Extreme Astrophysics—The High-Resolution Fly's Eye Experiment

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The earth is constantly bombarded by high-energy particles of unknown origin. These particles, known as cosmic rays, have energies up to and beyond 10^{20} eV (10^{20} eV = 16 J, which is nearly the energy packed into a major league fastball). These are the highest energy particles in the universe. Their origin is unknown, and they represent one of the mysteries of modern science. What are they? How do they attain their enormous energies? How do they propagate to earth? Compounding the inherent difficulty of studying extraterrestrial particles is the rarity of these ultra-high-energy cosmic rays. Above 10^{20} eV, only one of these particles will pass through a square kilometer of the earth in a century. Figure 1 shows the cosmic-ray spectrum from 1 GeV (i.e., a billion electron-volts to above 10^{20} eV). The HiRes experiment located in Dugway, Utah, seeks to gain an understanding of the properties of these particles: how many there are, where they come from, and what they are.

The HiRes Experiment

When a UHECR enters the atmosphere, it interacts with the molecules in the air, creating an EAS. The EAS is composed of billions of particles (electron, positrons, gamma rays, and muons) traveling at the speed of light towards the earth. The passage of the charged particles excites nitrogen molecules in the air. These excited molecules emit fluorescence light. Because this light is emitted isotropically, a detector does not need to be "in the beam" to be detected—therefore, a relatively small detector with an enormous aperture will do the job. The HiRes detector consists of two independent sites separated by 12.6 km so that each event may be viewed stereoscopically. This stereoscopic view gives the detector depth perception and allows us to measure the distance to each event. At each site, there is a set of 5-m^2 mirrors, each equipped with a 256-PMT camera placed in the focal plane. Each PMT has a 1^o field of view. The HiRes I site has 21 mirrors covering an elevation range from 3^o to 17^o, and the HiRes II site has 44 mirrors covering an elevation range from 3^o to 31^o. Both sites provide a 2-π azimuthal coverage of the sky. The aperture of the full HiRes detector is 10,000 km^2 sr at 10^{20} eV. In HiRes I, the shower images are stored in sample-and-hold electronics with a 5.6-µs window; in HiRes II, the information is digitized with a 10-MHz flash (analog-to-digital converter) system. The air-fluorescence technique (Figure 2) used in our experiments allows us to detect the passage of an air shower with the HiRes instrument. The entire longitudinal development of the air shower is obtained by recording the amount of light detected in each PMT.

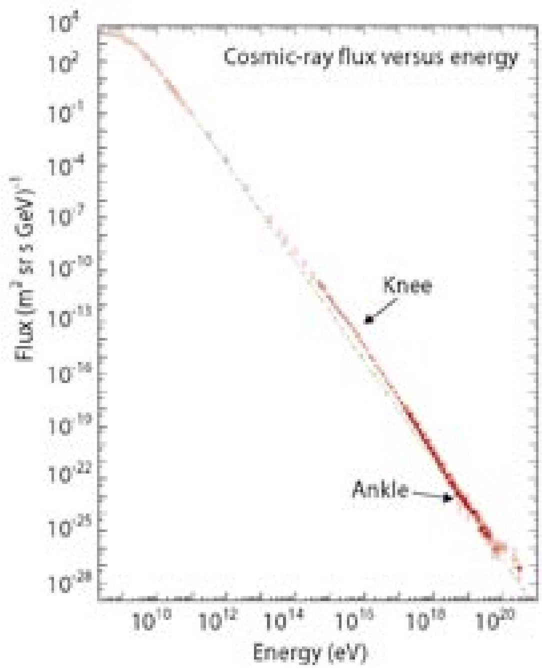

Figure 1. The cosmic-ray spectrum from 1 GeV to 10^{20} eV. The spectrum is well represented by a power law but with two features. At an energy of roughly 10^{15} eV, the spectrum begins to fall faster with energy (which is the knee of the cosmic-ray spectrum), and at an energy of roughly $10^{18.5}$ eV, the spectrum hardens slightly (which is the ankle of the cosmic-ray spectrum). Above 10^{20} eV, the flux is about one particle per square kilometer per century.

UHECR Science

A UHECR flux above an energy of 6 x 10^{19} eV is of fundamental importance in astrophysics studies. Protons with energies in excess of this will interact with microwave background radiation and lose energy through pion production—this process is known as the GZK effect (for Greisen, Zatsepin, and Kuzmin, the co-discoverers of the effect).[1,2] The mean-free path for this interaction is roughly 20 million light years; therefore, the flux of particles above this energy is expected to fall rapidly—unless the "point" sources of these particles are relatively close to the earth. If the point sources *are* close to the earth, the particles should point back to them because at these energies the particles bend via intergalactic magnetic fields at relatively small ($< 2^\circ$) angles. However, the particles that we detected to date do not appear to point back to any objects capable of accelerating particles to these energies.[3]

At present, there is disagreement between the only two experiments that have measured the flux at these energies—the HiRes and the Akeno Giant Air Shower Array (AGASA). The AGASA is a traditional scintillator array composed of 111 particle detectors spread over 100 km^2. Figure 3 shows the present status of the world's dataset.[4] The curve on the figure is what one would expect if the sources of UHECRs were uniformly distributed throughout the universe and if the GZK effect were included. (The data from HiRes and AGASA are indicated in the legend.) Although the HiRes data are consistent with this curve, the AGASA data are not. The overall offset of the two datasets is due to systematic uncertainties in the absolute energy scale of the two experiments. The HiRes data were taken in "monocular" mode—determining the distance to the air shower (and therefore the energy of the primary cosmic ray) is not made directly but relies instead on a fit to the shower profile. At present, neither experiment has the statistical power or an understanding of systematic effects to make a definitive statement on the existence of the GZK effect.

If the GZK effect is not present, then there are many possible explanations, most of which involve exciting new physics. The solutions can be grouped into either a "top-down" or a "bottom-up" scenario. In the top-down scenario, the particles are the decay products of very massive particles, possibly relics left from the Big Bang.[5,6] In the bottom-up scenario, the particles are accelerated to high energies by astrophysical sources such as gamma-ray bursts or active galactic nuclei. In these scenarios, super-GZK events can be caused by a suppression of the proton-photon interaction at high energies, which would clearly violate Lorentz invariance and may be a signal of quantum gravity.[7,8] The super-GZK events may also be caused by the existence of a new strongly interacting particle (for example, a massive, stable hadron) that does not suffer from the energy loss in the 3-K radiation field.[9,10] Moreover, there may be unseen "local" astrophysical sources of UHECRs or ultra-high-energy neutrinos that may propagate over cosmological distances and interact with (massive) relic neutrinos within 160 million light years of the earth. If the latter were the case, a cascade of gamma rays and hadronic particles (known as the "Z-burst" model) would be detected.[11]

Each of the scenarios described above make different predictions as to the nature of UHECRs—are they protons, gamma rays, heavy nuclei, neutrinos, or some as yet undiscovered particle? Each of these particles is expected to have a different cross section; therefore, they will interact at different depths in the atmosphere, and the resulting air shower will have a different altitude of maximum development. Because the HiRes experiments observe the entire longitudinal development of the air shower, we can measure the altitude of the maximum shower with a resolution of roughly 30 g/cm^2. Although shower-to-shower fluctuations preclude us from measuring the particle type on an event-by-event basis, we can determine the average composition of the UHECRs using the air-fluorescence technique. Finally, we want to know where these UHECRs are coming from. Do they come from point sources (if so, which objects are accelerating particles to such high energies) or are they isotropic? There is preliminary evidence from AGASA that the UHECRs come in clusters. If this claim is correct, it would imply that there are numerous stable sources of UHECRs. With an angular resolution of 0.4°, HiRes can verify or repudiate this claim.

Conclusion

Because the GZK effect is predicted to occur at a well-defined energy, knowing the true energy of each event is critical. Systematic errors must therefore be of the same order or smaller than statistical errors. The systematic errors in the current HiRes analysis are caused by a 10% uncertainty in the absolute fluorescence yield and by the attenuation of particles as they are absorbed in the atmosphere. To reduce the errors from atmospheric absorption, we have installed a set of lasers that allow us to continuously monitor the atmosphere over the entire aperture of the detectors. With these lasers, we can make atmospheric corrections on an event-by-event basis and calculate the aperture of the experiment on an hourly timescale. Most importantly, because HiRes was built to view all events stereoscopically, we can determine the shower distance and inclination angle from purely geometrical considerations. Figure 4 shows the stereo reconstruction of a typical event. Once the geometry of the shower is known, crosschecks can be performed on the atmospheric attenuation (because the two detector sites are, in general, a different distance from the shower). Such a crosscheck will allow us to better measure and control systematic uncertainties. A complete stereo analysis is now under way. Within five years of taking data, HiRes will detect 50 events with energies in excess of 6×10^{19} eV and 20 events above 10^{20} eV if there is no GZK effect. With these results, we will be able to make a statistically significant measurement of the GZK effect. Within the next several years, HiRes will have solved a major riddle of modern physics—the nature of the highest-energy particles in the universe.

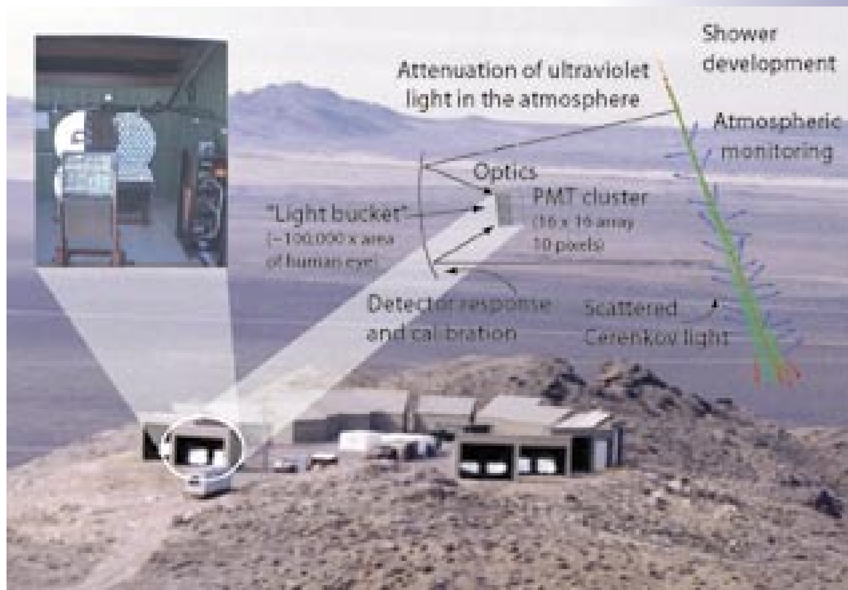

Figure 2. Schematic view of the detection of an EAS using the air-fluorescence technique. The electromagnetic particles in the air shower excite nitrogen molecules in the atmosphere, which radiate ultraviolet light. This light passes through the atmosphere (as much as 40 km) where it is absorbed and scattered. The surviving light is reflected from the mirrors and focused onto a fast camera composed of PMTs.

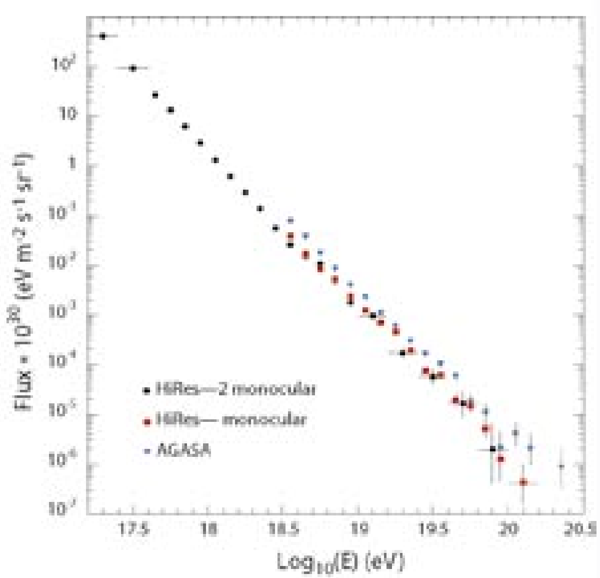

Figure 3. The UHECR as measured by HiRes in monocular mode and the AGASA experiment. The flux has been multiplied by E^3 to show the structure. The offset between the two experiments arises from systematic uncertainties in the absolute energy calibration of the two detectors. Although the HiRes data are consistent with the existence of the GZK effect, the AGASA data indicate that the spectrum hardens above 10^{20} eV.

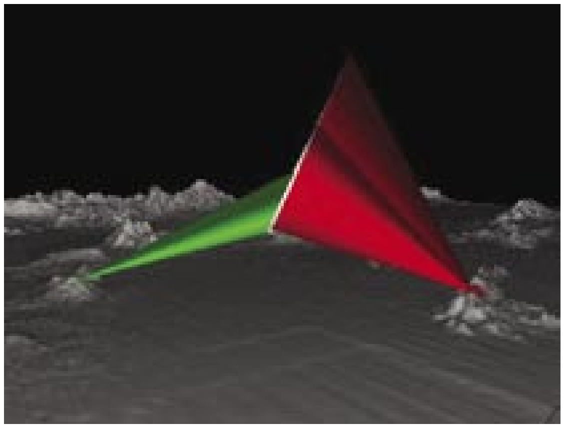

Figure 4. A typical event as seen by HiRes in stereo mode. Each detector determines a plane in which the shower lies. The intersection of the two planes determines the full three-dimensional geometry of the event.

References

1. K. Greisen, "End to the cosmic-ray spectrum," *Physical Review Letters* **16**(17), 748 (1966).
2. G.T. Zatsepin and V.A. Kuzmin, "Upper limit of spectrum of cosmic rays," *Journal of Experimental and Theoretical Physics* **4**(3), 78 (1966).
3. J.E. Elbert and P. Sommers, "In search of a source for the 320-EeV fly's eye cosmic ray," *Astrophysical Journal* **441,** 151 (1995).
4. T. Abu-Zayyad *et al.*, "Measurement of the flux of ultra-high-energy cosmic rays from monocular observations by the high resolution fly's eye experiment," submitted to *Physical Review Letters.*
5. P. Bhattacharjee, C.T. Hill, and D.N. Schramm, "Grand unified theories, topological defects, and ultrahigh-energy cosmic rays," *Physical Review Letters* **69,** 567 (1992).
6. C.T. Hill, D.N. Schramm, and T.P. Walker, "Ultrahigh-energy cosmic rays from superconducting cosmic strings," *Physical Review D* **36,** 1007 (1987).
7. S. Coleman and S.L. Glashow, "High-energy tests of Lorentz invariance," *Physical Review D* **59,** 151 (1999).
8. G. Amelino-Camelia and T. Piran, "Planck-scale deformation of Lorentz symmetry as a solution to the ultra-high-energy cosmic rays and the TeV-photon paradoxes," *Physical Review D* **64,** 036005 (2001).
9. G.R. Farrar, "Detecting light-gluino-containing hadrons," *Physical Review Letters* **76,** 4111 (1996).
10. I.F.M. Albuquerque, G.R. Farrar, and E.W. Kolb, "Exotic massive hadrons and ultra-high-energy cosmic rays," *Physical Review D* **59,** 015021 (1999).
11. T.J. Weiler, "Cosmic-ray neutrino annihilation on relic neutrinos revisited: A mechanism for generating air showers above the Greisen-Zatsepin-Kuzmin cutoff," *Astroparticle Physics* **11,** 303 (1999).

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