The Mystery of Ultra-High Energy Cosmic Rays

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Abstract. Cosmic rays with energies well above 10^{19} eV are messengers of an unknown extremely high-energy universe. The current state and future prospects of ultra high energy cosmic ray physics are briefly reviewed.

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INTRODUCTION

Cosmic rays have been known to be of *cosmic* origin since 1912 and by 1938 Pierre Auger had shown that cosmic ray primaries reach energies in excess of 10^{15} eV with the detection of extensive air-showers [1]. Since then cosmic rays have been observed with energies up to $\sim 10^{20}$ eV. Fermi acceleration in supernova remnants may be responsible for accelerating cosmic rays up to $\sim 10^{15}$ eV, but more powerful sources are required to explain higher energy events. No sources of cosmic rays have been identified thus far and their origin remains a mystery about to become a century old.

Fig. 1 shows a compilation of direct and indirect (via air showers) cosmic ray observations unified into a single spectrum. For comparison, the equivalent center-of-mass energies involved in the collisions in terrestrial accelerators are indicated in the energy axis. The spectrum is well fit by power-laws with spectral index $\gamma \simeq 2.7$ for energies below $\sim 10^{15}$ eV and $\gamma \simeq 3.1$ for energies above $\sim 10^{15}$ eV, with a time varying low energy cutoff due to solar magnetic fields. The composition of cosmic rays is well understood below $\sim 10^{14}$ eV. The spectrum is dominated by protons, followed by He, C, N, O, and finally Fe nuclei. At higher energies, indirect evidence points to a change from proton to Fe dominated spectrum between $\sim 10^{15}$ eV and $\sim 10^{17}$ eV [2] with a possible change back to lighter nuclei above $\sim 10^{18}$ eV [3]. For energies above $\sim 10^{19.5}$ eV the composition is unknown.

At the highest energies, the present state of observations is particularly puzzling. Fortunately, the necessary experiments to resolve these puzzles are starting to operate now. The puzzles begin with the uncertainty surrounding the Greisen-Zatsepin-Kuzmin (GZK) cutoff [4]. Contrary to earlier expectations, cosmic rays with energies around 10^{20} eV have been detected by a number of experiments (for reviews see [5]). If these ultra-high energy cosmic rays (UHECRs) are protons, they are likely to originate in extragalactic sources, since at these high energies the Galactic magnetic field cannot confine protons in the Galaxy. However, extragalactic protons with energies above

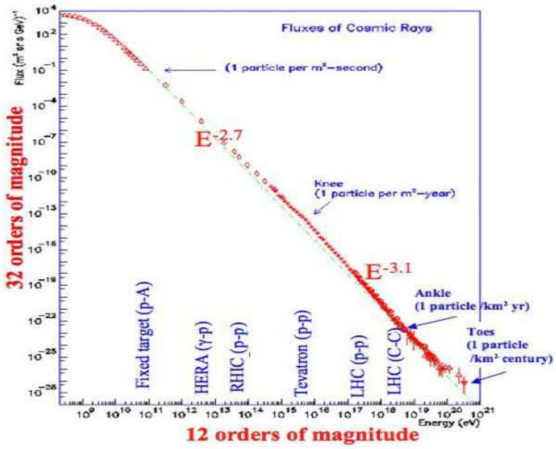

FIGURE 1. Spectrum of cosmic rays.

$\sim 10^{20}$ eV produce pions through interactions with the cosmic microwave background (CMB) and consequently lose significant amounts of energy as they traverse intergalactic distances. Thus, in addition to the extraordinary energy requirements for astrophysical sources to accelerate protons to $\gtrsim 10^{20}$ eV, the photopion threshold reaction suppresses the observable flux above $\sim 10^{20}$ eV. These conditions were expected to cause a natural high-energy limit to the cosmic ray spectrum known as the GZK cutoff.

The Akeno Giant Airshower Array (AGASA) reported that the spectrum of cosmic rays does not end at the expected GZK cutoff [6]. The significant flux observed above 10^{20} eV together with a nearly isotropic distribution of event arrival directions challenges astrophysically based explanations as well as new physics alternatives. In addition, the reported small scale clustering [7] tends to rule out most scenarios [8].

This challenging state of affairs is stimulating both to theoretical investigations as well as experimental efforts. The explanation may hide in the experimental arena such as an over estimate of the flux at the highest energies. This explanation has been proposed by the High Resolution Fly's Eye (HiRes) collaboration which reports a spectrum consistent with a GZK *feature* [9] . These two experiments have exposures around $\sim 10^3$ km^2 sr yr with conflicting results at the highest energies (above $\sim 10^{20}$ eV) where limited statistics and systematic errors prevent a clear resolution.

New experiments are coming on line that will resolve this conflict. The Pierre Auger Observatory [10] has already released a spectrum based on data taken during construction with an exposure similar to AGASA [11]. As shown in Fig. 2, there is a systematic shift between Auger and HiRes spectra and the AGASA spectrum that can be due to a systematic error in the energy estimation of about 25%. Auger used the fluorescence analysis to calibrate the energies of hybrid events while using the surface detector for exposure and statistics in the spectrum calculation. The systematic shift in energy may be due to the need to use Monte-Carlo simulations to extract the energy of events in surface detectors. The structure of the GZK feature will only become clear once another order of magnitude of exposure is reached. In any scenario (GZK feature or not), events past

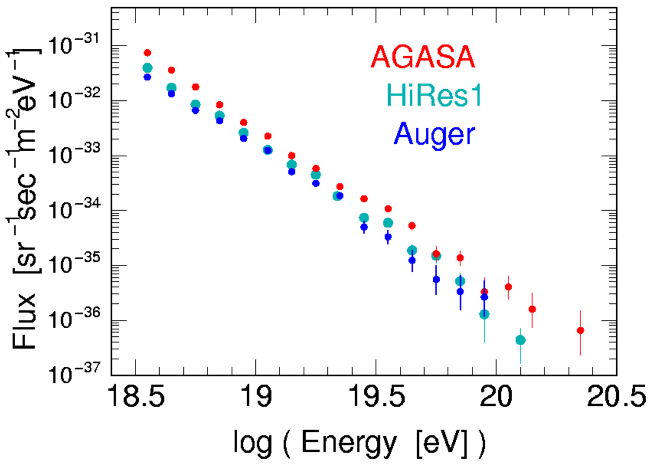

FIGURE 2. UHECR spectrum from AGASA, HiRes, and Auger.

10^{20} eV pose theoretical challenges which should be explained in the future by either astrophysically novel sources or new fundamental physics.

PRESENT STATE OF UHECR OBSERVATIONS

Ultra-high energy cosmic rays are the highest energy messengers of the present universe. Cosmic rays are observed with energies as high as 3×10^{20} eV and with fluxes well above upper limits on high-energy gamma-ray fluxes. However, the origin of cosmic rays remains a mystery hidden by the fact that these relativistic particles do not point back to their sources. These charged particles are deflected by magnetic fields that permeate interstellar and intergalactic space. Galactic magnetic fields are known to be around a few micro Gauss in the Galactic disk and are expected to decay exponentially away from the disk [12]. Intergalactic fields are observed in dense clusters of galaxies, but it is not clear if there are intergalactic magnetic fields in the Local Group or the Local Supergalactic Plane. On larger scales, magnetic fields are known to be weaker than $\sim$ 10 nano Gauss [13].

As cosmic ray energies reach 10^{20} eV per charged nucleon, Galactic and intergalactic magnetic fields cannot bend particle orbits significantly and pointing to cosmic ray sources becomes feasible. Recent high-resolution simulations of large-scale structure formation in a ΛCDM universe can follow the magnetic field evolution from seed fields to present fields in galaxies and clusters [14]. The intergalactic medium fields in these simulations are consistent with Faraday rotation measurements at the 10^{-9} – 10^{-8} Gauss level. In addition to simulating the field evolution, cosmic ray protons are propagated through a volume of 110 Mpc radius. The deflection from the source position to the arrival direction for protons with arrival energy of 4×10^{19} eV are $\sim 1^\circ$ in the densest regions [14]. For protons arriving with 10^{20} eV the deflections are less than $\sim 0.1^\circ$ (which is significantly smaller than the resolution of UHECR observatories) [14]. Therefore, at ultra high energies there is finally the opportunity to begin cosmic ray

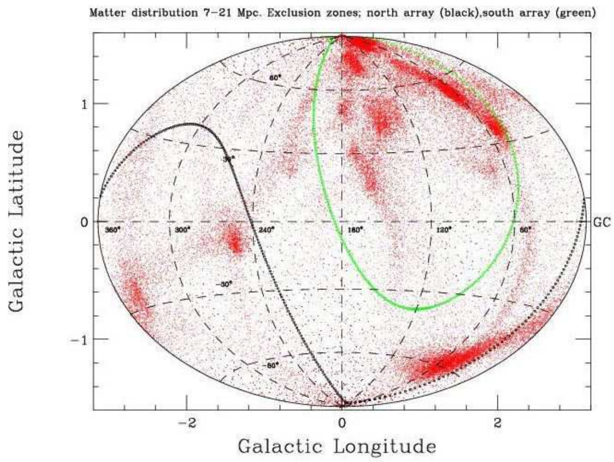

FIGURE 3. Dark Matter distribution in the sky between 7 and 21 Mpc. CRs at the highest energies should display the source distribution within 50 Mpc.

astronomy.

In addition to the ability to point back to the source position, cosmic ray protons of energies around 10^{20} eV should display a well-known spectral feature called the GZK cutoff [4]. This cutoff was proposed in 1966 by Greisen, Zatsepin and Kuzmin as a natural end to the cosmic ray spectrum due to photopion production off the then recently discovered cosmic microwave background radiation. The presence of microwave photons through cosmic space induces the formation and subsequent decay of the Δ^+ resonance for protons with energies above $\sim 10^{20}$ eV that traverse distances longer than ~ 50 Mpc. The effect of photopion production is to decrease the energy of protons from distant sources resulting in a hardening of the spectrum between 10^{19} eV and 10^{20} eV followed by a sharp softening past 10^{20} eV. Depending on the maximum energy of ultra high-energy cosmic ray sources and their distribution in the universe, the spectrum may harden again past the GZK feature displaying the injected spectrum of nearby sources.

In Fig. 3 the distribution of dark matter is shown at a distance ranging from 7 to 21 Mpc. This anisotropic distribution of dark matter in the local universe shows a possible anisotropic distribution of UHECR sources in this nearby volume. If sources of UHECRs correlate with the dark matter distribution (e.g., if they reside in galaxies), this kind of anisotropy should be observed in the sky as a large number of UHECRs with energies above $\sim 4 \times 10^{19}$ eV are detected. The relatively local nature of UHECR sources is expected due to the GZK effect which limits the range of cosmic rays above 10^{20} eV to $\lesssim 50$ Mpc. Futhermore, if future experiments observe clustering in small scales, a source density can be derived [15].

At present, observations of cosmic rays at the highest energies have yielded measurements of the spectrum, arrival direction distribution, and composition of UHECRs below 10^{20} eV. The cosmic ray spectrum past 10^{20} eV should show the presence or absence of the GZK feature, which can be related to the type of primary (e.g., protons) and source (injection spectrum and spatial distribution) of UHECRs. Two of the largest exposure experiments, AGASA and HiRes reported conflicting results at the highest energies (above $\sim 10^{20}$ eV) where limited statistics and systematic errors prevent a clear resolution.

AGASA was a 100 km^2 ground array of scintillator and muon detectors. AGASA data shows a distribution of arrival directions which is mainly isotropic with an indication of clustering of cosmic rays at the highest energies and smallest angles [7]. In addition, the spectrum shows the lack of a GZK cutoff around 10^{20} eV (see Fig. 2). The flux above 10^{20} eV does not show the expected GZK cutoff with the detection of 11 Super-GZK events, i.e., 11 events with energies above 10^{20} eV [6]. These findings argue against the notion of extragalalactic proton sources of UHECRs and for a unexpected new source at the highest energies.

In contrast, the HiRes monocular spectrum indicates smaller fluxes past 10^{20} eV which is consistent with a GZK feature [9]. HiRes is composed of fluorescence telescopes built in two different sites in the Utah desert to be used as a stereo fluorescence detector. While stereo results have recently reached comparable exposure to AGASA, monocular data have larger exposure. Mono HiRes analysis shows no evidence of clustering of arrival directions on small scales [16, 17] and a decrease in flux consistent with the GZK feature. In addition to the spectrum and distribution of arrival directions, HiRes data indicates that between $\sim 10^{18}$ eV and $10^{19.5}$ eV the composition shifts from a heavier (iron dominated) component to lighter (proton dominated) component [3] .

The implications of the differing results from AGASA and HiRes are especially intriguing at the highest energies. The discrepancies between HiRes and AGASA spectra corresponds to $\sim 25\%$ systematic error in energy scales. Possible sources of systematic errors in the energy measurement of the AGASA experiment were comprehensively studied to be at around 18 % [18]. Systematic errors in HiRes are still being evaluated, but are likely to be dominated by uncertainties in the absolute fluorescence yield, the atmospheric corrections, and the calibration of the full detector, which could amount to at least $\sim 20\%$ systematic errors in energy calibration.

Although control of systematic errors is crucial, the statistics accumulated by both HiRes and AGASA are not large enough for a clear measurement of the GZK feature. The disagreement between the two experiments is only about 2 σ using when systematic energy corrections of 15% are considered, which are well within the possible range of systematic errors [19]. The systematic energy shifts between AGASA and HiRes (and Auger) through the range of observed energies are easily seen in Fig. 2). Finally, the low exposure above 10^{20} eV of both experiments prevents an accurate determination of the GZK feature or lack of it. The lessons for the future are clear: improve the statistics significantly above 10^{20} eV and understand the sources of systematic errors.

PREVIEW OF THE NEXT GENERATION

Neither AGASA nor HiRes have the necessary statistics and control of systematics to determine in a definitive way the existence of either the GZK feature or of a novel source of Super-GZK events. Moreover, if the AGASA clusters are an indication of point sources of UHECRs, a large number of events per source will be necessary to study their nature. In order to discover the origin of UHECRs a much larger aperture

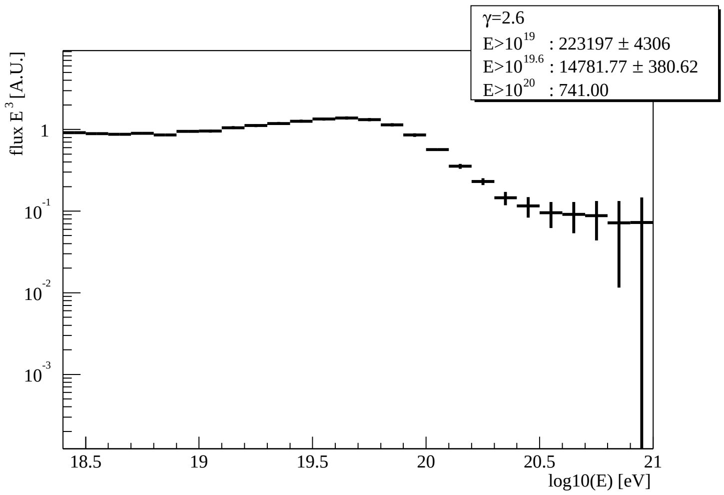

FIGURE 4. Auger North + South statistics at the GZK feature.

observatory is now under construction, the Pierre Auger Project [10]. Other projects under development include the Telescope Array [20] and the Orbiting Wide-field Light-collectors (OWL) mission [21].

The Pierre Auger Project will consist of two giant airshower arrays one in the South and one in the North. Auger is being built to determine the spectrum, arrival direction, and composition of UHECR in a full sky survey. The survey should provide large event statistics and control of systematics through detailed detector calibration of the surface array and fluorescence detectors individually in addition to the cross-calibration of the two detection techniques through the observation of hybrid and stereo-hybrid events. The Auger Observatory in the South will have 1600 water Cherenkov detectors covering 3000 km^2 and four sites of fluorescence telescopes. At present, three of the four fluorescence telescope sites have been taking data and over 1100 tanks have been deployed. Auger South should be finished by early 2007. Depending on the UHECR spectrum, Auger South should measure the energy, direction and composition of about 60 events per year above 10^{20} eV and about 6000 events per year above 10^{19} eV. In addition, it should be able to detect a few neutrino events per year if the UHECRs are extragalactic protons.

The Auger surface array is composed of stand alone 1.5 meter tall water tanks that are powered by solar cells, timed by GPS systems, and communicate via radio antennas. Three photomultipliers per tank register the Cherenkov light when shower particles cross the tanks. Having three photomultipliers per tank allows the self-calibration of each tank in the field. The height of the tanks makes the ground array an excellent detector for inclined showers. Inclined showers and their asymmetries allow for a novel method for composition studies and for the detection of neutrino showers from horizontal and Earth skimming high energy neutrinos.

The fluorescence detectors at the Auger observatory have a complete calibration system. The atmospheric monitoring includes lasers, lidars, ballon radio sondes, cloud monitors, and movable calibration light sources [22]. In addition, the whole telescopes including mirrors are calibrated from front to end with light sources. Hybrid detection is a powerful measurement of individual showers and can be used to reach large statistics on energies down to 10^{18} eV with the use of fluorescence and a small number of tanks per event. The ability to study events at 10^{18} eV in the Southern hemisphere will be crucial in confirming the reported anisotropies toward the Galactic Center region. The combination of mono fluorescence events that trigger even a single tank allows for great angular reconstruction of events comparable to stereo events.

The Auger collaboration consists of about 250 scientists from 16 countries. The first science results of the observatory were presented during the Summer of 2005. Auger reported no evidence for anisotropies [23]. In addition, it reported the first hybrid spectrum [11]. The Auger spectrum as seen in Fig. 2 shows that a systematic energy shift is needed to reconcile AGASA data. Auger used fluorescence data to normalize the energy scales with exposure and statistics accumulated for the surface detector. This combination uses the strengths of each technique. Once the full Auger detector has run for about 2 years, an order of magnitude improvement in the exposure should bring a resolution to the GZK problem and the identification of the first sources.

Another upcoming experiment is the Telescope Array (TA) which consists of a hybrid detector of three fluorescence telescopes overlooking a scintillator array of about 400 km^2 with 1.2 km spacing. The design limits the exposure at the highest energies but is suited to energies from $\sim 10^{17}$ eV to $\sim 10^{19}$ eV, where a transition between Galactic and extragalactic UHECRs are expected. TA should be able to see some super-GZK events but with significantly smaller statistics than the Auger project. Instead, TA will concentrate on a study the features in the spectrum and composition at the transition from Galactic to extragalactic that may involve a simultaneous hardening and a heavy to light primaries transition.

Two space missions have been proposed to study UHECRs, EUSO and OWL. EUSO is unlikely to be completed due to difficulties with servicing the International Space Station (ISS) where it was to be deployed. The OWL mission consists of a pair of satellites placed in tandem in a low inclination, medium altitude orbit. The large aperture should translate to high statistics at the highest energies and the stereo capabilities of the two satellite design should help control systematics at the largest energies.

CONCLUSION

After decades of attempts to discover the origin of UHECRs, present results are inconclusive with new efforts showing great promise. Past experiments showed the need to understand and control systematic effects within each technique and to cross-calibrate the two techniques presently available for UHECR studies (ground arrays and fluorescence). In addition, the lack of sufficient statistics has limited the discussion of an excess flux or a drop in flux around the GZK feature. Next generation experiments are gearing up to accumulate the necessary statistics while having a better handle on the systematics. In the following decade, we may see the growth of a new astronomy with ultra-high energy charged particles and finally resolve the almost century old puzzle of the origin of cosmic rays.

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