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ULTRA HIGH ENERGY COSMIC RAYS AND THE MAGNETIZED UNIVERSE

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ABSTRACT

The current state and future prospects of ultra high energy cosmic ray physics are reviewed. These cosmic rays with energies well above 10^{18} eV are messengers of an unknown extremely high-energy universe.

Key words : ultra high energy cosmic rays – magnetic fields

I. INTRODUCTION

Cosmic rays have been known to be of *cosmic* origin since 1912 when Victor Hess took electroscopes in balloons above 5000 m. 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. Since then cosmic rays have been observed up to $\sim 10^{20}$ eV. Fermi acceleration in supernova remnants may be responsible for accelerating cosmic rays below $\sim 10^{15}$ eV, but more powerful sources seem to be required for the higher energy events. No sources of cosmic rays have been identified and their origin remains a mystery about to become a century old.

Figure I shows a compilation of direct and indirect (via air showers) cosmic ray observations unified into a single spectrum. The spectrum is well fit by power-laws with spectral index $\gamma \simeq 2.7$ for energies below $\sim 10^{15}$ eV and $\gamma \simeq 3$ for energies above $\sim 10^{15}$ eV, with a 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 Si and Fe nuclei. At higher energies, Kascade reports evidence to a change from proton to Fe dominated spectrum between $\sim 10^{15}$ eV and $\sim 10^{17}$ eV (Kampert *et al.* 2004) and HiRes reports a possible change back to protons above $\sim 10^{18}$ eV (Abbasi *et al.* 2004). For energies above $\sim 10^{19}$ 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 operations now. The ultra-high energy cosmic ray (UHECR) puzzles begin with the lack of the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen 1966, Zatsepin and Kuzmin 1966). Contrary to earlier expectations, cosmic rays with energies above 10^{20} eV have been detected by a number of experiments (for reviews see Bhattacharjee and Sigl 2000, Olinto 2000, Cronin, 2004, Stecker 2003). If these particles 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 a few times $\sim 10^{20}$ 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.

As reported by the most recent compilation of the Akeno Giant Airshower Array (AGASA) data (Takeda *et al.* 2003), the spectrum of cosmic rays does not end at the expected GZK cutoff. 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 (Takeda *et al.* 1999) ends to rule out most scenarios.

This challenging state of affairs is stimulating both for 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 based on an analysis of their monocular data (Abbasi *et al.* 2004b) which is consistent with a GZK *feature*. Currently, these two experiments with the largest exposures have conflicting results at the highest energies (above $\sim 10^{20}$ eV) where limited statistics and systematic errors prevent a clear resolution. As new experiments come on line, the structure of the GZK feature will become clear. In any scenario (GZK feature or not), events past 10^{20} eV pose theoretical challenges which will be explained in the future by either astrophysically novel sources or new fundamental physics.

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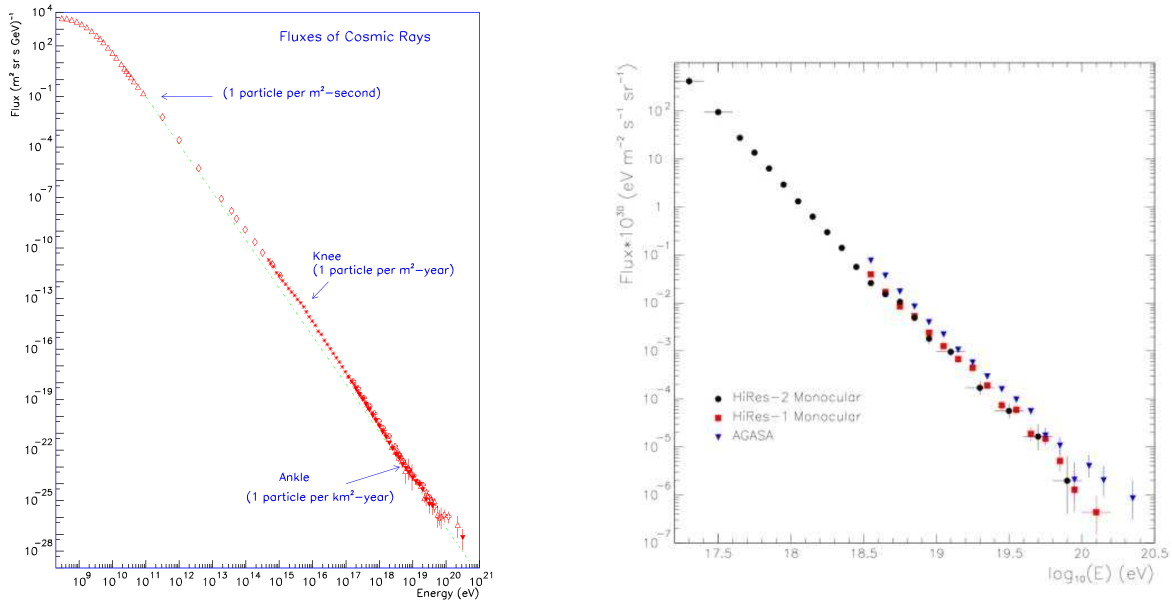

Fig. 1.— Left Panel: Spectrum of cosmic rays. Right Panel: Spectrum at the highest energies from AGASA (triangles) and HiRes (circles and squares).

II. PRESENT STATE OF UHECR OBSERVATIONS

Ultra-high energy cosmic rays are the highest energy messengers of the present universe. The highest energy cosmic photons observed thus far reach up to $\sim 10^{13}$ eV. Extragalactic photons of higher energies loose a significant fraction of their energies due to pair production in the cosmic background radiation as they traverse large regions of intergalactic space. In contrast, 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 (see *e.g.,* Kronberg 1994). 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 (see *e.g.,* Dolag *et al.* 2004, and many other contributions to these proceedings).On larger scales, magnetic fields are known to be weaker than ~ 10 nano Gauss (Blasi *et al.* 1999). A recent model proposed by Lemoine (2004) to fit cosmic ray data from $\sim 10^{15}$ eV to $\sim 10^{20}$ eV argues for $B\sqrt{l_c} \sim 2 \times 10^{-10}\mathrm{G}\sqrt{Mpc}$ (see Figure II).

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 (see many other contributions to these proceedings including Dolag *et al.* 2004, Ryu *et al.* 2004, and Miniati *et al.* 2004). 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 can reach around 1 degree in the densest regions (Dolag *et al.* 2004). For protons arriving with 10^{20} eV the deflections are less than $\sim 0.1°$ (which is significantly smaller than the resolution of UHECR observatories). Therefore, at ultra high energies there is finally the opportunity to begin cosmic ray 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 feature. In 1966, Greisen, Zatsepin and Kuzmin proposed 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.

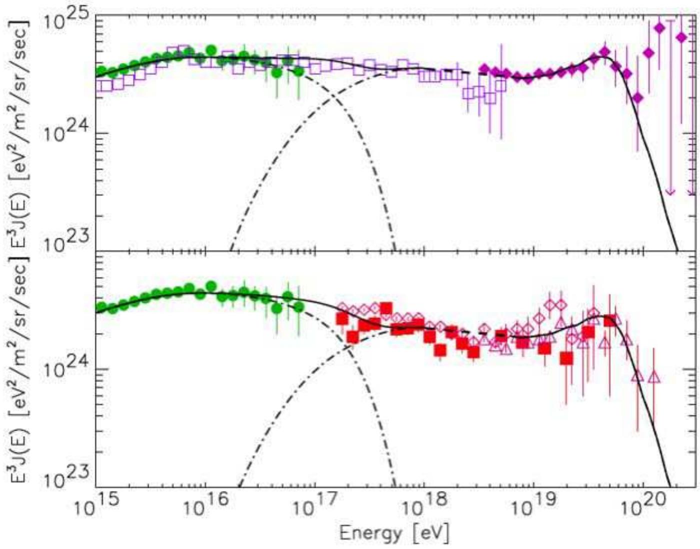

Fig. 2.— Model of Galactic and Extragalactic Cosmic rays by Lemoine (2004) compared to data from Akeno and Agasa (upper panel) and Hires and Fly's Eye (lower panel).

The search for the origin of the highest energy particles is being undertaken by a number of experiments. 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. Currently, the two largest exposure experiments, the Akeno Giant Airshower Array (AGASA) and the High Resolution Fly's Eye (HiRes) have conflicting results at the highest energies (above $\sim 10^{20}$ eV) where limited statistics and systematic errors prevent a clear resolution (see Figure I).

AGASA is 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 (Takeda *et al.* 1999). In addition, the spectrum shows the lack of a GZK cutoff around 10^{20} eV. 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 (Takeda *et al.* 2003). 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 (Abbasi *et al.* 2004b). HiRes reports only two events with energies above 10^{20} eV. 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 do not have comparable exposure to AGASA yet, monocular data do have comparable exposure. Mono HiRes analysis shows no evidence of clustering of arrival directions on small scales 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 10^{18} eV and $10^{19.3}$ eV the composition shifts from a heavier (iron dominated) component to lighter (proton dominated) component.

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 $\sim 30\%$ 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 % (Takeda *et al.* 2003). 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. Figure III shows the range of 400 simulated spectra of protons propagating in intergalactic space with injection spectral index of 2.8 for AGASA and 2.6 for HiRes exposures. In addition, the data from AGASA and HiRes are shown with a systematic energy shift of -15% for AGASA and +15% for HiRes (De Marco *et al.* 2003). The disagreement between the two experiments is only about 2 σ using these arbitrarily chosen systematic corrections, which are well within the possible range of systematic errors.

The systematic energy shifts between AGASA and HiRes through the range of observed energies is more easily seen when the two spectra are plotted on a flux

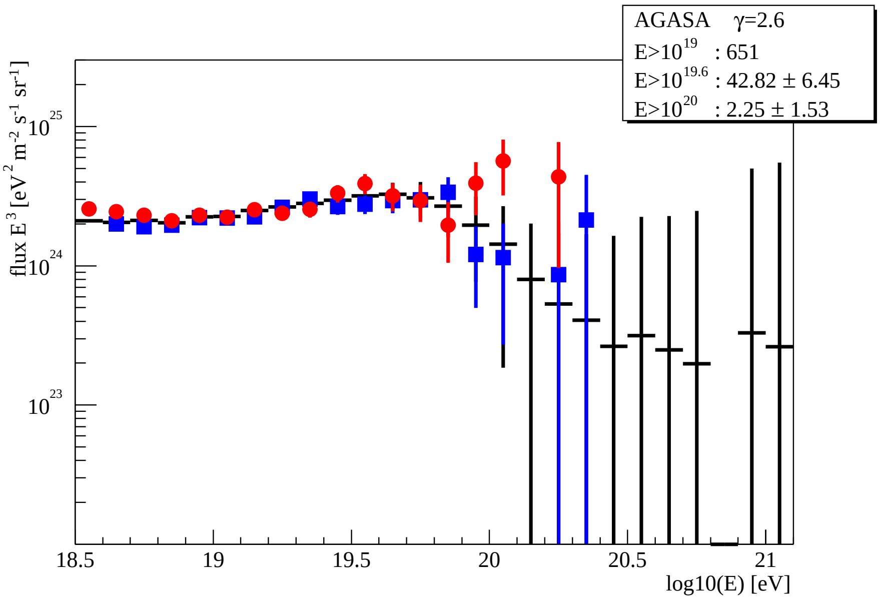

Fig. 3.— AGASA with -15% energy shift and HiRes with +15% shift (DeMarco *et al.* 2003).

versus energy plot (see Figure I). In addition, the discrepancies between the two experiments are not as accentuated as in the traditional plots of flux times E^3. 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.

III. POSSIBLE SOURCES OF UHECRS

The puzzle presented by the observations of cosmic rays above 10^{20} eV have generated a number of proposals that can be divided into *Astrophysical Zevatrons* and *New Physics* models. Astrophysical Zevatrons are also referred to as bottom-up models and involve searching for acceleration sites in known astrophysical objects that can reach ZeV energies (= 10^{21} eV). New Physics proposals can be either hybrid or pure top-down models. First we discuss astrophysical Zevatrons followed by new physics models.

(a) Astrophysical Zevatrons

Cosmic rays can be accelerated in astrophysical plasmas when large-scale macroscopic motions, such as shocks, winds, and turbulent flows, are transferred to individual particles. The maximum energy of accelerated particles, $E_{\rm max}$, can be estimated by requiring that the gyroradius of the particle be contained in the acceleration region: $E_{\rm max} = Ze\,B\,L$, where Ze is the charge of the particle, B is the strength and L the coherence length of the magnetic field embedded in the plasma. For $E_{\rm max} \gtrsim 10^{20}$ eV and $Z \sim 1$, the only known astrophysical sources with reasonable BL products are neutron stars, active galactic nuclei (AGNs), radio lobes of AGNs, and clusters of galaxies (see *e.g.,* Hillas 1984).

Shocks in clusters of galaxies seem unable to accelerate protons to energies above $\sim 10^{19}$ eV (Kang *et al.* 1996). In addition, the propagation in clusters and in the extragalactic medium should generate a GZK feature. Jets from the central black-hole of an active galaxy end at a termination shock where the interaction of the jet with the intergalactic medium forms radio lobes and 'hot spots'. Of special interest are the most powerful AGNs where shocks can accelerate particles to energies above $\sim 10^{19}$ eV via the first-order Fermi mechanism (Biermann and Strittmatter 1987, Kang *et al.* 1996). A nearby specially powerful source may be able to reach energies past the cutoff and fit the observed spectrum (Blasi and Olinto 1999). However, extremely powerful AGNs with radio lobes and hot spots are rare and far apart and are unlikely to match the observed arrival direction distribution. If M87 or CenA are the primary sources of UHECRs, a concentration of events in their directions should be seen at the highest energies. The next known nearby source after M87 is NGC315 which is already too far at a distance of ~ 80 Mpc. Any unknown source between M87 and NGC315 would likely contribute a second hot spot, not the observed isotropic distribution. The very distant radio lobes should contribute a GZK cut spectrum.

The possibility of stronger Galactic and extragalactic magnetic fields may reduce the problem with the isotropy of the arrival directions. In particular, a strong Galactic wind can significantly alter the paths of UHECRs such that the observed arrival directions of events above 10^{20} eV would trace back to the North Galactic Pole which is close to the Virgo cluster where M87 resides (Ahn *et al.* 1999). The proposed wind would focus most observed events within a very narrow energy range into the northern Galactic pole and render point source identification fruitless. Full sky coverage of future experiments will be a key discriminator of such proposals.

The smallest objects of interest as accelerators are neutron stars. Neutron star not only have the ability to confine 10^{20} eV protons, the rotation energy of young neutron stars is more than sufficient to match the observed UHECR fluxes (Venkatesan *et al.* 1997). However, ambient magnetic and radiation fields induce significant losses inside a neutron star's light cylinder. The plasma that expands beyond the light cylinder is free from the main loss processes and may be accelerated to ultra high energies. In particular, newly formed, rapidly rotating neutron stars may accelerate iron nuclei to UHEs through relativistic MHD winds beyond their light cylinders (Blasi *et al.* 2000). This mechanism naturally leads to very hard injection spectra ($\gamma \simeq 1$). In this case, UHECRs originate mostly in the Galaxy and the arrival directions require that the primaries be heavier nuclei. Depending on the structure of Galactic magnetic fields, the trajectories of iron nuclei from Galactic neutron stars can be consistent with the observed arrival directions of the highest energy events. This proposal should be constrained once the primary composition is clearly determined.

Transient high energy phenomena such as gamma-ray bursts (GRBs) may also be a source of ultra-high energies protons (Waxman 1995, Vietri 1995). In addition to both phenomena having unknown origins, GRBs and UHECRs have other similarities that argue for a common source. Like UHECRs, GRBs are distributed isotropically in the sky, and the average rate of γ-ray energy emitted by GRBs is comparable to the energy generation rate of UHECRs of energy $> 10^{19}$ eV in a redshift independent cosmological distribution of sources. However, recent GRB counterpart identifications argue for a strong cosmological evolution for GRBs. The distribution of UHECR arrival directions and arrival times do not support a common origin for GRB and for UHECR above $\sim 10^{20}$ eV. Events past the GZK cutoff require that only GRBs from $\lesssim 50$ Mpc contribute. Since less than about *one* burst is expected to have occurred within this region over a period of 100 yr, the unique source would appear as a concentration of UHECR events in a small part of the sky. In addition, the signal would be very narrow in energy $\Delta E/E \sim 1$. Again, a strong intergalactic magnetic field can ease the arrival direction difficulty dispersing the events of a single burst but also decreasing the flux below the observed level depending on burst characteristics.

(b) New Physics Models

The UHECR puzzle has inspired a number of models that involve physics beyond the standard model of particle physics. New Physics proposals can be top-down models or a hybrid of astrophysical Zevatrons with new particles. Top-down models involve the decay of very high mass relics that could have formed in the early universe.

The most economical among hybrid proposals involves a familiar extension of the standard model, namely, neutrino masses. If some flavor of neutrinos have mass (~ 0.1 eV), the relic neutrino background is a target for extremely high energy neutrinos to interact and generate other particles through the Z-pole (Fargion *et al.* 1999, Weiler 1999). This proposal requires very luminous sources of extremely high energy neutrinos throughout the universe that are now being constrained by neutrino experiments. Neutrino energies need to be $\gtrsim 10^{21}$ eV which implies primary protons in the source with energies $\gtrsim 10^{23}$ eV. The decay products of the Z-pole interaction are dominated by photons, which gives another clear test to this proposal. In addition, the neutrino background only clusters on large scales, so the arrival direction for events should be mostly isotropic. Preserving a small scale clustering may be another challenge to this proposal.

If none of the astrophysical scenarios or the hybrid new physics models are able to explain present and future UHECR data, one alternative is to consider top-down models. The idea behind these models is that relics of the very early universe, topological defects (TDs) or superheavy relic (SHR) particles, produced after or at the end of inflation, can decay today and generate UHECRs. Defects, such as cosmic strings, domain walls, and magnetic monopoles, can be generated through the Kibble mechanism as symmetries are broken with the expansion and cooling of the universe. Topologically stable defects can survive to the present and decompose into their constituent fields as they collapse, annihilate, or reach critical current in the case of superconducting cosmic strings (see *e.g.,* Hill 1983, Schramm and Hill 1983). The decay products, superheavy gauge and higgs bosons, decay into jets of hadrons, mostly pions. Pions in the jets subsequently decay into γ-rays, electrons, and neutrinos. Only a few percent of the hadrons are expected to be nucleons. Typical features of these scenarios are a predominant release of γ-rays and neutrinos and a QCD fragmentation spectrum which is considerably harder than the case of Zevatron shock acceleration.

ZeV energies are not a challenge for top-down models since symmetry breaking scales at the end of inflation typically are $\gg 10^{21}$ eV. Fitting the observed flux of UHECRs is harder since the typical distances between TDs is the Horizon scale or several Gpc. The low flux hurts proposals based on ordinary and superconducting cosmic strings which are distributed throughout space. Monopoles usually suffer the opposite problem, they would in general be too numerous. Inflation succeeds in diluting the number density of monopoles and makes them too rare for UHECR production. Once two symmetry breaking scales are invoked, a combination of horizon scales gives room to reasonable fluxes. This is the case of cosmic necklaces (Berezinsky and Vilenkin 1997), which are hybrid defects where each monopole is connected to two strings resembling beads on a cosmic string necklace. The UHECR flux is ultimately generated by the annihilation of monopoles with antimonopoles trapped in the string (Berezinsky *et al.* 1998). In these scenarios, protons dominate the flux in the lower energy side of the GZK cutoff while photons tend to dominate at higher energies depending on the radio background. If future data can settle the composition of UHECRs from 0.01 to 1 ZeV, these models can be well constrained. In addition to fitting the UHECR flux, topological defect models are constrained by limits from EGRET on the flux of photons from 10 MeV to 100 GeV.

Another interesting possibility is the proposal that UHECRs are produced by the decay of unstable superheavy relics that live much longer than the age of the universe (Berezinsky *et al.* 1997). SHRs may be produced at the end of inflation by non-thermal effects such as a varying gravitational field, parametric resonances during preheating, instant preheating, or the decay of topological defects. These models need to invoke special symmetries to insure unusually long lifetimes for SHRs and that a sufficiently small percentage decays today producing UHECRs. As in the topological defects case, the decay of these relics also generates jets of hadrons and the main UHE component would be photons. These particles behave like cold dark matter and could constitute a fair fraction of the halo of our Galaxy. Therefore, their halo decay products would not be limited by the GZK cutoff allowing for a large flux at UHEs. In addition, the arrival direction distribution should be close to isotropic but show an asymmetry due to the position of the Earth in the Galactic Halo (Berezinasky *et al.* 1998) and the clustering due to small scale dark matter inhomogeneities (Blasi and Seth 2000).

IV. 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 observatories are now under construction, the Pierre Auger Project (Cronin 2001), and other observatories are under development, such as the Telescope Array (Fukushima *et al.* 2003), the Extreme Universe Space Observatory (Teshima *et al.* 2003) and the Orbiting Wide-field Light-collectors (OWL) mission (Stecker *et al.* 2004).

The Pierre Auger Project will consist of two giant airshower arrays one in the South and one in the North each with 1600 water Cherenkov detectors covering 3000 km^2 and four sites of fluorescence telescopes. 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. Depending on the UHECR spectrum, Auger 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 (see Figure IV). In addition, it should be able to detect a few neutrino events per year if 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. 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 Southern Auger Observatory is already operating with over 500 surface detector tanks deployed and two fluorescence telescope sites completed. The first science results of the observatory should be presented in the Summer of 2005.

Another upcoming experiment is the recently approved Telescope Array (TA) which consists of a hybrid detector of three fluorescence telescopes overlooking a scintillator array. The array would cover 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 $\sim 10^{20}$ 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 is planning to concentrate their efforts in

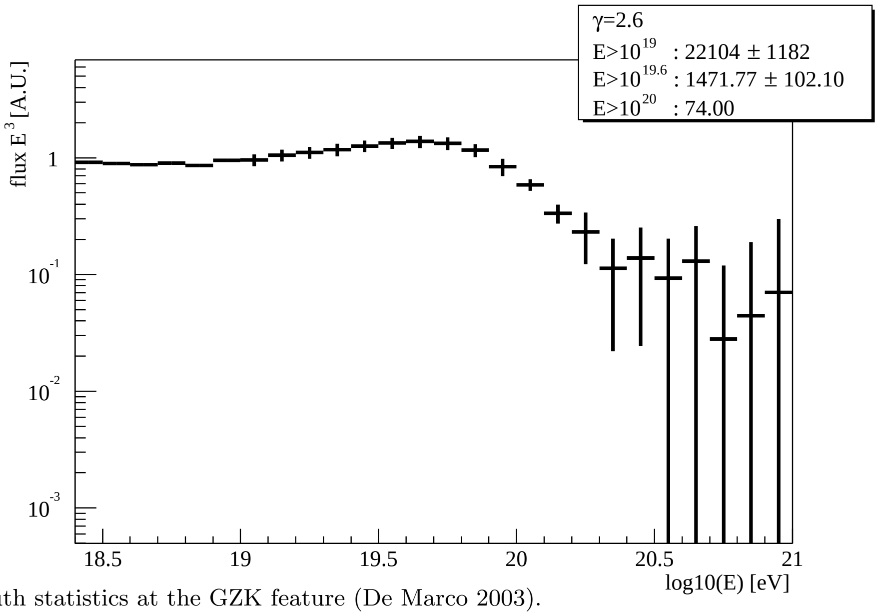

Fig. 4.— Auger South statistics at the GZK feature (De Marco 2003).

having a broad reach in energies to study the spectrum and composition through the transition from Galactic to extragalactic that may involve a simultaneous heavy to light primaries transition.

Finally, the Extreme Universe Space Observatory (EUSO) is a fluorescence detector designed for the International Space Station (ISS) aiming at observations of extremely high energy cosmic-rays (EHECRs), i.e., cosmic rays between 10^{20} and 10^{22} eV. EUSO is designed to observe showers from above the atmosphere with full sky coverage due to the ISS orbit. This project is a good complement to ground arrays since, it will focus on larger energy scales and will have a different set systematic of effects. Their threshold may be above 5×10^{19} eV depending on technical features of the fluorescence detectors. The telescope's expected angular resolution is ~ 0.2 degrees and the energy resolution about $\sim 20\%$. The aperture may reach 3×10^6 km^2-sterad with a 10% duty cycle. This can translate into about 3000 events per year for energies above 10^{20} eV.

On an even larger scale, the proposed OWL mission consists of a pair of satellites placed in tandem in a low inclination, medium altitude orbit. The OWL telescopes is planned to together point at a section of atmosphere of area $\sim 6 \times 10^5$ km^2. The large aperture should translate into high statistics at the highest energies and the stereo capabilities of the two satellite design should help control systematics at the largest energies.

V. CONCLUSION

After decades of attempts to discover the origin of ultra-high energy cosmic rays, present results are still inconclusive. The results from past experiments show the need to understand and control systematic effects within each technique and to cross-calibrate the two main techniques presently available for UHECR studies (ground arrays and fluorescence). In addition, the lack of sufficient statistics limits 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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