly viable discipline (e.g., on the same level as TeV γ-ray astronomy), a telescope with a collection area at least an order of magnitude greater will be required. The committee agrees with the conclusion of the Panel on Neutrino Astrophysics that a neutrino detector with an effective area of order 1 km^2 "might usher in the era of high-energy neutrino astrophysics." (*Neutrino Astrophysics: A Research Briefing*, National Academy Press, Washington, D.C., 1995). The scale of such a detector will require a coalescence of resources of groups and the formation of a truly international collaboration. It should be emphasized that both the largely U.S.-funded DUMAND and the AMANDA experiments are already international collaborations.

Both the DUMAND and the AMANDA experiments can, in principle, be scaled up to give a net collection area of 1 km^2. The cost of a kilometer-scale detector is estimated to be of the order $100 million; this is sufficiently large that the decision to proceed must be deferred until the results of the detectors now being built are in. Equally relevant will be the results from TeV γ-ray astronomy which will provide some realistic picture of the TeV photon sky.

7

Long-duration Ballooning

Long-duration ballooning (flights of 10 days or more) will have a significant impact on the scientific objectives discussed in this report. Long-duration ballooning techniques have been developed and are currently capable of supporting flights of 1- to 2-ton payloads for periods up to 2 weeks, with the potential for even longer flights. This development offers a near-space scientific mission capability with an order-of-magnitude improvement over traditional balloon flights. For many investigations, the effect of residual atmosphere is negligible, and the exposures rival those of the Shuttle/Spacelab.

This developing revolution in scientific research on balloons began with the solution of the manufacturing defects that plagued the program in the first half of the 1980s. The NASA conventional ballooning program is now enjoying unprecedented success; approximately 97 percent of the balloons flown over the past 6 years performed as expected. This balloon reliability has been accompanied by, and indeed enabled, the development of long-duration flight capabilities. The long-duration balloon program has performed extremely well up to the present with several circumnavigations of the Antarctic continent lasting from 9 to 14 days. A complementary capability in the Northern Hemisphere, which would approximately double the number of flights that could be supported each year, is being explored. Conventional balloon-borne payloads are being modified, and new payloads are being developed for long-duration flights to exploit the order-of-magnitude increased flight time that should produce results comparable to some space missions.

- The ability to fly significant payloads on long flights near the top of the atmosphere offers a great opportunity for access to space for a variety of high-priority cosmic-ray missions, as well as for investigations in other disciplines, such as solar, infrared, and γ-ray astronomy.

Conventional ballooning continues to provide the capability for 0.5- to 1.5-day flights. The semipermanent launch site at Fort Sumner, New Mexico, is routinely used for U.S. turnaround flights (i.e., those that occur during the few weeks in both spring and fall when the prevailing east-west high-altitude wind direction changes, leading to light and variable high-altitude winds). Fort Sumner is also used for winter flights between the fall and spring turnaround periods (i.e., October to May). Launches from the National Scientific Balloon Facility (NSBF) home base at Palestine, Texas, are limited to the summer months, when the stratospheric winds carry the balloons westward, so the flights can be terminated over the low-population-density regions of the western United States. Conventional balloons are also launched from remote sites in northern Canada and Australia—the site being optimized for science investigations, ease of recovery, and safety to populated areas. The more numerous conventional flights provide essential scientific opportunities as well as a platform for the development of payloads for spaceflight and for exposure on long-duration balloon flights.

7.1 Status of long-duration ballooning (LDB)

7.1.1 Southern Hemisphere launch sites

Four exploratory long-duration flights (5 to 14 days) were carried out during 1987 and 1988 (two each year) from Alice Springs, Australia, to South America. The experience gained during these flights set the stage for LDB development in Antarctica. Reliable capabilities for balloon tracking, command and telemetry communications, and maintaining stable altitudes for periods in excess of a week were developed and proven. A cooperative agreement with the NSF Office of Polar Programs, responsible for all U.S. activities in Antarctica, was initiated in 1988. NSF provides the logistics for the flights, including payload recovery, and NASA provides the launch services and flight operations, including tracking of the balloons.

The first circumnavigation of Antarctica with a heavy-lift balloon occurred in the 1990-1991 Austral summer. The flight trajectory and altitude profile are shown in Figure 7.1. The latitude of the trajectory deviated very little from the ~78 degree latitude of the launch site at McMurdo, because of the stable circumpolar wind pattern. The balloon essentially returned to its launch site after 9 days at its float altitude, which was remarkably constant due to the more or less uniform solar heating. Other circumnavigations have been carried out annually. Minimal ballasting is required to sustain the float altitudes because the Sun is always above the horizon and the temperature is therefore relatively constant. Typically, diurnal altitude variations of only a few percent result from the changes in solar heating as the Sun's declination angle varies between 11 and 36 degrees. More than one circumnavigation is technically feasible but, because recovery of the payload is often a programmatic requirement, termination must take place in an acceptable recovery area. Science payloads on the 800,000-m^3 (28 million cubic foot) balloons in standard use for conventional balloons flights were flown during the 1992-1993 and

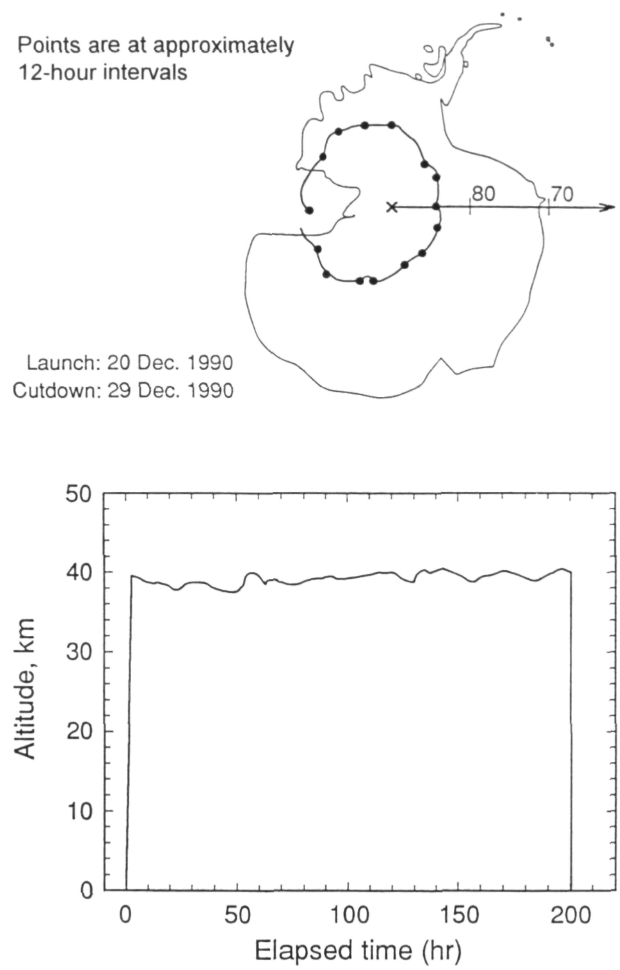


Figure 7.1. Flight trajectory (top) and altitude profile (bottom) for the first Antarctic circumnavigations of the pole.

1993-1994 seasons. Altogether, 11 LDB flights have occurred, 7 of them in Antarctica, and all were successful. One payload was lost in the ocean due to termination command problems (subsequently corrected) that were simultaneously being experienced by conventional balloon flights. This is an excellent record for an emerging launch capability that will provide an order-of-magnitude increase in observing power. It is now ready to be fully exploited scientifically.

A third LDB flight path in the Southern Hemisphere (after Australia-Brazil and Antarctica) could be realized by conducting flights between New Zealand and Argentina. At about 43 degrees south, Christchurch, New

Zealand, is conveniently located for the launch site, and Argentina's long north-south geographic situation is especially attractive for flight terminations in South America. Optimal wind conditions at this site do not occur at the same time as those in Antarctica, so this site could provide launch opportunities at a different time of the year. The geomagnetic rigidity cutoff at this latitude varies from about 1.4 to 10.2 GeV in contrast to the very low cutoffs accessible from Antarctica, something that might be of use to some specialized investigations.

7.1.2 Northern Hemisphere launch sites

The circumpolar flights in Antarctica have demonstrated that long-duration ballooning is a viable approach for cosmic-ray investigations, as well as for several other research areas. In order to mitigate the expected oversubscription for long-duration flights, the committee encourages NASA to develop a complementary ballooning capability elsewhere. In the Arctic, plans are being made to conduct the first long-duration flight in the Northern Hemisphere between Inuvik, Canada, and Greenland (in a westward direction) in July 1995. Logistics for the Inuvik launch site will be much less demanding than McMurdo, since Inuvik can be reached by highway. In fact, the new mobile balloon launcher used by NSBF can be driven to Inuvik. Furthermore, the recovery in Greenland can be based on using the large Hercules LC-130 for recovery, whereas the much smaller Twin Otter aircraft are generally used for Antarctic recoveries. Therefore, whereas payloads to be flown in Antarctica must be designed for quick disassembly into several pieces small enough to facilitate recovery with the Twin Otter, this restriction will not hold for recoveries on the Greenland ice sheet.

7.1.3 Future possibilities

Currently, LDB flights utilize the same zero-pressure balloons employed in conventional flights, and they have the same suspended weight limitations. In Antarctica, the maximum science payload is currently limited not by the balloons but by the launch vehicle to less than about 1,800 kg (1 kg = 2.2 pounds), for 2,700-kg suspended weight at liftoff. For midlatitude many-day-long flights, the science weight must be reduced to accommodate the ballast needed to limit the altitude excursions during day-night transitions. At latitudes above the Arctic and Antarctic circles, balloons remain in sunlight 24 hours a day and the ballast requirement is reduced. The extra weight can be used for more science payload. The Arctic and Antarctic launch seasons are 6 months apart so it is possible to conduct two long-duration balloon campaigns each year. Presently, only two flights are conducted each campaign, but if the demand grows beyond this capability, NASA could increase the number of flights that can be carried out annually. If the launch rate per site per season can be raised to 3 to 4 flights per campaign, it should be possible to launch a total of 6 to 8 flights per year. For these reasons, NASA should increase its capability to launch and recover heavier payloads from Antarctica and develop a launch capability for the Arctic.

7.2 Developing the payloads

By using this LDB capability, the potential for obtaining important new observations is very high. To exploit this capability fully, payload development funding must be increased.

Small flight projects by individual investigators are an important component of a healthy science program. They ensure stability and continuity in science programs, provide a foundation for future programs, and help to maximize the ultimate science return from bigger projects. They also provide an excellent training ground for graduate students who are then prepared for high-tech jobs. Within NASA the funding for balloon payloads comes from the research base. This base also provides support for retrospective data analysis, theoretical studies, ground-based and suborbital investigations, and advanced technology development, and it is very limited at present.

Funding is needed for new payloads and for extensive refurbishment of existing payloads to take advantage of the opportunity to answer many of the questions in cosmic-ray physics as well as other branches of space science.

The scientific objectives discussed in the earlier sections of this report that are amenable to investigations from balloons are outlined in Table 2.2. The table shows both what can, and therefore should, be done from high-altitude balloons and what ultimately will require exposures in space. There are two different reasons why exposures in space are required: (1) being above the atmosphere eliminates questions and uncertainties associated with atmospheric backgrounds and (2) an exposure of a year or more is needed to obtain the statistical level of data to permit precise answers to the scientific question at issue. In general, balloons offer significant scientific payoff in the near term, while making possible the testing and development of detectors needed for future spaceflights. The capability of recovery and reflight of payloads makes this a program where prudent risk can be taken and innovative technologies can be developed and tested. Adequate funding should be made available, not only for building the necessary hardware, but also for the full theoretical effort to understand the meaning of the results.

7.3 An example

The following is an example of the power of LDB to meet the scientific requirements for the next decade in cosmic-ray physics: Among the most important goals for cosmic-ray physics is measurement of the cosmic-ray spectrum and composition to an energy around 10^{15} eV. It has long been recognized that this knee in the energy spectrum holds a key to understanding the origin of galactic cosmic radiation, but study of this high-energy range has been slow because of the extremely low particle fluxes. The energy spectrum in this range is crucial to understanding cosmic-ray acceleration: an attractive and convincing theory has been developed for diffusive shock acceleration by supernova blast waves that naturally accounts for the essential observed features of most of the relativistic particles in the galaxy. Direct measurements, heretofore, have been possible only up to about 10^{14} eV, above which the data come from studies of extensive air showers (EAS). An LDB program known as GOAL, for Galactic Origin and the Acceleration Limit, has been proposed to study the composition of the most abundant components of cosmic rays in the energy range between 10^{14} and 10^{15} eV.

GOAL would be an intensive, sustained program of experiment and theory, and would involve a large number of researchers in the discipline. This could be conducted on a rapid time scale; essentially 5 years from start to end of mission.

7.4 Conclusion

For many years the scientific ballooning community has anticipated relatively long-duration balloon flights with payloads of substantial size and weight. With the recent success in Antarctica of flights that lasted from 9 to 14 days, this capability seems to be more or less at hand. Routine flights of such durations open new horizons for both cosmic-ray and other scientific investigations, and they enable experiments that could not previously even be considered for balloons. In addition, expansion of the demonstrated Antarctic capability to midlatitudes in both hemispheres should open the way for a variety of investigations that do not benefit from polar flights. As has been the case since the beginning of the space age, ballooning provides a low-cost development and test platform for many new instruments that will eventually be placed in orbit, as well as a training ground for new generations of scientists. In addition, long-duration balloon flights should now be competitive, for many investigations of importance to this community, with Shuttle or even free-flyer exposures. The opportunity before us now is to capitalize on the new LDB capabilities without losing the traditional advantages of conventional ballooning: low-cost, quick-turnaround flight opportunities in which experimenters can afford to accept the risk of using new technological approaches in conducting their investigations.

8

Interdisciplinary Aspects

8.1 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 for it to be 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 the 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.

8.2 Particle physics

Cosmic rays have been an important means of discovery for particle physics, and this source is likely to continue to produce new 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 higher (center-of-mass energy of around 40 TeV). This energy is beyond that of any accelerator planned for the next 20 or 30 years. In addition, the atmospheric neutrino beam provides a known neutrino source that can be used for searches for neutrino oscillations.

Hadronic interactions at ultrahigh energy 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 grams per square centimeter 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.

Neutrino oscillations Transitions in flight of neutrinos of one type into neutrinos of another type may occur if neutrinos have small but nonzero masses. This oscillatory behavior, if it exists, would be an important probe of the fundamental theory of elementary particles. Neutrino oscillations are characterized by a matrix of neutrino masses and mixing angles, where the angles represent the degree to which different "flavors" of neutrinos mix. The mixing occurs over a length scale that depends on the mass difference between different neutrino flavors, on the energy of the neutrinos, and on the medium in which the neutrino beam propagates.

In the past few years, underground experiments designed primarily to search for proton decay have given hints of neutrino oscillations with large mixing and with mass differences in the range $m_1^2 - m_2^2 \sim 10^{-2}\,\mathrm{eV}^2$. The anomalous observation is that the ratio of muon-type neutrinos to electron-type neutrinos is significantly different from the value of approximately 2 expected for neutrinos produced by cosmic-ray interactions in the atmosphere. The relation of these possible oscillations to proposed solutions of the solar neutrino problem with oscillations of ν_e into other flavors is not clearly understood, but it is the subject of much interest at present. There are proposals to follow up on these indications of oscillations among atmospheric neutrinos both with long-baseline experiments using neutrino beams from accelerators and with further underground experiments using the atmospheric neutrino beam.

All of the next-generation neutrino telescopes can check and extend these studies by measuring the zenith-angle distribution of neutrino-induced muons. A first step in this effort has been done with data from the Kamiokande nucleon decay detector. As the direction varies from near horizontal to vertically upward, the neutrino path length (distance from its production in the atmosphere to its interaction in the water or ice) varies from several hundred kilometers to the diameter of Earth. With sufficient angular resolution it may even be possible to observe oscillatory structure corresponding to oscillation lengths of several hundred to several thousand kilometers. At PeV energies, high-energy telescopes have some capability to detect and identify electron and tauon as well as muon neutrinos. This would open the possibility of studying oscillations over cosmic distances.

8.3 Antimatter

If antinuclei heavier than antideuterium 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 nonconservation 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 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 heavier antinuclei would open an interesting window on this question. Balloon-borne payloads on long-duration flights could reach this level of sensitivity. Exposure of a large payload in space could increase the sensitivity by two orders of magnitude to 10^{-9} in 3 years.

8.4 Dark matter

Another cosmic-ray window on cosmology relates to the dark matter, which probably constitutes more than 90 percent of the mass of the universe. The largest part of this dark matter must be a non-baryonic particle that is unknown in the Standard Model of particle physics, most likely a weakly interacting massive particle (WIMP). Annihilation of pairs of such particles in the halo of our galaxy could produce antiprotons, positrons, and photons, which could be detected by cosmic-ray experiments. In general, these end products provide a discovery potential, but astrophysical uncertainties (~10^2), particularly the time the WIMP is confined in the halo of our galaxy, prevent measurements from being utilized to set limits. This also means, of course, that the strength of a possible signal cannot be predicted accurately.

The most promising photon signal would be from monochromatic γ-ray lines, which could result from $\chi\bar{\chi} \rightarrow \gamma\gamma$ or $\chi\bar{\chi} \rightarrow V\gamma$, where χ is the WIMP (and $\bar{\chi}$ its antiparticle) and V is a heavy quark bound state. A successful search would require that the annihilation cross section be large; that there be some concentration of WIMPs (e.g., toward the galactic center); and that the backgrounds, currently not that well known, be favorable. Measurements over the range from 1 to 10^3 GeV will require a combination of techniques (ASTROGAM in the 10-GeV region and ground-based measurements with atmospheric-Cherenkov telescopes and air-shower arrays like MILAGRO at energies greater than 10 GeV).

Antiprotons could provide a more likely detection signal, especially those of very low energy (< 1 GeV), where the background of secondary antiprotons from interactions of cosmic rays in the interstellar gas is suppressed by kinematics. Improved measurements of these antiprotons are coming from the IMAX, CAPRICE, BESS, and HEAT balloon payloads. Even if an excess of antiprotons is observed, however, this by itself will not be a "smoking gun" for dark matter, since there is still too much uncertainty about antiproton production in cosmic-ray propagation.

WIMPs can interact with nuclei in the Sun or Earth and be captured, sinking to the core gravitationally. There they can annihilate in pairs to heavy quarks, and among the final annihilation products will be ordinary neutrinos which can be detected by large proton-decay or cosmic-ray detectors nearer the surface of Earth. The neutrino signals are of two types: (1) contained events in which the ν_e or ν_μ interacts with a nucleus in the detector and (2) throughgoing events in which a ν_μ interacts with rock outside the detector, making a muon that is identified as it passes through the detector. This means of detecting WIMPs has several advantages over looking for halo annihilation products, including more sensitivity to high-mass WIMPs, easier distinction of signal from background, and particularly event rates that are much more predictable for capture and annihilation in the Sun or Earth. Thus, meaningful limits can be set if no signal is seen. Of particular interest now as a dark matter candidate is the lightest supersymmetric particle, most likeiy a neutralino. Supersymmetry is the theoretical favorite for an extension of the Standard Model, and there are many planned searches for neutralinos. The underground detector Kamiokande has already eliminated a very small portion of the multiparameter space available for neutralinos. Its sensitivity was 770 m^2 years for Earth and 215 m^2 years for the Sun, but new detectors MACRO and Super Kamiokande will cover $\sim 10^3$ m^2, and those using strings of photomultipliers in deep water (DUMAND, NESTOR, NT-36) or Antarctic ice (AMANDA) are to be $\sim 10^4$ m^2, with the possibility of reaching $\sim 10^6$ m^2. With this last area, much of the useful neutralino parameter space can be covered.

The hypothesis that the dark matter of the universe includes a major component in the form of primordial black holes is still not verified or eliminated. The smallest black holes would have evaporated by now, and those evaporating in the present epoch would be about 10^{15} g. The existence of primordial black holes (PBH) can be inferred from the cosmic background γ radiation or the cosmic background of neutrinos, which would have accumulated from evaporation of the smaller black holes. However, this radiation could also arise from other causes so that at best an upper limit to the density can be deduced. The best possibility of direct detection comes from the observation of γ radiation in the final phases of black hole evaporation (Hawking radiation). In this case the duration of the bursts is a fraction of a second, with the precise decay scenario and time constant heavily dependent on the particle physics model assumed. The temperature of the PBH is $T = 10^{13}/M$ GeV, where M is in grams, and the luminosity of its radiation is α /M^2. As it loses mass toward the end of its life, T increases abruptly, and it can radiate all fundamental particles of rest mass less than a few times T. The final stages of evaporation are sensitive to physics up to the Planck scale and could hold important clues to the coupling of gravity and quantum theory. The CYGNUS air-shower array, which is sensitive to γ-ray bursts, has recently improved the upper limit on the local rate-density of evaporating PBHs by two orders of magnitude, and the recently authorized MILAGRO experiment (air-shower array plus water-Cherenkov detector), as well as the new generation of atmospheric-Cherenkov experiments, could improve that limit by another three orders of magnitude, increasing the possibility of detections.

The MILAGRO detector and the atmospheric-Cherenkov telescopes may have the sensitivity to provide vital information on another aspect of dark matter and consequently on the issue of neutrino mass. The connection arises because at present the model of dark matter that best fits the structure of the universe on all distance scales has about 5 percent baryonic dark matter; the rest is divided into about 75 percent cold dark matter (the non-baryonic particles discussed above) and 20 percent hot dark matter particles. The latter, in contrast to the former, were relativistic at the time they fell out of equilibrium in the early universe and are most likely neutrinos with mass, a characteristic they do not possess in the Standard Model. The required mass is ~5 eV, which may be that of one species or shared among two or all three light, weakly interacting neutrinos.

A "smoking gun" for this mixed dark matter scenario is the redshift at which the initial large galaxies formed, and that information is contained in the spectrum of redshifted starlight. Active galactic nuclei produce a spectrum of γ rays that can interact with that starlight, producing e^+e^- pairs (if the center-of-mass energy exceeds 1 MeV) and obscuring the AGN. By seeing at what γ energies between 10 and 10^3 GeV (the range MILAGRO and the atmospheric-Cherenkov telescopes cover) AGNs at various distances can be detected, the spectrum of starlight could be determined, provided there are enough nearby AGNs.

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, in which too few electron neutrinos, ν_e, from the Sun have been detected in four underground experiments (Homestake, Kamiokande, SAGE, and GALLEX). The favored scenario for explaining this deficit in terms of neutrino oscillations has $\nu_e \rightarrow \nu_\mu$, the muon neutrino, leading to the conjecture that the tau neutrino, ν_τ, has the 5-eV mass needed for dark matter. This conclusion ignores another cosmic-ray result, namely, that ν_e and ν_μ produced as decay products in the atmosphere are not detected in the expected ratio. The double ratio, to remove most calculational uncertainties, of the number of observed ν_μ's to ν_e's to their calculated fluxes is about 0.6, instead of unity in three experiments (IMB, Kamiokande, and Soudan II). This result can be interpreted also in terms of neutrino oscillations with $\nu_\mu \rightarrow \nu_\tau$ and requiring a very small mass difference between the two types of neutrinos. If this is correct, the ν_τ alone cannot be dark matter. Instead, either that role is shared between the ν_μ and ν_τ, each having a mass of ~2.5 eV (and where the deficit of solar ν_e's is because ν_e's oscillate to an unknown sterile neutrino), or all three weakly interacting neutrinos are nearly degenerate in mass (~1.7 eV), with $\nu_e \rightarrow \nu_\mu$ for the solar and $\nu_\mu \rightarrow \nu_\tau$ for the atmospheric neutrino deficits. The model where ν_μ and ν_τ masses are both 5-eV works especially well in fitting the structure of the universe on all distance scales. Since the pattern of neutrino masses can provide crucial clues to the more encompassing theory beyond the Standard Model, the importance of these cosmic-ray experiments to particle physics is great indeed.

Of less significance, but useful in learning about the mixings among neutrinos is the interplay of cosmic rays and supernovas. By studying the composition of cosmic rays it should be possible to determine whether the r-process of rapid neutron capture in a supernova explosion is responsible for most of the production of elements heavier than iron. If it is, then the ν_e - ν_μ and ν_e - ν_τ mixing angles are severely restricted. Otherwise the energetic ν_μ's and ν_τ's ($\langle E \rangle \approx 25$ MeV) produced in the supernova can convert to ν_e's, which have much higher energy than the thermal ν_e's ($\langle E \rangle \approx 11$ MeV). The higher-energy ν_e's, having a larger cross section, will reduce the neutron density via $\nu_e + n \rightarrow e^- + p$, diminishing heavy element formation.

Of great importance to cosmology and particle physics is the possible existence of topological defects left over from phase transitions in the early universe. For example, Higgs particles could play a significant role in the production of such defects. The simplest defect is the monopole, and the prolific production of these is such an issue that one of the main arguments for an inflation theory is that these get inflated away so that few or none could be observed by us now. If they are a small component of cosmic rays, they have distinctive features, such as their extreme ionizing power. Many experiments (e.g., MACRO) have and are looking for monopoles, because their discovery would be of such significance. The next simplest topological defect to the point-like monopole is the one-dimensional cosmic string. These could possess remarkable amounts of energy; hence, it has been proposed that they might be the means of accelerating very-high-energy cosmic rays. Of special interest in this regard is the highest-energy cosmic ray, 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, and cosmic strings could provide the explanation. This is clearly a motivation to pursue the study of the highest possible cosmic-ray energies.

There has been an excellent synergy between cosmic rays and particle physics. Initial cosmic-ray discoveries spawned much of particle physics, and the developments of particle physics, both in experimental techniques and in the physics itself, have aided and spurred further cosmic-ray work. As outlined above, the continued discovery potential in cosmic rays can aid considerably the further development of particle physics.

9

Recommendations

There are recent results in each of the three regions of the cosmic-ray energy spectrum shown in Figure 1.1 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. These opportunities are summarized in the following section.

9.1 Priorities

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 galaxy, possibly from shock acceleration in supernova remnants. 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 will require

- sensitive measurements of elemental and isotopic composition at higher energy, together with measurements of 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 electrons, positrons, and antiprotons to explore cosmic-ray transport in the galaxy, to search for possible exotic sources of cosmic rays, and to refine our understanding of the effects of the Sun and the heliosphere on particles in this energy range.

NASA's Explorer program provides the opportunity to make significant advances in these investigations through extended exposure of new instrumentation above the atmosphere. The International Space Station Alpha could also provide a platform for certain types of detectors, and cooperative experiments on foreign spacecraft should also be considered.

Balloon-borne investigations, particularly with long-duration balloons, are necessary to provide scientific returns on a short time scale and to develop the instrumentation needed for future spaceflights. Crucial for progress in the field is support of science payloads for the balloon program.

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 shown in Figure 4.1). 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 are now opportunities to make great progress here.

- Direct measurements of the composition and energy spectra of the individual species to significantly higher energy than that in existing measurements are required in order to explore and understand the knee region.

This is essentially the GOAL initiative to make use of the long-duration balloon program to extend direct measurements to 10^{15} eV. This is one of several outstanding scientific opportunities accessible to long-duration ballooning. Eventually, the large detectors required to extend the composition measurements to high energy should be lifted into orbit for even longer exposures outside the atmosphere.

- Extending the spectrum through the knee region to 10^{16} eV and beyond will require the use of ground-based detectors to overcome the very low intensities of these high-energy particles.

The exploration of higher energies will be carried out by hybrid air-shower experiments that have thresholds around 10^{14} eV. Direct measurements to 10^{15} eV are essential to provide an order of magnitude overlap in energy with the ground-based experiments, thus making possible an unambiguous interpretation of the indirect experiments.

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 will 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.

The first step in this program is to complete construction of the High-Resolution Fly's Eye and related detectors. This is essential for understanding the cosmic radiation in the high-energy region where there may be a transition from galactic to extragalactic sources or to particles accelerated in remote regions surrounding our galaxy. At the same time, we should move toward the goal of constructing giant arrays with sufficient collecting power to answer definitively the question of whether there is a cutoff of the cosmic-ray spectrum around 5×10^{19} eV due to propagation over cosmological distances through the cosmic microwave background. The excitement of this effort is highlighted by a few events with energies so great ($> 10^{20}$ eV) that they must have come from relatively nearby, even though potential nearby sources of such energetic particles are at present unknown.

Gamma-ray astronomy The most important goal in γ-ray astronomy is increased sensitivity over a broad energy range. This can be achieved by the development of existing atmospheric-Cherenkov telescope techniques in the 100- to 1000-GeV-energy range and their extension down to the 30-GeV range where they will overlap with space observations, including the exciting results of the Compton -Gamma-Ray Observatory. The MILAGRO detector, now under construction, will make complementary observations in the TeV range and above.

Neutrino astronomy While continuing with the construction of neutrino telescopes with acceptances of ~20,000 m^2 for >TeV neutrinos, it is also time to study the possibility of constructing a much larger detector with acceptance 0.1 km^2 or greater.

9.2 Theory

The scientific program outlined in this report is based primarily on initiatives to observe more intensively certain parts of the cosmic-ray spectrum and composition. In order to realize the full scientific potential of these initiatives, it is essential to have a strong parallel effort devoted to advancing our theoretical understanding of the phenomena.

Such a balanced effort will return many more scientific dividends than one without the support for theory.

For example, our interest in understanding the composition of cosmic rays in the region just below the knee has been considerably sharpened by advances in the theory of particle acceleration. Most scientists now believe that the bulk of cosmic rays below the knee are accelerated by strong blast waves propagating out from supernova explosions, but there are a number of ideas about the maximum energy produced by this mechanism and the efficiency of electron acceleration relative to that of ions. More theoretical work will be needed to interpret new data and establish the constraints placed on the theories by the data.

The committee recommends a long-term commitment for support of theoretical investigations in parallel with the experimental program in cosmic-ray physics. This commitment should include support for individual researchers and for groups, together with the requisite computer facilities and infrastructure. Concomitant with this support is the need to ensure that theorists are included at an early phase in the planning of major new observational and experimental programs, so that their expertise can be utilized in targeting critical observations.

9.3 Large international projects

At least three large ground-based cosmic-ray projects are in various stages of development. These include an atmospheric-Cherenkov facility for ground-based γ-ray astronomy in the energy range 30 to 300 GeV, a kilometer-scale detector for neutrino astronomy, and a pair of large cosmic-ray detectors (located in the Southern and Northern Hemispheres) for the study of the properties of cosmic rays with energies $\geq 10^{19}$ eV.

The cost of each of these projects will be in the range of $30 million to $100 million. Because of the great expense and the international interest in these projects, the most reasonable (and responsible) way to finance them is through international collaboration. Then the financial load on any given country is not too large.

In order to achieve this objective it is essential that the design, prototype development, and management of these projects be international from the outset. The example of the Superconducting Super Collider is to be avoided. In that project the design and management were established before international support was sought. There are excellent examples of international collaboration in the design and construction of collider detectors. For the case of the large cosmic-ray detectors the interest is equally widespread and the possibility of engaging scientists from every continent is possible.

It may be possible to enlist the help of international agencies such as UNESCO and groups such as the Megascience Forum organized by the Organization for Economic Cooperation and Development. One can also take the opportunity to involve countries that for various reasons are not now scientifically active. These include the countries of eastern Europe and the former Soviet Union, which have a long tradition in cosmic-ray physics. There are countries with powerful economies, principally in the Pacific region, that have not emphasized fundamental science. An effort should be made to involve these countries in large projects. Finally, one should try to engage scientists from South America and South Africa.

The fruits of genuine international collaboration will be not only the timely development of projects but also the furthering of international understanding in a small but significant way.

9.4 Interdisciplinary and interagency projects

Many of the efforts recommended here, including support of theory, fall across traditional disciplinary and agency boundaries. Methods for coping with the resulting institutional problems are evolving. They include the following:

- ad hoc committees established from time to time to give advice to the granting agencies;
- procedures for consultation among program offices in NASA, DOE, and NSF, as well as among different programs within each agency;
- national laboratories as focal points for certain investigations;
- location of several different, but related, experiments at the same site; and
- reports of the National Research Council Board on Physics and Astronomy (such as the present Report).

The committee does not see a panacea for the interdisciplinary nature of cosmic-ray physics. Indeed, as in many fields, the flow of science frequently outgrows missions defined in a particular era, and the most vibrant and dynamic activities often occur at the boundaries of established disciplines. The committee urges continuing attention to this problem and continued evolution of institutional support for these interdisciplinary scientific efforts.

9.5 Future directions

A field of science advances by a combination of theoretical and experimental efforts. A broad view of the support needed to make progress on the important scientific questions discussed in this report leads the committee to recommend the following:

- NASA should provide the opportunity to measure cosmic-ray electrons, positrons, ultraheavy nuclei, isotopes, and antiparticles in space.
- NASA, NSF, and DOE should facilitate direct and indirect measurement of the elemental composition to as high an energy as possible. Support of long-duration ballooning and support of hybrid ground arrays will be needed to accomplish this end.
- NSF and DOE should support the new Fly's Eye and provide for U.S. participation in the big projects on the horizon, which include giant arrays, ground-based γ-ray astronomy, and neutrino telescopes.
- NASA, NSF, and DOE should support a strong program of relevant theoretical investigations.

The implementation of this vision for cosmic-ray physics will lay the foundation for future advances and ensure that this remains a rich and productive field.

Glossary

γ: Gamma ray, a high-energy photon, a form of electromagnetic radiation.

ν_e: The electron neutrino, which is associated with the electron and radioactive decay and interacts with ordinary matter through the weak force.

ν_μ: The muon neutrino, which is associated with the muon and interacts with ordinary matter through the weak force.

π^0: The neutral pi meson, a light hadronic particle that decays most of the time into two γ rays.

ACE: NASA's Advanced Composition Explorer mission, scheduled for launch in 1997. ACE will perform a comprehensive analysis of the isotopic composition of the solar wind, solar energetic particles, and cosmic rays.

AESOP: Anti-Electron Sub-Orbital Payload, which is designed to measure cosmic-ray positrons and electrons.

AGASA: A 100-km^2 air-shower detector array located in Japan.

AGATE: A proposed high-energy γ-ray experiment in space.

AGN: Active galactic nuclei, a class of energetic centers of galaxies.

Akeno array: A giant air-shower detector array exploring energies above 10^{17} eV, located in Japan.

AMANDA: Antarctic Muon and Neutrino Detector Array, a muon and neutrino detector employing strings of photodetectors in holes drilled in the ice.

Ariel-6: A United Kingdom mission launched in 1978 that measured the composition of cosmic rays beyond the Fe Group ($Z \geq 30$).

ASCA: Advanced Satellite for Cosmology and Astrophysics, a Japanese mission for measuring cosmic X rays.

ASTROGAM: A proposed experiment that would have used the Astromag superconducting magnet facility on the International Space Station Alpha to measure high-energy γ rays.

BESS: Balloon-Experiment with Superconducting Solenoid, a Japanese-American experiment to measure cosmic-ray antiprotons and search for anti-helium.

Blazars: A class of AGN showing high variability in flux and polarization; a large fraction exhibits apparent superluminal motion, indicating relativistic flow.

CANGAROO: A Japanese imaging atmospheric-Cherenkov telescope located in Australia.

CAPRICE: A balloon-borne Cosmic Anti-Particle Ring-Imaging Cherenkov Experiment to measure positrons, antiprotons, and light isotopes below 3 GeV.

CASA-MIA: A densely instrumented air-shower array at the Dugway Proving Ground in Utah. The Chicago Air Shower Array detects all charged particles and the buried Michigan Array detects muons.

Cherenkov radiation: The light emitted by relativistic particles as they travel through a medium faster than the speed of light in that medium.

COMPTEL: The Compton Telescope experiment on NASA's Compton Gamma-Ray Observatory.

CRN: The Cosmic-Ray Nuclei experiment flown on Spacelab-2 to measure the composition of high-energy cosmic rays

CYGNUS: An air-shower array at Los Alamos National Laboratory used for ultrahigh-energy γ-ray astronomy.

DICE: The Dual Imaging Cherenkov Experiment.

DUMAND: The Deep Underwater Muon and Neutrino Detector.

EAS: Extensive air shower, a cascade of particles generated by the interaction of a high-energy cosmic-ray particle in the atmosphere.

EASTOP: The air-shower array located above the MACRO experiment at Gran Sasso National Laboratory in Italy.

EGRET: The Energetic Gamma-Ray Experiment Telescope, a γ-ray detector on NASA's Compton Gamma-Ray Observatory.

Fly's Eye detector: A giant air-shower detector array exploring energies above 10^{17} eV, located in Utah.

GALLEX: The European gallium solar-neutrino detector in the underground laboratory at Gran Sasso National Laboratory in Italy.

Geotail: A Japanese-American mission, launched in 1992, to measure particles and fields in Earth's magnetotail.

GeV: Giga-electron-volt, or 10^9 eV.

GLAST: A proposed large, high-energy γ-ray space telescope.

GOAL: Galactic Origin and the Acceleration Limit, a suggested initiative, involving a number of LDB flights, to study the composition of cosmic rays near the "knee."

Greisen-Zatsepin cutoff: A cutoff of the cosmic-ray spectrum around 10^{19} eV predicted by Greisen and Zatsepin as a consequence of interactions with the 2.7 K cosmic microwave background radiation. The cutoff occurs if the sources of the highest-energy cosmic-ray protons and nuclei are sufficiently distant.

GRO: NASA's Compton Gamma-Ray Observatory.

Gyroradius: The radius of curvature of the path of a charged particle moving in a magnetic field.

Haverah Park Array: A giant air-shower detector array that explored energies above 10^{17} eV, located in the United Kingdom.

HEAO-3: NASA's third High-Energy Astronomical Observatory, launched in 1979, which included two experiments to measure the elemental composition of cosmic rays with > 0.5 GeV/nucleon. The Heavy-Nuclei Experiment measured elements from Ca to U ($Z = 20$ to 92), while the French-Danish C2 experiment measured the elements from Be to Ni.

HEAT: The High-Energy Antimatter Telescope, a balloon-borne magnetic spectrometer designed to measure cosmic-ray positrons and electrons.

HEGRA: A complex array of air-shower detectors and atmospheric-Cherenkov telescopes designed primarily for high-energy γ-ray astronomy, operated by a German-Spanish collaboration, and located on La Palma in the Canary Islands.

IMAX: NASA's balloon-borne Isotope Matter/Antimatter eXperiment, which measured the abundance of antiprotons and H and He isotopes from 0.2 to 3 GeV/nucleon in a 1992 balloon flight.

ISEE-3: NASA's third International Sun-Earth Explorer was launched into a halo orbit about the first Lagrangian point in 1978. ISSE-3 included the first high-resolution instruments to measure cosmic-ray isotopes.

ISOMAX: NASA's balloon-borne ISOtope MAgnet eXperiment, which is designed to measure the abundance of ^{10}Be and other light isotopes at energies above 1 GeV/nucleon.

ISSA: The International Space Station Alpha.

JACEE: The Japanese-American Cooperative Emulsion Experiment, a series of balloon flights to measure the primary cosmic radiation around 100 TeV.

KASCADE: The Karlsruhe (Germany) air-shower experiment.

Lagrangian: The mathematical function from which the equations of motion for a system of particles and fields can be derived.

Lagrangian points: The five stable gravitational positions in the vicinity of two large orbiting bodies.

LDB: Long-duration ballooning.

LDEF: Long-duration exposure facility, a NASA satellite that orbited for several years to test the space environment and was retrieved by the Space Shuttle.

Lorentz factor: The ratio of the total energy of a particle to its mass. A large Lorentz factor means the particle velocity is nearly equal to the velocity of light in vacuum.

Luminosity: The energy radiated per time from an object.

MACRO: The joint Italian-U.S. Muon and Cosmic-Ray Observatory in the Gran Sasso National Laboratory in Italy.

MASS: The balloon-borne Matter-Antimatter Superconducting Spectrometer, a joint Italian-U.S. project.

MIA: See CASA-MIA.

MIDEX: The middle-class Explorer missions in NASA's astrophysics and space physics programs.

MILAGRO: A detector consisting of an instrumented pool of water surrounded by an air-shower array, designed for ground-based γ-ray astronomy.

Mir: The Russian space station.

MSU: Moscow State University.

Negatron: A term used to distinguish the negatively charged electron from its antiparticle, the positron.

NESTOR: A joint Greek-Russian deep underwater detector designed for high-energy neutrino astronomy. Named after the ancient king of Pylos, it is to be deployed in the Aegean Sea.

Neutralino: Hypothetical, spin-one-half, neutral particle, predicted by supersymmetry as the counterpart of the photon, the Z^0, and the neutral Higgs boson.

PeV: Peta-electron-volt, or 10^{15} eV.

RICH: Ring-Imaging Cherenkov, a detector that images the ring of Cherenkov radiation from high-energy particles.

Rigidity: The ratio of a particle's momentum to its electrical charge.

SAGE: The Soviet-American Gallium Experiment, a neutrino detector collaboration between the former Soviet Union (now with Russia) and the United States.

SAMPEX: NASA's Solar, Anomalous, and Magnetospheric Particle Explorer, the first of the small Explorer-class missions, launched in 1992 to study solar energetic particles, "anomalous" and galactic cosmic rays, and magnetospheric heavy ions and electrons.

Schwarzschild radius: The radius around a massive object at which the free-fall velocity is equal to the velocity of light.

Sokol: A calorimeter detector used to measure the primary cosmic-ray spectrum and composition in the multi-TeV energy range. Flown on the Russian Cosmos satellites.

SPASE: The South Pole Air Shower Experiment.

Tauon: A lepton, also denoted τ, related to the electron, but much more massive.

TeV: Tera-electron-volt, or 10^{12} eV.

THISTLE: A balloon-borne Tracking Heavy Isotope Spectrometer Telescope for Low-Energy cosmic rays.

TIGER: The Trans-Iron Galactic Element Recorder, a balloon-borne instrument funded by NASA designed to measure cosmic-ray nuclei with $26 \leq Z \leq 40$.

TRD: Transition Radiation Detector.

TREK: A large-area detector flown on the Mir space station to measure the composition of cosmic-ray nuclei with $Z > 50$.

Type I and II supernovas: A spectroscopic classification of supernovas that indicates the presence (II) or absence (I) of hydrogen lines near maximum light emission. This classification divides the progenitor stars into those that have (I), or have not (II), shed their outer hydrogen layers before they explode as supernovas.

Ulysses: A NASA/European Space Agency mission, launched in 1989, with a trajectory that took the spacecraft out of the ecliptic plane, over the Sun's poles.

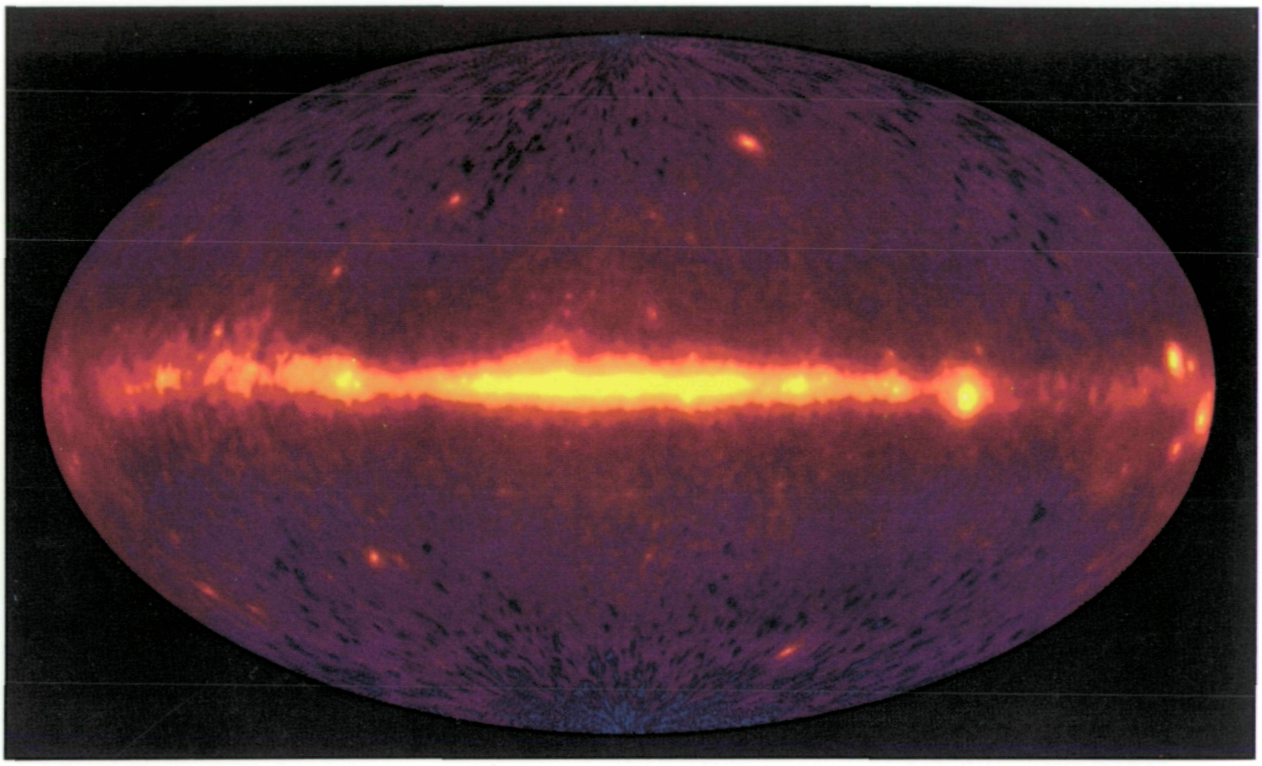
WIMP: Weakly interacting, non-baryonic, massive particle; a hypothetical particle whose existence might explain the dark matter problem.

Wind: A NASA mission, launched in 1994, to measure interplanetary plasma, fields, and energetic particles.

WR star: Wolf-Rayet stars, very luminous, massive stars that rapidly lose mass through high-velocity stellar winds.

X_{max}: The depth into the atmosphere at which the air shower from a high-energy cosmic-ray particle reaches its maximum size.

Yakutsk array: A giant air-shower detector array exploring energies above 10^{17} eV, located in the former Soviet Union.



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