

THE HIGHEST-ENERGY COSMIC RAYS

What in the cosmos can possibly be accelerating protons to 10^{20} electron volts and beyond? And how can they preserve such extreme energies while plowing through the cosmic microwave background on their way to us?

Thomas O'Halloran, Pierre Sokolsky and Shigeru Yoshida

The unexpected discovery of the cosmic microwave background by Arno Penzias and Robert Wilson¹ in 1965 is now the centerpiece of our understanding of the Big Bang and the subsequent evolution of the universe. (See PHYSICS TODAY, November 1997, page 32.) The discovery also set off something of a race to verify one of its implications for cosmic rays. In 1966, Kenneth Greisen (Cornell University) pointed out that the most energetic cosmic-ray particles would be affected by interaction with the ubiquitous photons of this microwave background.² Greisen predicted that, if cosmic-ray sources were far enough away from us and if their energy spectrum extended beyond 10^{20} eV then the ultrahigh-energy protons and nuclei would interact inelastically with the background radiation.

The threshold for this energy sapping interaction is the onset of pion photoproduction. Greisen predicted that a smooth power-law cosmic-ray energy spectrum would therefore be abruptly cut off near 5×10^{19} eV. The same effect was independently predicted by G. T. Zatsepin and V. A. Kuzmin in the Soviet Union. From the first, this Greisen-Zatsepin-Kuzmin (GZK) cutoff has been much sought after by cosmic-ray physicists looking at the highest energies.³ (See the box on page 32.)

Unfortunately for the observers, the cosmic-ray flux at these energies is only about one event per century per square kilometer of detector array. Therefore, our progress in understanding the high-energy end of the cosmic-ray spectrum has been painfully slow. Nonetheless, in 1991 and 1993, two very different experiments observed events that appear to be clearly beyond the predicted cutoff. The 1991 event, which still holds the record, had an incident energy of 3.2×10^{20} eV far beyond anything we can produce with an accelerator. It's a single particle or nucleus with the kinetic energy of a well-hit tennis ball.

A number of new experiments and experimental proposals are in the works to further investigate this energy region. We examine here the implications of the energy spectrum measurements on our understanding of the origin of cosmic rays, and we discuss the newer experimental methods that extend and confirm the previous measurements.

A question of origin

Below 10^{15} eV the cosmic-ray energy spectrum obeys an approximate power law, falling like $E^{-2.7}$. (See figure 1.) The present consensus⁴ is that this form reflects the Fermi acceleration of cosmic rays in our Galaxy by supernova shock-wave remnants and subsequent propagation in the Galactic magnetic field. Beyond the so-called knee near 10^{15} eV the spectrum steepens and there is some evidence that the mean mass of cosmic-ray particles increases. Presumably that's because protons, with larger Larmor radii than the heavier nuclei, have an easier time escaping from the Galaxy's magnetic field.

It is difficult, however, to account for the E^{-3} spectrum beyond the knee with supernova models. Other acceleration mechanisms are needed. It is possible that cosmic rays beyond the knee are of extragalactic origin; they show little evidence of anisotropy favoring the plane of the Galactic disk. At the highest energies, above 10^{19} eV, acceleration mechanisms require either very high magnetic fields or very large acceleration regions. There, the most likely sources are certainly extragalactic.

Extragalactic candidates include some classes of radio galaxies with jets of outflowing matter.⁵ They exhibit strong radio emission, which we take to be synchrotron radiation from the accelerating electrons in the jet's "hot spot." That suggests the existence of relativistic shock waves possibly powerful enough to accelerate protons up to 10^{20} or 10^{21} eV.

There are many other kinds of extragalactic objects with strong radio or x-ray emission that might be good acceleration sites for cosmic rays. But any such acceleration mechanism has to compete with energy-loss processes such as synchrotron radiation in strong magnetic fields or collisions with matter and photons surrounding the acceleration site. For example, active galactic nuclei, where accretion disks are believed to flow into supermassive black holes, emit strong x-radiation. But their density of matter and photons prevents acceleration to 10^{20} eV. Hot spots in the jets of radio galaxies are favored, because they don't seem to be burdened with very dense accumulations of matter or photons. Therefore the time required for acceleration to 10^{20} eV in a radio galaxy jet is likely to be shorter than the characteristic energy-loss time due to collisions.

THOMAS O'HALLORAN, now at the University of Utah's High Energy Astrophysics Institute, is an emeritus professor of physics at the University of Illinois at Urbana-Champaign. PIERRE SOKOLSKY is a professor of physics at the University of Utah in Salt Lake City. SHIGERU YOSHIDA is an assistant professor of physics at the University of Tokyo's Institute for Cosmic Ray Research.

The GZK Cutoff

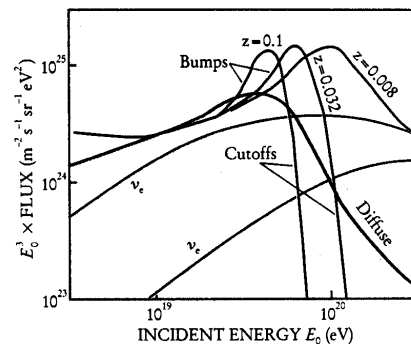
One might think that the present universe is transparent to ultrahigh-energy cosmic rays, with only small energy losses due to collisions with dust particles and optical photons. But that's no longer true when cosmic-ray energies approach 10^{20} eV. At those extreme energies, the main process of collisional energy loss is photopion production off the ubiquitous low-energy photons of the 3 K cosmic microwave background (CMB). The pion photoproduction cross section for protons has a strong resonance at a center-of-mass energy of about 1.2 GeV, not far above the kinematic threshold. The corresponding energy in the reference frame of CMB isotropy is about 10^{20} eV.

This threshold and resonance effect creates the sharp Greisen-Zatsepin-Kuzmin structure in the energy spectrum we would expect to see on Earth (see figure at right). The spectrum should also exhibit a bump created by the accumulation of recoil protons that have fallen below the pion-production threshold, and now see a transparent universe. In 1987 Christopher Hill, David Schramm and Thomas Walker⁹ calculated the detailed spectral shape produced by this effect.

The "laboratory" threshold energy is not a constant when sources are at cosmological distances. If we consider scattering at a distance and time corresponding to a cosmological redshift z , the relevant blackbody temperature of the CMB back then was $1 + z$ times its present 3 K value. That lowers the required threshold energy and produces faster energy loss above the threshold. For sources with high redshifts, the cosmological effect on the spectral shape becomes very important.¹⁰ The cutoff energy falls below 10^{19} for $z = 1$.

It is, of course, unlikely that the sources of most of the ultrahigh-energy cosmic rays all have the same redshift. If they are distributed throughout the universe, the cutoff energy approaches a universal value near 4×10^{19} eV. This reflects the fact that nearby sources dominate the highest energy contribution to the observed spectrum, simply because the longer the journey, the harder it is to remain above threshold.

The extragalactic spectral shape below about 3×10^{18} eV depends strongly on the contributions of cosmic radiation in early epochs, corresponding to $z > 2$. But that part of the spectrum is probably dominated by sources in our own Galaxy; so it can tell us little about the early history of cosmic radiation. There is, however, one potential probe of this history: the flux of secondary neutrinos produced by the decay of photopions created by cosmic rays colliding with CMB photons. Because neutrinos can travel over cosmological distances unscathed, their flux strongly depends on the ultrahigh-energy cosmic rays at early epochs. But because the relevant neutrino flux is, at most, equal to the flux of 10^{19} eV cosmic rays, their detection is a rather remote prospect.



EXPECTED EFFECTS of GZK CUTOFF on the cosmic-ray energy spectrum.¹⁰ The cutoff depends on the redshift distribution of sources, as indicated by the red curves for single sources labeled by redshift z . The bump below each cutoff is due to the accumulation of recoil protons that have fallen below the pion-production threshold and now see a transparent universe. If sources are universally distributed over a range of redshifts, one expects the "diffuse" spectrum (shown green) and the lower of the two neutrino spectra (shown blue). The higher neutrino flux curve assumes greater cosmic ray production early in the epoch of galaxy formation.

Acceleration sites also have to be large enough to confine the cosmic-ray particles during the acceleration process. This means that the site must be larger than the synchrotron radius of 10^{20} eV protons in the magnetic field in question. Very few astronomical objects other than radio-galaxy hot spots satisfy this requirement.

In the end, we may have to invoke exotic new physics beyond the accepted theories to explain the most energetic cosmic rays. It has been proposed that they originate in the decay of topological spacetime defects such as cosmic strings or monopole-antimonopole atoms. Such theories would predict a continuing cosmic-ray flux all the way up the grand-unification mass scale (10^{23} eV) of the decaying particle. The signature for such a scenario would be a cosmic-ray flux rebound (and a large diffuse neutrino flux) above the GZK cutoff.

A little detector history

The study of ultrahigh-energy cosmic rays began in earnest after World War II with the construction of the Volcano Ranch ground array in New Mexico.³ This array of particle detectors (plastic scintillation counters) spread out over about 25 km² of desert

was initiated by John Linsley (University of New Mexico). Such arrays measure the density of charged particles reaching the ground in the "extensive air shower" generated in the atmosphere by an incident high-energy cosmic ray. (See the box on page 33.)

Monte Carlo simulations and analytic calculations of purely electromagnetic showers by Greisen and Bruno Rossi in the 1940s indicated that the integrated charge density at ground level was proportional to the incident particle energy. An incident hadron will generate a shower that can be thought of as a superposition of individual electromagnetic showers fed by a hadronic core largely composed of pions. Fluctuations in shower development made energy estimates rather uncertain, and the absolute energy scale was not well understood. But the pioneering data of the Volcano Ranch experiment showed that the cosmic-ray spectrum extended well past the knee, and possibly all the way to near 10^{20} eV.

This evidence for a continuing energy spectrum stimulated proposals for additional ground arrays. The SUGAR array, built in Australia in the late 1960s, had ten times Volcano Ranch's collecting area. Using scintillation detectors spread about 1 km apart, SUGAR measured the density of shower muons hitting the ground. The Haverah Park array in England, built by a Leeds University group, used an array of water tanks, in which charged particles would identify themselves by generating Cerenkov light

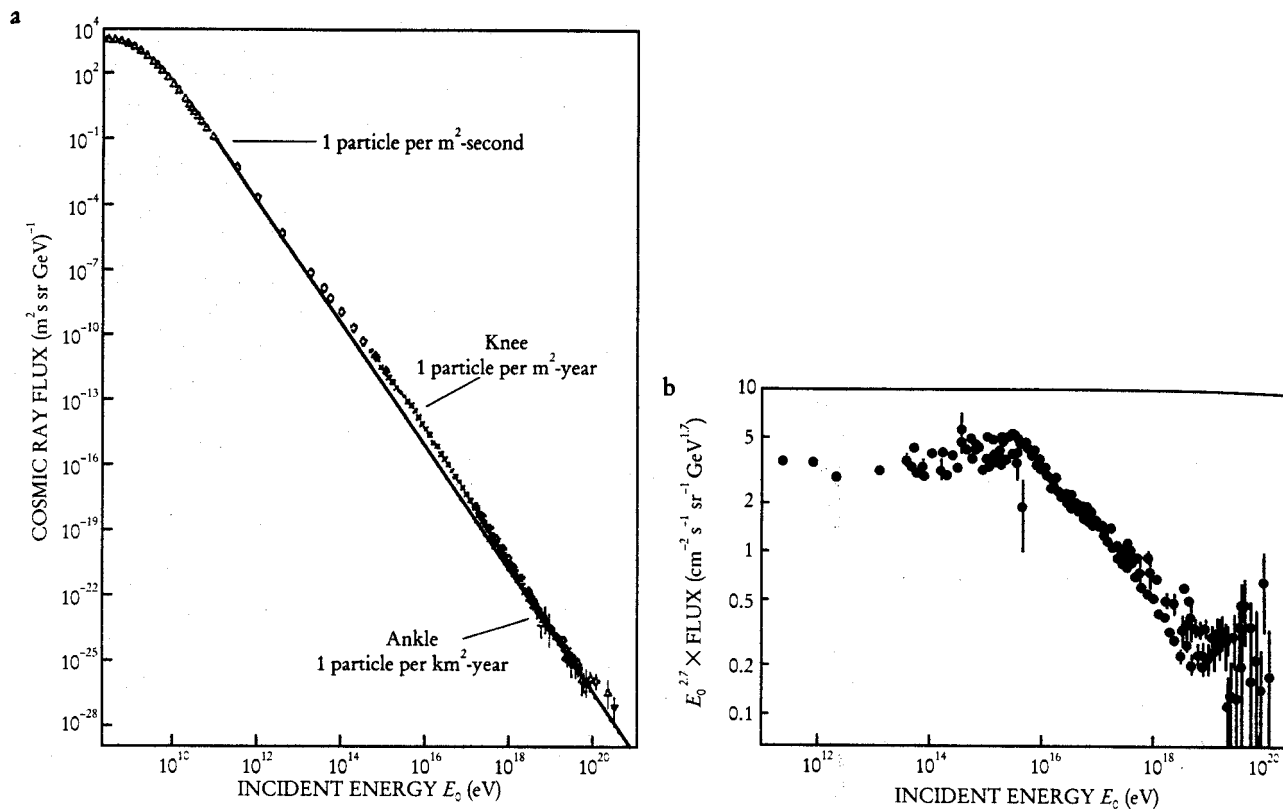


FIGURE 1. OBSERVED ENERGY SPECTRUM of high-energy cosmic rays. a: The straight line shows an E_0^{-3} falloff for comparison. Integrated fluxes (per steradian) expected beyond the energies of several spectral landmarks are indicated. At the highest energies one will need enormous collecting areas. b: Multiplying the flux by $E_0^{2.7}$ flattens the spectrum below 10^{16} eV, and suggests why the landmarks at higher energies are called the "knee" and the "ankle."

to determine the particle density at ground level. A Soviet group built a ground array of plastic scintillators near Yakutsk in Siberia. It also pointed optical detectors at the sky in search of the tightly collimated forward atmospheric (Cerenkov radiation produced along with the particles in an extensive air shower.

Except for Yakutsk, none of these arrays is still in active use. The largest ground array presently in operation is the Akeno Giant Air Shower Array (AGASA), completed in 1991 by a Japanese group led by Motohiko Nagano (University of Tokyo). AGASA covers an area of 100 km^2 , studded with scintillation counters and muon detectors.

A refinement introduced by Haverah Park's Michael Hillas has become the cornerstone of the technique for determining E_0 , the incident energy, with a ground array. It is called the p (600) method: From Monte Carlo studies, Hillas determined that the density of particles near 600 meters from the shower core is proportional to E_0 , and appears to be particularly insensitive to shower development fluctuations.

Atmospheric fluorescence

A very different technique for studying ultrahigh-energy cosmic rays was developed by George Cassiday, Eugene Loh and colleagues at the University of Utah. It is based on a prototype detector built by Greisen to study directly the longitudinal development of extensive air showers in the atmosphere, by means of the nitrogen fluorescence excited by the shower's charged particles. Unlike Cerenkov radiation, this ultraviolet fluorescence is isotropic; it can be viewed from any angle by appropriate optical detectors. This fluorescence yields about four photons per meter of ionizing trajectory, at any altitude up to about 10 km. The light is emitted in several bands from 300 to 400 nm, wavelengths at which the atmosphere is quite transparent.

Extensive Air Showers

When a high-energy cosmic ray enters the atmosphere it produces a cascade of particles called an extensive air shower. The initiating particle's energy is divided among the large number of secondary particles created in the first interaction, which typically occurs at an altitude of 20 km. These secondary particles in turn interact deeper in the atmosphere, further subdividing the energy. Most of the energy of these secondaries is eventually carried by electrons and photons, the end products of pion decay.

This avalanche process continues until the shower particle energies drop below the critical threshold energy E_c for inelastic particle production (about 100 MeV.) After that, particles can lose energy only by ionizing air molecules, and their number begins to decrease exponentially. The depth in the atmosphere at which most particles fall below E_0 is X_{\max} , the depth at which the shower has its maximum particle density. If all the primary energy E_0 were converted to electrons and photons, the number N_{\max} of shower particles at this maximum would be proportional to the incident energy, because in that case, $E_0 / N_{\max} = E_c$. For a given primary energy, X_{\max} depends on the atomic number of the incident nucleus. For heavy nuclei, X_{\max} is higher in the atmosphere than for protons.

A small fraction of the energy in a shower is carried by muons and neutrinos from the decay of charged pions. Muons typically reach the ground intact. Their multiplicity at ground level depends on the number and distribution of charged pions in momentum and altitude, all of which depends on whether the primary particle is a proton or a heavier nucleus. Therefore muon multiplicity can be used to estimate the composition of cosmic rays. Incident Fe nuclei, for example, yield nearly twice the number of muons at ground level as do incident protons of the same E_0 . The fraction of E_0 lost to neutrinos and muons decreases with increasing incident energy. At 10^{20} eV, it is estimated to be only 5%.

One records this fluorescence with a mosaic of photomultiplier tubes, appropriately called a fly's eye, which subdivides the hemisphere of the sky into pixels. As a shower develops through the atmosphere, a pixel detects a time-dependent signal proportional to the number of ionizing particles passing through its field of view. The moving shower defines a track through the atmosphere, which translates into a track of pixels in the detector. The integral of the reconstructed shower profile is directly proportional to the primary energy. The method is essentially calorimetric, measuring the total energy deposition in the atmosphere by means its fluorescence. It does not require a complex Monte Carlo calculation to determine the energy scale. One simply has to know nitrogen's fluorescence efficiency for ionizing particles.

Our University of Utah group built its first fluorescence detector-Fly's Eye I-in 1982. A second eye, called Fly's Eye II, was built three years later, 3.5 km away from the first. We could then detect an extensive air shower in stereo, with much more precision and redundancy. The Fly's Eye experiment took data from 1982 to 1992. Of course, this method works only on dark, moonless nights with good weather. So, over that decade, we could monitor the sky only about 10% of the time.

Recent results

By 1994, final results from the Fly's Eye⁶ and preliminary results from AGASA⁷ became available. Figure 2 shows the resulting spectra. A general feature of the high-energy data is the flattening of the spectrum near 10^{19} eV, confirming hints from the older arrays.

The Fly's Eye data comprise two subsets: poorer resolution monocular data (figure 2a) and stereo data (figure 2b), with better resolution but lower statistics. The Fly's Eye stereo spectrum exhibits significant structure between 1018 and 1019 eV. The more abundant monocular data also show the flattening above 10^{19} eV but their resolution is not fine enough to confirm the pronounced dip structure near 3×10^{19} eV indicated in the stereo data.

The AGASA data (figure 2c) confirm the E^{-3} spectrum below 10^{17} eV. This power-law falloff changes somewhere around 10^{19} . But limited statistics and resolution make it difficult to determine the precise energy at which the break occurs. Although the Fly's Eye and the AGASA array employ quite different methods for determining the shower energy, their spectral measurements are consistent with one another. As we discuss below, the high-energy spectral break may well be correlated with a change in the cosmic-ray composition.

There is some evidence of the predicted GZK cutoff and a universal distribution of sources. If we simply extrapolate the lower-energy Fly's Eye and AGASA spectra beyond 10^{20} eV, we would expect the two experiments together to have seen about twenty events above that energy, instead of the two they actually did see.

Composition of cosmic rays from 10^{17} to 10^{19} eV

Important, albeit indirect, information on cosmic-ray composition can be garnered from the altitude at which an extensive air shower reaches its maximal density of particles. (See the box on page 33.) For a given nuclear species, the atmospheric depth X_{\max} of the shower maximum increases logarithmically with primary energy. If one plots X_{\max} against E_0 , different nuclei will exhibit similar logarithmic slopes ("elongation rates"), but quite different intercepts. Although one can't make the precise composition measurements that can be done at lower energies, one can distinguish light, predominantly protonic primaries from the heavier nuclei such as iron.

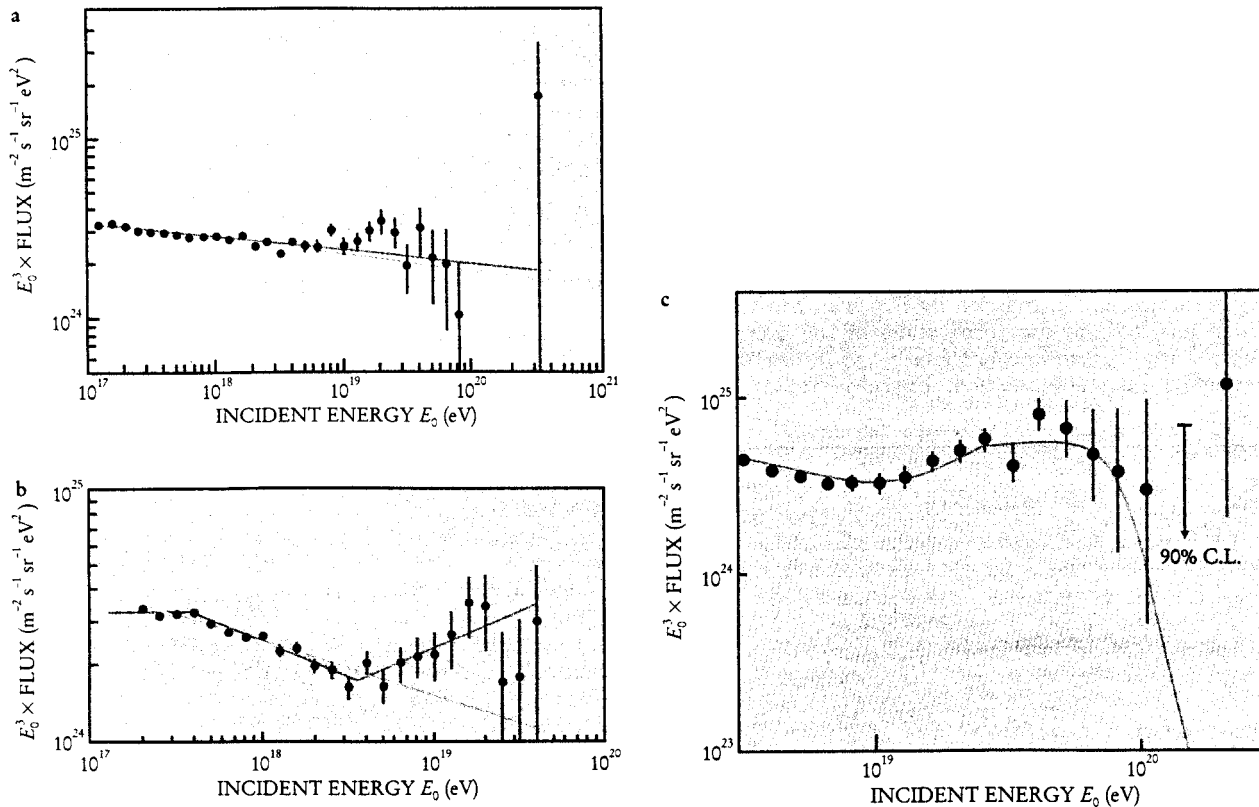


FIGURE 2. COSMIC-RAY ENERGY SPECTRA measured by a: the monocular Fly's Eye I fluorescence telescope, b: the binocular Fly's Eye II, and c: the AGASA ground array. The superposed straight lines are meant to guide the eye, and the curve in panel c is a prediction of the GZK cutoff.

Furthermore, a mixed cosmic-ray flux whose mean nuclear mass decreases with increasing energy will appear to have a larger elongation rate than one expects for a single nuclear species. Figure 3 shows the Fly's Eye stereo data and the expected X_{\max} energy dependence for incident protons and iron nuclei. It is evident that the cosmic-ray composition appears to be getting lighter in the decade between 10^{18} and 10^{19} eV the same energy interval in which we see a significant flattening of the slope of the energy spectrum. A straightforward interpretation of this coincidence would be that a light, hard-spectrum flux of extragalactic origin begins to dominate over the softer, heavier Galactic component somewhere around 5×10^{18} eV.

The hypothesis that the highest-energy cosmic rays are extragalactic is also supported by measurement of their apparently isotropic distribution. The microgauss Galactic magnetic field bends the trajectories of charged particles, but the Larmor radius of a 10^{19} eV proton is comparable to the radius of the Galactic disc. Its trajectory would be deflected by only a few degrees within our Galaxy. If cosmic rays beyond 10^{19} eV were protons originating in the Galaxy, we would expect to see a strong enhancement toward the Galactic plane. At lower energies, where the Galactic field thoroughly tangles up trajectories, the observed isotropy is consistent with heavy nuclei of local origin.

The two highest-energy events

In 1993 the AGASA ground array detected a giant air shower whose primary energy was estimated to be 2.1×10^{20} eV, clearly beyond the GZK cutoff. This event hit the array almost dead center, and 23 detectors surrounding the shower core measured

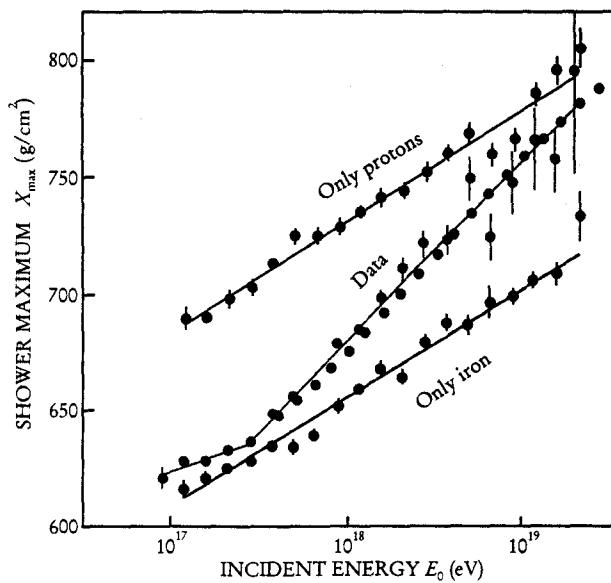


FIGURE 3. MEAN ATMOSPHERIC DEPTH X_{\max} , of the maximum shower-particle density, shown as a function of incident energy. For pure proton and iron fluxes, the points are Monte Carlo simulations. The actual data points, from Fly's Eye stereo measurements, are nicely fitted (blue line) by the superposition of a hard proton spectrum and a softer iron spectrum. Atmospheric depth is given in terms of air column density, which is essentially pressure, arrival times and electron densities. The shower was so unusually extensive that it triggered detectors more than 2 km from the core (see figure 4). Therefore the reconstruction of the lateral distribution of electrons was excellent.

The largest uncertainty in the energy estimation is our ignorance of the dependence of the shower attenuation of $p(600)$ on atmospheric depth at this extreme energy. But even if we assume there is no shower attenuation at all in the atmosphere, we get a lower E_0 bound of 1.7×10^{20} eV, still well beyond the GZK cutoff.

Data from five muon detectors yielded an estimated muon density of 42.8 per m^2 at 600 m from the core (figure 4b), which agrees well with extrapolation of lower energy shower data to 2.1×10^{20} eV. So do all the other parameters of this record ground-array shower. There was nothing peculiar about it, except for its remarkable energy. There is no particular indication from the observed muon content that the primary particle was a gamma ray or a very heavy nucleus.

The even more energetic 3.2×10^{20} eV event was recorded on 15 October 1991, not by a ground array but by the Fly's Eye. Unfortunately it was seen only by Fly's Eye I, because its trajectory was in the Fly's Eye II blind spot. Nonetheless, the event appears to have been well reconstructed. The trajectory's closest approach to the detector was 13 km. Its longitudinal shower profile is shown in figure 4c. The detector was in good working order at the time, and the weather was clear. If, in fact, the atmospheric attenuation of the ultraviolet light was stronger than our reconstruction programs assumed, the true energy would be even higher than 3.2×10^{20} eV. The position of the shower maximum is consistent with either an incident proton or a heavy nucleus. Because the event was recorded only by Fly's Eye I, the reconstruction is not overconstrained. Therefore it is important to have an independent lower bound on E_0 . But the very fact the shower did not trigger Fly's Eye II helps us derive that lower bound, which turns out to be 1.4×10^{20} eV.

What are they telling us?

If the systematic errors and energy resolutions claimed for these two spectacular events are correct, they seem to imply the continuation of a cosmic-ray flux beyond the GZK cutoff. However, the energy resolution can be checked only at lower energies, where there are adequate statistics. Therefore, until we have more ultrahigh-energy events in hand, our interpretations must be very cautious.

The two record events do seem to spoil the simple picture proposed by Greisen, Zatsepin and Kuzmin. And they pose other puzzles.⁸ The GZK effect limits the distance that the cosmic ray could have traveled and yet maintained its observed energy. The attenuation length (over which the energy falls by a factor of e) for protons with E_0 above 3×10^{20} eV is about 30 megaparsecs (1 Mpc = 3×10^6 light-years), and it is even smaller for gamma rays or heavy nuclei. Therefore these two events are very unlikely to have originated at distances greater than 50 Mpc. By cosmological standards, that's the local neighborhood. Furthermore, after they entered our Galaxy, their enormous momenta would have kept their trajectories from being bent by more than a few degrees by the Galaxy's magnetic field.

Magnetic bending in intergalactic space is more problematical, because the character of the intergalactic fields is not well known. Theoretical models and observational limits on Faraday rotation yield estimates of about 10^{-9} gauss. That would mean that the bending of 10^{20} eV cosmic rays over 50 Mpc is still quite small. So we can expect such events to point back to their origins within an error box 10° on a side.

Most acceleration models predict that the sources of ultrahigh-energy cosmic rays lie in active galactic nuclei or other radio galaxies. Accordingly, astronomers have searched for all such possible sources out to 50 Mpc within the error boxes of the highest-energy events. But they have found no candidate sources. If the energies are correct, then either the intergalactic magnetic fields are much stronger than we thought or the sources are not obvious active radio galaxies.

Proponents of exotic decay processes such as superconducting cosmic strings or monopole-antimonopole atoms will be cheered by the apparent lack of astrophysical candidates. It is obviously of great importance to confirm the existence of cosmic rays beyond 10^{20} eV by increasing the sensitivity of detector complexes at least tenfold. We also need a better handle on the nature of these ultraenergetic particles. If they all turn out to be heavy nuclei and the intergalactic fields are stronger than we expect, then magnetic bending might well render arrival directions useless for identifying point sources.

The next generation

The High Resolution Fly's Eye Detector (HiRes) is a collaboration between the universities of Adelaide, Illinois and Utah and Columbia University. It will have at least an order of magnitude more sensitivity to cosmic rays above 10^{20} eV than the original Fly's Eye pair. HiRes is designed to study the cosmic-ray energy flux above 3×10^{18} eV, and to measure its composition and anisotropy with significantly improved resolution.

Approved as a construction project in 1994, HiRes is scheduled for completion in the summer of 1999. In addition to the original Fly's Eye I site, HiRes will occupy a new site 12.5 km away. The new facility will achieve its increased aperture and improved resolution by decreasing the pixel size from 5.5° to 1° on a side, and by doubling the mirror area to 3.5 m^2 . At the highest energies, the aperture is $13\,000 \text{ km}^2 \text{ sr}$.

With its enhanced signal-to-noise ratio, HiRes should easily detect showers that come no closer than 30 km. Better sampling along the shower trajectory will allow even short tracks to be well reconstructed. Furthermore, HiRes will see all events in stereo, so that one will always have two independent measurements of E_0 and the longitudinal shower profile. One will thus be able to measure directly the detector's resolution as a function of energy and X_{max} . That's crucial to ascertaining, for instance, that an apparently continuing spectrum is not an artifact due to a spill-down effect produced by the detector's resolution.

Figure 5 shows two of the HiRes mirror units together with their photomultiplier clusters. Each mirror unit consists of four glass segments that form a single spherical mirror. In its focal plane is a close-packed cluster of 256 hexagonal phototubes. An ultraviolet filter in front of the cluster cuts out light below 300 nm and above 420 nm. The two HiRes sites will have a total of 64 mirrors.

The Telescope Array project is another undertaking of the University of Tokyo's cosmic-ray group, this time in collaboration with HiRes. This proposal envisages a number of air fluorescence detectors with a total aperture of more than $40\,000 \text{ km}^2 \text{ sr}$. In terms of detection sensitivity, that's 50 times larger than the present AGASA array. The Telescope Array is designed to be the ultimate ground-based fluorescence detector for high-statistics, high-resolution measurement of the highest energy cosmic rays. Prototype detectors are now being constructed by a consortium of Japanese universities and installed at the Dugway Proving Ground, 25 km from the HiRes sites. Joint test observation with HiRes is scheduled to begin soon.

The Pierre Auger Project is another ambitious proposal. Led by James Cronin (University of Chicago), it envisages two huge surface arrays—one in Utah, the other in Argentina—to provide full sky coverage. (See PHYSICS TODAY, February 1997, page 19, for a detailed description.) Each site will actually be a hybrid facility, with several fluorescence telescopes designed to operate in coincidence with the ground array. If the cosmic-ray energy spectrum continues without a GZK cutoff, the two Auger sites together should see about 60 events per year above 10^{20} eV.

FIGURE 4. THE TWO HIGHEST ENERGY EVENTS ever seen. For the 2.1×10^{20} eV event seen in 1993 by the AGASA array, the circle radii in (a) are logarithmic representations of the signals recorded by individual ground detectors within several kilometers of the shower core, and (b) shows the density of all shower particles (in blue) and muons (in red) recorded by ground detectors in the outer reaches of the shower. For the 3.2×10^{20} eV event seen in 1991 by the Fly's Eye, (c) shows the evolving shower (as measured by fluorescence) at various atmospheric depths along its trajectory. The shower had its maximum at an air column density of about 800 g/cm^2 . The curves in panels b and c are extrapolations from data at lower energies.

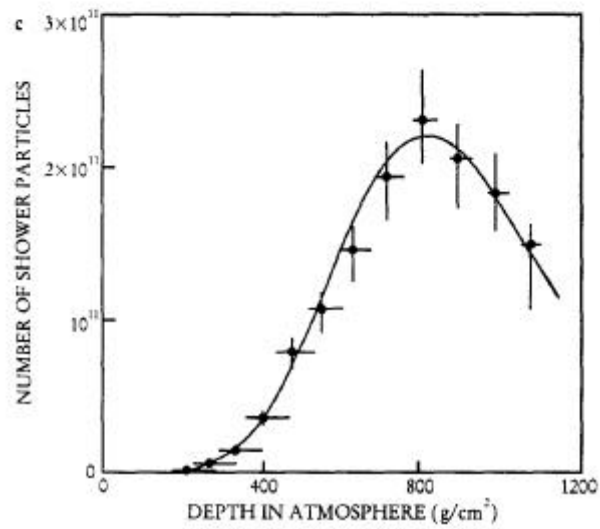
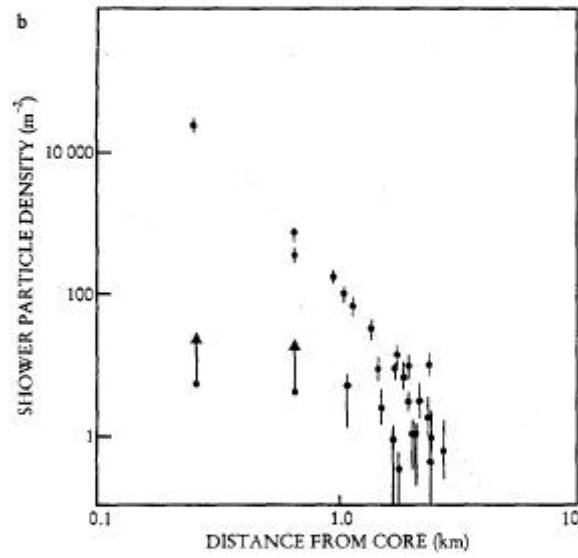
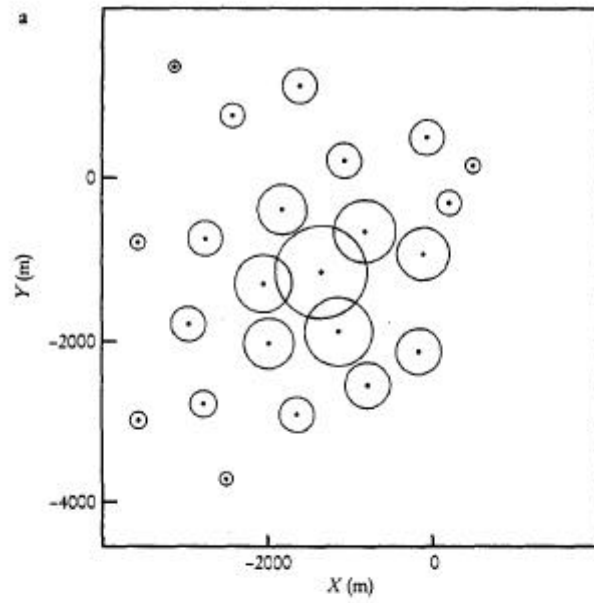




FIGURE 5. MIRROR UNITS for HiRes, the High Resolution Fly's Eye Detector. Each of the facility's 64 spherical-mirror units will comprise four glass segments and a cluster box (seen here from behind) in the focal plane, containing a mosaic of 256 hexagonal photomultiplier tubes. Two such units will be enclosed in each of 32 garage-type sheds arrayed over the project's two sites. Some of this may change in March, when a revised Auger proposal is expected in response to a review just completed by a subcommittee of DOE's High Energy Physics Advisory Panel.

The OWL detector, proposed by a consortium led by NASA's Goddard Space Flight Center, is even more futuristic. The plan is to put a fly's eye detector into low Earth orbit. A set of downward looking mirrors or compound Fresnel lenses would observe fluorescent light signals from a fiducial area of about a million km^2 . With such an enormous aperture, this experiment could measure the cosmic-ray flux out to 10^{21} eV. It could even look for ultrahigh-energy neutrino events. A neutrino flux is expected, for example, from the decay of pions produced in the GZK mechanism. (See the box on page 32.) NASA is currently supporting feasibility studies for this very ambitious proposal.

Cut off or not cut off?

A number of very different experiments have now confirmed that the spectrum of the highest-energy cosmic rays exhibits significant structure. It is likely that these particles come to us from outside the Galaxy. But the long-sought GZK cutoff for ultraenergetic travelers over intergalactic distances remains elusive. Two spectacular events have been detected well beyond the predicted cutoff.

Sources for these two ultraenergetic cosmic rays cannot be very far off, but no obvious astrophysical candidates have been identified with their arrival directions. In the next five years HiRes and AGASA should shed considerably more light on events at these highest observed energies.

If the spectrum is shown to continue well past 10^{20} eV, we will certainly need much larger apertures like those envisioned in the Telescope Array, Auger and OWL proposals. The next decade should provide very interesting data. We will see if the cosmic spectrum is indeed cut off by pion-production losses, or if it continues on to energies approaching the grand unification energy scale energy of 10^{23} eV. It will be interesting to watch the twists and turns in astrophysical theory required to explain the results.

References.

1. A. A. Penzias, R. W. Wilson, *Ap. J.* **142**, 419 (1965).
2. K. Greisen, *Phys. Rev. Lett.* **16**, 748 (1966).
3. P. Sokolsky, P. Sommers, B. R. Dawson, *Phys. Rep.* **217** No.5, 225 (1992).
4. C. J. Cesarsky, *Ann. Rev. Astron. Astrophys.* **18**, 289 (1980).
5. P. Biermann, P. Strittmatter, *Astrophys. J.* **322**, 643 (18987).
6. D. J. Bird et al., *Phys. Rev. Lett.* **71**, 3401 (1993); *Astrophys. J.* **424**, 491 (1994); *Astrophys. J.* **441**, 151 (1995).
7. S. Yoshida et al., *Astropart. Phys.* **3**, 105 (1995).
8. J. W. Elbert, P. Sommers, *Astrophys. J.* **441**, 151 (1995).
9. C. T. Hill, D. Schramm, T. Walker, *Phys. Rev. D* **36**, 1007 (1987). C. T. Hill, J. Cronin, G. Goldhaber, T. O'Halloran, *Adult Onset Cosmology: Its Diagnosis and Treatment*, Stirnweiss, New York (1995).
10. S. Yoshida, M. Teshima, *Prog. Theor. Phys.* **89**, 833 (1993).