Cosmic rays: the most energetic particles in the universe

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Cosmic rays are an ever present aspect of nature. The birth of the field of elementary-particle physics can be traced to studies of cosmic rays. Now advances in technology and new instrumentation are changing the nature of cosmic-ray research. New forms of astronomy are being created. Ground-based instruments, spawned by cosmic-ray techniques, permit the observation of astrophysical objects emitting radiation in very-high-energy gamma rays, ($\geqslant$100 GeV), high-energy neutrinos ($\geqslant$1 TeV), and the most energetic particles found in the cosmic radiation ($\geqslant 5\times10^{19}$ eV). At these energies the galactic and intergalactic magnetic fields deflect the cosmic-ray protons by only a few degrees. The interaction of these cosmic rays with the cosmic background radiation limits the possible sources to redshifts far less than unity. The origin of these highest-energy cosmic rays is not understood. The present status of knowledge of these cosmic rays and the prospects for solving the mystery concerning their origin are the subjects of this brief article. [S0034-6861(99)00602-9]

I. INTRODUCTION

Cosmic rays are a source of ionizing radiation incident on the whole earth. The intensity of this ionizing radiation varies with magnetic latitude, with altitude, and with solar activity. The attribution "cosmic rays" is misleading in that the radiation consists principally of fully ionized atomic nuclei incident on the earth from outer space.

The field of elementary-particle physics owes its origin to discoveries made in course of cosmic-ray research, and the study of cosmic rays has contributed to the understanding of geophysical, solar, and planetary phenomena. The existence of cosmic rays also has its practical side. An example is radio-carbon dating, first suggested by Libby (1965). Radioactive C^{14} is produced by the collisions of the cosmic rays with the N^{14} in the atmosphere. This produces an activity of 15 disintegrations per minute per gram of natural carbon in all living matter. On death, the C^{14} decays with a half-life of 5600 years. Thus the specific activity of C^{14} provides an accurate archeological clock for the dating of objects in history and prehistory.

This article presents a very personal view of the most important questions for future research. I restrict it to energies well above 1 TeV (10^{12} eV) where most of the observations are ground based due to low fluxes. As in many fields, new technologies permit unique investigations that could only be dreamed of in the past. If we take a broad definition of cosmic rays they consist not only of electrons and nuclei, but of other particles as well, particularly gamma rays and neutrinos, which, being neutral, point back to their source.

At present there are many programs under development around the world that seek to measure high-energy neutrinos in the primary cosmic radiation (Gaisser *et al.*, 1995). These are neutrinos that come directly from astrophysical sources, as distinct from being produced by ordinary cosmic rays in the atmosphere. The detectors consist of large volumes of antarctic ice or seawater instrumented with photomultipliers. At present there are major experimental efforts under way or proposed. It is expected that high-energy neutrino detectors will make discoveries in astronomy, cosmology, and fundamental-particle physics.

In recent years astronomy has been extended to sources emitting γ rays with energies more than 100 GeV. Numerous galactic and extragalactic sources have been observed with ground-based instruments which detect the Čerenkov radiation emitted by the showering of the high-energy γ rays. At these energies the satellite detectors, the Compton Gamma-Ray Observatory, and even the new detector Gamma-ray Large Area Space Telescope (to be launched about 2005) do not have the sensitivity necessary to observe sources at energies above 100 GeV. This rapidly expanding area of astronomy has been the subject of a number of recent reviews (Weekes *et al.*, 1998; Ong, 1998).

In the remainder of this paper I shall concentrate on the cosmic rays above 10^{14} eV where most observations have been made with ground-based instruments.

II. A BRIEF HISTORY

The history of research in cosmic rays is a fascinating one, filled with serendipity, personal conflict, and experiments on a global scale. The discovery of cosmic rays, attributed to Victor Hess (1912), had its origin in the obsession of some scientists to understand why a heavily shielded ion chamber still recorded radiation. It was assumed that this was some residual radiation from the earth's surface and by placing the ion chamber at some distance above the earth's surface the detected radiation would be reduced. When Victor Hess took an ion chamber several thousand meters above the earth in a balloon, it was found that the radiation level actually rose, leading to the conclusion that the radiation was arriving from outer space.

It took more than 30 years to discover the true nature of the cosmic radiation, principally positively charged atomic nuclei arriving at the top of the atmosphere (Sekido and Elliot, 1985; Simpson, 1995). Many hypotheses were offered for the nature of these cosmic rays. One of the most interesting ideas was that of Robert A. Millikan (Millikan and Cameron, 1928). Millikan noted Aston's discovery of nuclear binding energies. He suggested that the cosmic rays were the result of the formation of complex nuclei from primary protons and electrons. In the 1920s electrons and ionized hydrogen were the only known elementary particles to serve as building blocks for atomic nuclei. The formation of atomic nuclei was assumed to be taking place throughout the universe, with the release of the binding energy in the form of gamma radiation, which was the "cosmic radiation." A consequence of this hypothesis was that the cosmic radiation was neutral and would not be influenced by the earth's magnetic field. A worldwide survey led by Arthur Compton demonstrated conclusively that the intensity of the cosmic radiation depended on the magnetic latitude (Compton 1933). The cosmic radiation was predominately charged particles. This result was the subject of an acrimonious debate between Compton and Millikan at an AAAS meeting that made the front page of the *New York Times* on December 31, 1932.

In 1938, Pierre Auger and Roland Maze, in their Paris laboratory, showed that cosmic-ray particles separated by distances as large as 20 meters arrived in time coincidence (Auger and Maze, 1938), indicating that the observed particles were secondary particles from a common source. Subsequent experiments in the Alps showed that the coincidences continued to be observed even at a distance of 200 meters. This led Pierre Auger, in his 1939 article in *Reviews of Modern Physics*, to conclude

> One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} eV is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension. (Auger *et al.*, 1939).

Auger and his colleagues discovered that there existed in nature particles with an energy of 10^{15} eV at a time when the largest energies from natural radioactivity or artificial acceleration were just a few MeV. Auger's amazement at Nature's ability to produce particles of enormous energies remains with us today, as there is no clear understanding of the mechanism of production, nor is there sufficient data available at present to hope to draw any conclusions.

In 1962 John Linsley observed a cosmic ray whose energy was 10^{20} eV (Linsley, 1962). This event was observed by an array of scintillation counters spread over $8\,\mathrm{km}^2$ in the desert near Albuquerque, New Mexico. The energetic primary was detected by sampling some of the 5×10^{10} particles produced by its cascade in the atmosphere. Linsley's ground array was the first of a number of large cosmic-ray detectors that have measured the cosmic-ray spectrum at the highest energies.

III. COSMIC-RAY SPECTRUM

After 85 years of research, a great deal has been learned about the nature and sources of cosmic radiation (Zatsepin *et al.*, 1966; Berezinskii *et al.*, 1990; Watson, 1991; Cronin, 1992; Sokolsky *et al.*, 1992; Swordy, 1994; Nagano, 1996; Yoshida *et al.*, 1998). In Fig. 1 the spectrum of cosmic rays is plotted for energies above 10^8 eV. The cosmic rays are predominately atomic nuclei ranging in species from protons to iron nuclei, with traces of heavier elements. When ionization potential is taken into account, as well as spallation in the residual gas of space, the relative abundances are similar to the abundances of elements found in the sun. The energies range from less than 1 MeV to more than 10^{20} eV. The differential flux is described by a power law:

$$dN/dE \sim E^{-\alpha}, \tag{3.1}$$

where the spectral index α is roughly 3, implying that the intensity of cosmic rays above a given energy decreases by a factor of 100 for each decade in energy. The flux of cosmic rays is about $1/\mathrm{cm}^2/\mathrm{sec}$ at 100 MeV and only of order $1/\mathrm{km}^2/\mathrm{century}$ at 10^{20} eV.

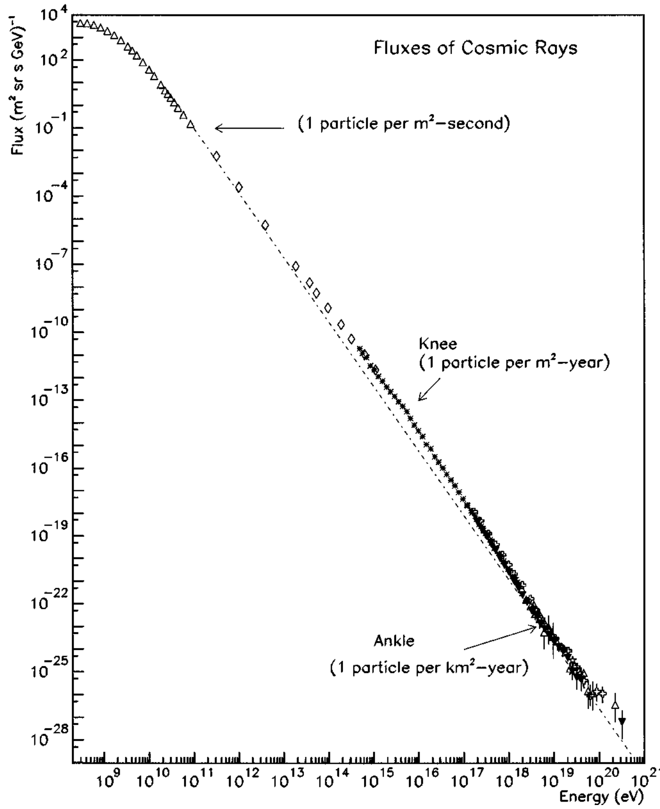

FIG. 1. Spectrum of cosmic rays greater than 100 MeV. This figure was produced by S. Swordy, University of Chicago.

The bulk of the cosmic rays are believed to have a galactic origin. The acceleration mechanism for these cosmic rays is thought to be shock waves from supernova explosions. This basic idea was first proposed by Enrico Fermi (1949), who discussed the acceleration of cosmic rays as a process of the scattering of the charged cosmic-ray particles off moving magnetic clouds. Subsequent work has shown that multiple "bounces" off the turbulent magnetic fields associated with supernova shock waves is a more efficient acceleration process

(Drury, 1983). At present there is no direct proof of this hypothesis. The argument for it is based on the fact that a fraction of the energy released by supernova explosions is sufficient to account for the energy being pumped into cosmic rays. A second point in favor of the hypothesis is that the index of the spectrum, 2.7 below 5×10^{15} eV, is consistent with shock acceleration when combined with the fact that the lifetime of the cosmic rays in our galaxy is about 10^7 years due to leakage of the rays out of the "bottle" provided by the magnetic field of our galaxy. Shock acceleration would provide an index of 2.0. The leakage out of the galaxy accounts for the steeper spectrum given by 2.7.

The spectrum steepens (the knee) to an index of 3.0 at about 5×10^{15} eV. In the most recent experiments, this bend in the spectrum is gradual. The conventional explanation of the knee is that the leakage of the cosmic rays from the galaxy depends on the magnetic rigidity E/Z. The knee results from the fact that, successively, the lighter components of cosmic rays are no longer contained in the galaxy as the energy increases. This hypothesis requires that the mean atomic number of the cosmic rays becomes progressively heavier as the energy rises. At the present time this prediction has not been convincingly demonstrated.

IV. TECHNIQUES OF MEASUREMENT

At energies below 10^{14} eV the flux of primary cosmic rays is sufficient to be measured directly with instruments on balloons and satellites. Above 10^{14} eV the flux is about 10/m^2/day. At this energy very-large-area detectors are required to measure the cosmic rays directly. But fortunately at this energy the cascades in the atmosphere produce a sufficient number of particles on the earth's surface so that the primary cosmic ray can be observed indirectly by sampling the cascade particles on the ground. This technique is just an application of Auger's experiment with modern technology. Observations made with a surface array of particle detectors can adequately measure the total energy and the direction of the primary cosmic ray. It should be noted that the atmosphere is an essential part of a surface detector. The technique has been extended to instruments that cover as much as 100 km^2 with individual detector spacings of 1 km. Much larger arrays will eventually be built. At energies above 10^{18} eV the density of particles at a fixed distance (500–1000 m) from the shower axis is proportional to the primary energy. The constant of proportionality is calculated by shower simulation.

A second technique has been used to measure the spectrum above 10^{17} eV. Optical photons in the range 300 nm to 400 nm are produced by the passage of the charged particles through the nitrogen of the atmosphere (Baltrusaitus *et al.*, 1985; Kakimoto, 1996). About four fluorescence photons are produced per meter for each charged shower particle. With an array of photomultipliers, each focused on a part of the sky, the longitudinal development of a shower can be directly measured and the energy inferred from the total amount of fluorescence light. The limitation of this technique is that it can only function on dark moonless nights, which amounts to only 10% of the time. The positive aspect of the technique is that it rather directly measures the energy of the shower dissipated in the atmosphere, which in most cases is a large fraction of the primary energy. Absolute knowledge of the fluorescence efficiency of the nitrogen, the absorption of the atmosphere, and the quantum efficiency and gain of the photomultipliers is required.

Neither technique is particularly effective in identifying the nature of the primary (nucleon, nucleus, or photon). The mean fraction of energy contained in the muonic component of the shower particles increases as the primary becomes heavier. The mean depth in the atmosphere where the cascade is at its maximum moves higher as the primary becomes heavier. Because of fluctuations in these quantities, neither technique offers hope of identifying the nature of the primary on an event by event basis.

V. PROPERTIES OF COSMIC RAYS ABOVE 10^{17} eV

Above 10^{17} eV the cosmic-ray spectrum shows additional structure. This structure is displayed in Fig. 2, where the differential spectrum has been multiplied by E^3 to better expose the observed structures. These data are the combined results of four experiments that have operated over the past 20 years. They are from the Haverah Park surface array in England (Lawrence *et al.*, 1991), the Yakutsk surface array in Siberia (Afanasiev *et al.*, 1995), the Fly's Eye fluorescence detector in Utah (Bird *et al.*, 1994), and the AGASA surface array in Japan (Yoshida *et al.*, 1995). Before plotting, the energy scale of each experiment was adjusted by amounts $\leqslant 20\%$ to show most clearly the common features. The method of energy determination in each of these experiments is quite different, and the fact that they agree within 20% is remarkable.

Above 5×10^{17} eV the spectrum softens from an index of 3.0 to an index of 3.3. Above 5×10^{18} eV the spectrum hardens, changing to an index of 2.7. Beyond 5×10^{19} eV the data are too sparse to be certain of the spectral index. There is no clear explanation of this structure. Above 10^{18} eV, the galactic magnetic fields are not strong enough to act as a magnetic "bottle" even for iron nuclei. If the cosmic rays continue to be produced in the galaxy, they should show an anisotropy that correlates with the galactic plane. No such anisotropy has been observed. The hardening of the spectrum to an index of 2.7 above 5×10^{18} eV may then be a sign of an extragalactic component emerging as the galactic component dies away.

VI. THE DIFFICULTY OF ACCELERATION

Above 10^{19} eV the precision of the spectrum measurement suffers from lack of statistics. There have been about 60 events recorded with energy greater than 5×10^{19} eV. Yet it is above this energy that the scientific mystery is the greatest. There is little understanding of how known astrophysical objects could produce par-

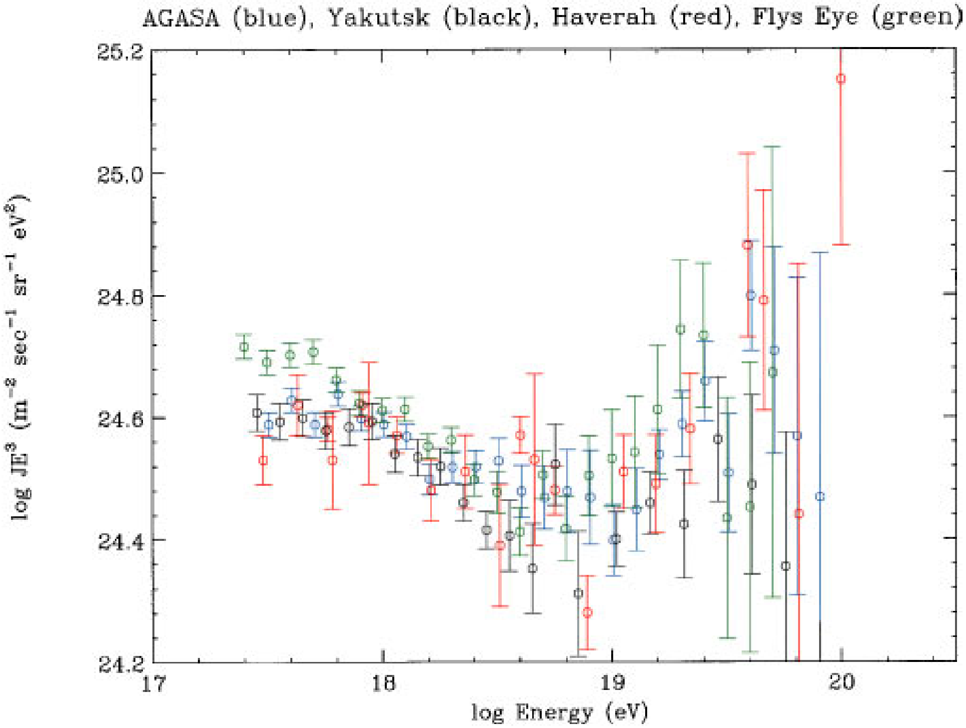

FIG. 2. (Color) Upper end of the cosmic-ray spectrum. Haverah Park points (red; Lawrence *et al.*, 1991) serve as a reference. Yakutsk points (black; Afanasiev *et al.*, 1995) have been reduced in energy by 20%. Fly's Eye points (green; Bird *et al.*, 1995) have been raised in energy by 10%. AGASA points (Yoshida *et al.*, 1995) have been reduced by 10%.

ticles of such energy. At the most primitive level, a necessary condition for the acceleration of a proton to an energy E in units of 10^{20} eV is that the product of the magnetic field B and the size of the region R be much larger than 3×10^{17} G-cm. This value is appropriate for a perfect accelerator such as might be scaled up from the Tevatron at Fermilab. The Tevatron has a product $BR=3\times10^{9}$ G-cm and accelerates protons to 10^{12} eV. Analogous acceleration of cosmic rays to energies above 10^{19} eV seems difficult, and the literature is filled with speculations. Two reviews that discuss the basic requirements are those of Greisen (1965) and Hillas (1984). While these were written some time ago, they are excellent in outlining the basic problem of cosmic-ray acceleration. Biermann (1997) has recently reviewed all the ideas offered for achieving these high energies. Hillas in his outstanding review of 1984 presented a plot that graphically shows the difficulty of cosmic-ray acceleration to 10^{20} eV. Figure 3 is an adaptation of his figure. Plotted are the size and strength of possible acceleration sites. The upper limit on the energy is given by

$$E_{18}\leqslant 0.5\beta Z B_{\mu\mathrm{G}} L_{kpc}. \tag{6.1}$$

Here the E_{18} is the maximum energy measured in units of 10^{18} eV. L_{kpc} is the size of the accelerating region in units of kiloparsecs, and $B_{\mu\mathrm{G}}$ is the magnetic field in μG. The factor β was introduced by Greisen to account for the fact that the effective magnetic field in the accelerator analogy is much less than the ambient field. The factor β in Hillas's discussion is the velocity of the shock wave (relative to c), which provides the acceleration. The plotted lines correspond to a 10^{20} eV proton with $\beta=1$ and 1/300. A line is also plotted for iron nuclei ($\beta=1$). With $Z=26$, iron is in principle easier to accelerate. Realistic accelerators should lie well above the dashed line. The figure is also relevant for "one-shot" acceleration, as it represents the electromotive force (emf) induced in a conductor of length L moving with a velocity β through a uniform magnetic field B.

Synchrotron energy loss is also important. For protons the synchrotron loss rate at 10^{20} eV requires that the magnetic field be less than 0.1 G for slow acceleration (the accelerator analogy; Greisen 1965). From Fig. 3 it can be seen that the acceleration of cosmic rays to 10^{20} eV is not a simple matter. Because of this, some authors have seriously postulated that cosmic rays are not accelerated but are directly produced by "top down" processes. For example, defects in the fabric of spacetime could have huge energy content and could release this energy in the form of high-energy cosmic rays (Bhattacharjee, Hill, and Schramm, 1992).

VII. NATURE'S DIAGNOSTIC TOOLS

There are some natural diagnostic tools that make the analysis of the cosmic rays above 5×10^{19} eV easier than at lower energies. The first of these is the 2.7-K cosmic background radiation (CBR). Greisen (1966) and Zatsepin and Kuz'min (1966) pointed out that protons, photons, and nuclei all interact strongly with this radiation, a phenomenon that has become known as the GZK effect.

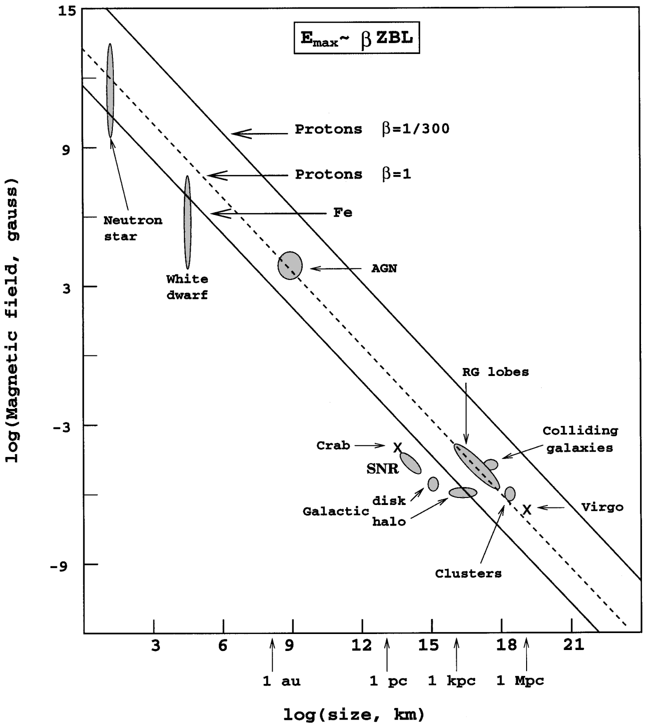

FIG. 3. Modified Hillas plot (Hillas, 1984). Size and magnetic field of possible sites of acceleration. Objects below the dashed line cannot accelerate protons to 10^{20} eV.

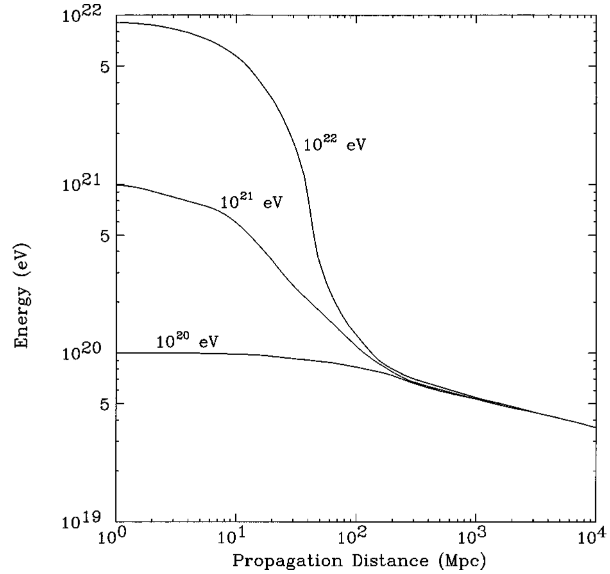

FIG. 4. Proton energy as a function of propagation distance through the 2.7-K cosmic background radiation for the indicated initial energies.

As an example, a collision of a proton of 10^{20} eV with a CBR photon of 10^{-3} eV produces several hundred MeV in the center-of-mass system. The cross section for pion production is quite large so that collisions are quite likely, resulting in a loss of energy for the primary proton. In Fig. 4 we plot the results of the propagation of protons through the CBR. Regardless of the initial energy of the proton, it will be found with less than 10^{20} eV after propagating through a distance of 100 Mpc (3×10^8 light years). Thus the observation of a cosmic-ray proton with energy greater than 10^{20} eV implies that its distance of travel is less than 100 Mpc. This distance corresponds to a redshift of 0.025 and is small compared to the size of the universe. Similar arguments can be made for nuclei or photons in the energy range considered. There are a limited number of possible sources that fit the Hillas criteria (Fig. 3) within a volume of radius 100 Mpc about the earth.

The fact that the cosmic rays, if protons, will be little deflected by galactic and extragalactic magnetic fields serves as the second diagnostic tool. The deflection of protons of energy 5×10^{19} eV by the galactic magnetic field ($\sim2\,\mu$G) and the intergalactic magnetic fields ($\leqslant10^{-9}$ G) is only a few degrees (Kronberg, 1994a, 1994b), so that above 5×10^{19} eV it is possible that the cosmic rays will point to their sources. We approach an astronomy, even for charged cosmic rays, in which the distance to the possible sources is limited.

VIII. COSMIC-RAY ASTRONOMY

The energy 5×10^{19} eV represents a lower limit for which the notion of an astronomy of charged particles from "local" sources can be applied. The GZK effect enhances the number of events from sources within a distance of 100 Mpc. Of these events, two particularly stand out with energies reported to be 2×10^{20} eV by the AGASA experiment (Hayashida *et al.*, 1994) and 3×10^{20} eV by the Fly's Eye experiment (Bird *et al.*, 1995; Elbert and Sommers, 1995). More recently a total of six events with energy $\geqslant10^{20}$ eV have been reported by the AGASA experiment (Takeda *et al.*, 1998). For all these events the probable distance to the source is less than 50 Mpc.

The events above 5×10^{19} eV are too few to derive a spectral index. It is not clear that a single spectrum is even the proper way to characterize these events. Since they must come from "nearby," the actual number of sources may not form an effective continuum in space, so the spectrum observed may vary with direction. The matter within 100 Mpc is not uniformly distributed over the sky. It is probably more fruitful to take an astronomical approach and plot the arrival directions of these events on the sky in galactic coordinates.

Arrival-direction data are available for the Haverah Park experiment (Watson, 1997), the AGASA experiment (Hayashida *et al.*, 1996), and for the most energetic event recorded by the Fly's Eye experiment (Bird *et al.*, 1995; Elbert and Sommers, 1995). In Fig. 5 we plot the arrival directions of 20 AGASA events and 16 Haverah Park events. The size of the symbols corresponds to the angular resolution. In addition, the error box for the most energetic event recorded by the Fly's Eye experiment is plotted. What is remarkable in this figure is the number of coincidences of cosmic rays coming from the same direction in the sky. Of the 20 events reported by AGASA, there are two pairs. The probability of a chance coincidence for this is about 2%. The addition of the Haverah Park events shows a coincidence with one of the AGASA pairs. However, the Fly's Eye event co-

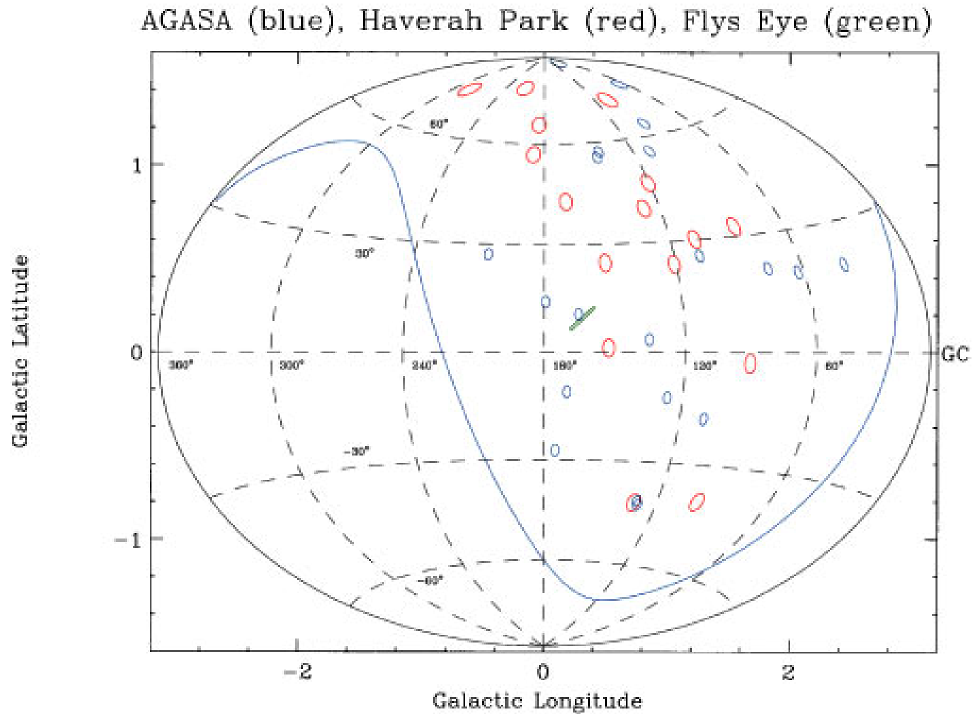

FIG. 5. (Color) Plot of arrival directions of cosmic rays with energy $\geq 5\times10^{19}$: red points, Haverah Park (Lawrence *et al.*, 1991); blue points, AGASA (Yoshida *et al.*, 1995); green point, Fly's Eye event with energy 3×10^{20} eV. The size of the symbols represents the resolution of each experiment. The empty region marked by the blue line is the part of the sky not seen by the northern hemisphere location of the observations.

incides with one of the AGASA events. It is not possible to estimate properly the probability of chance overlaps, but the possibility that these overlaps may be real should not be ignored. The triple coincidence contains the AGASA event of 2×10^{20} eV, the Haverah Park event of about 1×10^{20} eV, and the AGASA event of 5×10^{19} eV. The Fly's Eye event of 3×10^{20} eV is in coincidence with the AGASA event of 6×10^{19} eV. The third pair contains AGASA events of 6×10^{19} eV and 8×10^{19} eV, respectively.

The triple coincidence is particularly interesting if it is not the result of pure chance. It contains cosmic rays separated by a factor of 4 in energy that have not been separated in space by more than a few degrees. This is an encouraging prospect for future experiments in which, with many more events, one may observe point sources, clusters, and larger-scale anisotropies in the sky. The crucial questions will be: Does the distribution of cosmic rays in the sky follow the distribution of matter within our galaxy or the distribution of ''nearby'' extragalactic matter, or is there no relation to the distribution of matter? Are there point sources or very tight clusters? What is the energy distribution of events from these clusters? Are these clusters associated with specific astrophysical objects? If there is no spatial modulation or no correlation with observed matter, what is the spectrum? This situation would imply an entirely different class of sources, which are visible only in the ''light'' of cosmic rays with energy $\geq 5\times10^{19}$ eV. Of course there may be a combination of these possibilities. If even crude data on primary composition are available, they can be divided into categories of light and heavy components, which may have different distributions. Crucial to these considerations is uniform exposure over the whole sky. And a final and fundamental question is: Is there an end to the cosmic-ray spectrum?

IX. NEW EXPERIMENTS

The flux of cosmic rays with energy $\geq 5\times10^{19}$ eV is about 0.03/km^2/sr/yr. It required five years for the AGASA array, with an acceptance of 125 km^2-sr, to collect 20 events above this energy. In 1999 an improved version of the Fly's Eye experiment (HiRes) will begin operation (Abu-Zayyad, 1997). It will have an acceptance of about 7000 km^2-sr above 5×10^{19} eV. With a 10% duty cycle it should collect about 20 events per year. The experiment will be located in northern Utah. Only half of the sky will be observed.

Experiments with far greater statistical power are required to make real progress. It is very likely that a combination of types of sources and phenomena are responsible for the highest-energy cosmic rays. Thus the experiment must be constructed so as not to have a bias towards a particular or single explanation for the cosmic rays. An ideal experiment should have uniform coverage of the entire sky. It should also be fully efficient at energies beginning at 10^{19} eV, as the present data available above that energy are very sparse. It should have the best possible means to identify the primary particle, although no experiment can make a unique identification on an event by event basis.

A number of experiments have been proposed or will be proposed in the next few years. These are all described in the Proceedings of the 25th International Cosmic-Ray Conference held in Durban in 1997. One of these seeks to satisfy all the general requirements outlined above. The experiment of the Pierre Auger Observatories (Boratav, 1997) consists of two detectors with acceptance 7000 km^2-sr. They will be located at mid-latitude in the southern and northern hemispheres, which will provide nearly uniform sky coverage. An important feature of the Auger experiment is its use of a hybrid detector that combines both a surface array and a fluorescence detector. Such an experiment will collect $\sim$450 events $\geqslant 5\times 10^{19}$ eV each year. Some 20% of the events may originate from point sources or tight clusters if the AGASA results (Hayashida *et al.*, 1996) are used as a guide.

Also being proposed is an all-fluorescence detector called the Telescope Array (Telescope Array Collaboration, 1997) to be located in the northern hemisphere. It would have an aperture of 70 000 km^2-sr (7000 km^2-sr with the 10% duty cycle). It would also co-locate two of its fluorescence units with the northern Auger detector.

A visionary idea has been offered in which the fluorescence light produced by a cosmic ray in the atmosphere would be viewed from a satellite (Linsley, 1997; Krizmanic, Ormes, and Streitmatter, 1998). There are many technical difficulties in such a project. It would, however, represent a next step in the investigations if the projects above are realized and no end to the cosmic-ray spectrum is observed. The estimated sensitivity of such a satellite detector for cosmic rays with energy $\geqslant 10^{20}$ eV would be 10–100 times that of the Pierre Auger Observatories.

X. CONCLUSION

It is now widely recognized that the investigation of the upper end of the cosmic-ray spectrum will produce new discoveries in astrophysics or fundamental physics. There are a number of complementary proposals for new experiments that will provide the needed observations within the next ten years.

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