Ultra High-Energy Cosmic Ray Observations

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Abstract. The year 2007 has furnished us with outstanding results about the origin of the most energetic cosmic rays: a flux suppression as expected from the GZK-effect has been observed in the data of the HiRes and Auger experiments and correlations between the positions of nearby AGN and the arrival directions of trans-GZK events have been observed by the Pierre Auger Observatory. The latter finding marks the beginning of ultra high-energy cosmic ray astronomy and is considered a major breakthrough starting to shed first light onto the sources of the most extreme particles in nature. This report summarizes those observations and includes other major advances of the field, mostly presented at the 30th International Cosmic Ray Conference held in Mérida, Mexico, in July 2007. With increasing statistics becoming available from current and even terminated experiments, systematic differences amongst different experiments and techniques can be studied in detail which is hoped to improve our understanding of experimental techniques and their limitations.

1. Introduction

Understanding the origin of the highest energy cosmic rays is one of the most pressing questions of astroparticle physics. Cosmic rays with energies exceeding $10^{20}$ eV have been observed for more than 40 years (see e.g. [1]) but due to their low flux only some ten events of such high energies could be detected up to recently. There are no generally accepted source candidates known to be able to produce particles of such extreme energies. Moreover, there should be a steeping in the energy spectrum near $10^{20}$ eV due to the interaction of cosmic rays with the microwave background radiation (CMB). This Greisen-Zatsepin-Kuzmin (GZK) effect [2] severely limits the horizon from which particles in excess of $\sim 6 \cdot 10^{19}$ eV can be observed. For example, the sources of protons observed with $E \geq 10^{20}$ eV need to be within a distance of less than 50 Mpc [3]. The non-observation of the GZK-effect in the data of the AGASA experiment [4] has motivated an enormous number of theoretical and phenomenological models trying to explain the absence of the GZK-effect and has stimulated the field as a whole. Only this year, with the final analysis of the HiRes-data [5] and the advent of high-statistics and high quality hybrid data from the Pierre Auger Observatory (PAO) [6], the situation has changed considerably: a suppression such as expected from the GZK-effect is now observed with high statistical significance. The very recent breaking news about the observation of directional correlations of the most energetic Pierre Auger events with the positions of nearby AGN [7] complements the observation of the GZK effect very nicely and provides evidence for an astrophysical origin of the most energetic cosmic rays. Another key observable allowing to discriminate different models about the origin of high-energy cosmic rays is given by the mass composition of cosmic rays. Unfortunately, such measurements are much more difficult due to their strong dependence on hadronic interaction models. Only primary photons can be discriminated safely from protons and nuclei and recent
upper limits to their flux largely rule out top-down models, originally invented to explain the apparent absence of the GZK-effect in AGASA data.

In this article, prepared for the TAUP conference in Sendai (Japan), we describe the status of each of these topics, as reported during the recent International Cosmic Ray Conference held in Mérida, Mexico, in July 2007 (ICRC2007) and in publications becoming available since.

2. Experiments and their Exposures

Most of the data available today at energies above $\sim 10^{18}$ eV are provided by the 100 km$^2$ AGASA array [4], the HiRes fluorescence telescopes [5] and the 3000 km$^2$ PAO [8]. Both, the AGASA and HiRes instruments have now closed while the PAO started operation during its construction phase in 2004. Even though its last surface detector stations are planned to be deployed in March 2008 only, it has already accumulated the largest exposure available today and it will continue to deliver more than about 7000 km$^2$sr for each year of operation. Table 2 lists for various experiments the approximate accumulated exposures and currently observed numbers of events claimed to be above 10 and 50 EeV, respectively. The table (based on [9]) includes for comparison smaller air shower arrays, such as the phased out Haverah Park [10] and AKENO [11] arrays, the Yakutsk [12], and the KASCADE-Grande array [13]. The Telescope Array (TA), led by a Japanese consortium in Millard County, Utah, USA, has just begun operation this year [14]. Like the PAO, the TA is a hybrid detector. It covers an area of 860 km$^2$ and comprises 576 scintillator stations and three FD sites on a triangle with about 35 km separation each equipped with 12 fluorescence telescopes.

Table 1. Exposure and approximate event numbers from various instruments.

| Experiment       | status    | km$^2$ sr yr @ 50 EeV | # events > 10 EeV | # events > 50 EeV | based on Ref. |
|------------------|-----------|-----------------------|-------------------|-------------------|--------------|
| Haverah Park     | 1962-1987 | $\sim$ 245             | 106               | 10                | [10]         |
| Yakutsk          | 1974-present | $\sim$ 900             | 171               | 6                 | [9, 12]      |
| AGASA            | 1993-2005 | 1620                  | 886               | 46                | [15]         |
| HiRes-I mono     | 1997-2006 | $\sim$ 4500           | 561               | 31                | [15, 17, 18] |
| HiRes-II mono    | 1999-2006 | $\sim$ 1500           | 179               | 12                | [15, 17]     |
| HiRes stereo     | 1999-2006 | $\sim$ 2400           | 270               | 11                | [19, 20]     |
| Auger            | 2004-present | $\sim$ 7000          | 1644              | 38                | [21, 22]     |
| TA               | 2007-present | 860×yrs               |                   |                   | [14]         |

In case of ground arrays, the aperture is calculated in a straightforward and model independent way, once the energy threshold for CR detection and reconstruction is exceeded. The only uncertainty arises from the reconstruction of the landing point of the shower, which again is safely reconstructed if only showers within the geometry covered by the array are considered. The situation is quite different for fluorescence telescopes. Here, the maximum distance out to which showers can be observed increases with increasing fluorescence light and thereby increasing energy. On the one hand, the growing aperture is very attractive and
cost effective, as it allows to observe more showers at high energies. On the other hand, the maximum distance out to which EAS can be seen is directly related to the signal-to-noise ratio in the light sensors of the cameras, the varying atmospheric conditions, etc. Moreover, an accurate reconstruction of the CR energy requires the observation of the position of the shower maximum, \(X_{\text{max}}\), in the field-of-view of the telescopes. This condition imposes a sensitivity also to the primary mass and consequently also to the hadronic interaction models employed in the aperture calculation.

The effect of growing apertures in case of fluorescence telescopes and constant apertures in case of ground arrays can be seen in Fig. 1. Note also the difference in the detection-/reconstruction thresholds of HiRes-I and -II. This is mostly because of the different ranges of elevation angles viewed by HiRes-I (3°-17°) and -II (3°-31°) cameras: low energy showers, which can - due to their low light level - only be observed near the telescopes, reach their shower maximum above the field-of-view of the cameras and thus cannot be reconstructed. Fig. 2 compares in more details the aperture of HiRes-II for p- and Fe-induced showers [23]. Note that the p- and Fe-apertures differ by more than a factor of 20 at \(E \approx 3 \cdot 10^{17}\) eV! Thus, without knowledge of the primary mass, the flux in this energy range is uncertain by a factor of 20 (or more, dependent on the hadronic interaction model used in the aperture calculation) and composition measurements will be very biased. We also illustrate the width of the experimental energy resolution which indicates that the rapid fall of the aperture distribution almost equals the energy resolution function. Fluctuations in the energy reconstruction by only one standard deviation or a shift of the overall energy scale within the uncertainty of the experiment causes changes in the aperture (and thereby the CR-flux) by a factor of about 6! Clearly, controlling all these uncertainties particularly at energies below \(10^{18}\) eV appears very difficult.

3. The Energy Spectrum

A very important step towards unveiling the origin of the sources of UHECR is provided by measurements of the CR energy spectrum. Four features are known to provide information about the CR origin: the prominent knee at \(E \approx 4 \cdot 10^{15}\) eV may signal the limiting energy of galactic CR accelerators and/or the onset of diffusion losses from the galaxy, the second knee at \(E \approx 10^{17}\) eV, still to be confirmed [24], is considered to be caused by the fading of

**Figure 1.** Accumulated exposures of various experiments. The data and exposures are based on Refs. [16, 19, 25, 13, 22].

**Figure 2.** HiRes apertures (from [23]) for pure proton and iron simulations compared to the energy resolution.
the heavy galactic CR component, the ankle at \( E \approx 4 \cdot 10^{18} \) eV is either due to the onset of the extragalactic CR component or due to energy losses of extragalactic protons by \( e^+e^- \) pair production in the CMB \[26\], and the GZK cut-off at \( E \approx 6 \cdot 10^{19} \) eV \[2\] is due to photo-pion production of extragalactic protons in the CMB.

Recent measurements of the CR energy spectrum by AGASA and HiRes have yielded results which differ in their shape and overall flux. A comparison including data from the PAO as presented at the ICRC 2007 is shown in Fig. 3. Generally, the error bars in such plots are of statistical nature only and neglect systematic uncertainties in the determination of the energy scale and exposure. Typical uncertainties of the energy scale are on the order of 20-25%. Ground arrays like AGASA rely entirely on EAS simulations with their uncertainties originating from the limiting knowledge of hadronic interactions (total inelastic cross sections, particle multiplicities, inelasticities, etc.). CORSIKA simulations \[27\] have shown that the muon density at ground predicted by different hadronic interaction models differ by up to 30%. Fluorescence telescopes, such as operated by HiRes and the PAO, observe the (almost) full longitudinal shower development in the atmosphere. In this way, the atmosphere is employed as a homogenous calorimeter with an absorber thickness of 30 radiation lengths or 11 hadronic interaction lengths. Corrections for (model dependent) energy ‘leakage’ into ground-mostly by muons and neutrinos - are below 10% and their uncertainties are only a few percent. As a consequence, fluorescence detectors provide an energy measurement which is basically independent from hadronic interaction models. Uncertainties in the energy scale arise most dominantly from the fluorescence yield in the atmosphere. Several measurements have been made in the past, e.g. the Auger Collaboration uses the fluorescence yield by Nagano et al. \[28\] and HiRes by Kakimoto et al. \[29\]. This is an unpleasant situation, which by itself may account for a \( \sim 10\% \) shift between the energy scales of Auger and HiRes. For this reason, major efforts have been started to remeasure the fluorescence yield as a function of temperature, pressure and humidity with high precision \[30\] in order to reduce this source of uncertainty.

Taking benefit of the Auger hybrid detector, the Auger Collaboration has used a clean set of hybrid data, in which EAS have been detected simultaneously by at least one fluorescence eye and the ground array, to calibrate their observatory \[21\]. To evaluate the observed differences in the energy scale of AGASA, HiRes and Auger in Fig. 3, an overall shift of +17% and −25% has been applied to the Auger and AGASA energy scale, respectively (c.f. Fig. 4). Such a shift remains well within the quoted uncertainties of the experiments (particularly when accounting for the different fluorescence yields used by HiRes and Auger) and yields a fairly good agreement.

**Figure 3.** Cosmic ray flux measurements (multiplied by \( E^3 \)) from AGASA \[4\], HiRes \[17\], and the PAO \[21\].

**Figure 4.** Same as Fig. 3 but with the energy scale of Auger and AGASA shifted by +17% and −25%, respectively.
of the data points, except perhaps at $E \gtrsim 10^{20}$ eV for AGASA and in the ankle region which appears sharper in the PAO data. The GZK-like suppression is clearly visible in both the HiRes and Auger data. Using different statistical approaches, HiRes quotes a significance of about 4.5 standard deviations and the PAO of more than 6σ. For example, fitting a power law to the Auger spectrum between $4 \cdot 10^{18} < E < 4 \cdot 10^{19}$ eV using a binned likelihood method yields $\gamma = -2.69 \pm 0.02$ (stat) $\pm 0.06$ (sys). Extrapolating this slope to higher energies one expects $167 \pm 3$ and $35 \pm 1$ events at $E > 4 \cdot 10^{19}$ and $10^{20}$ eV, respectively, whereas 66 and 1 event are observed. The observation of the GZK-effect 40 years after its prediction provides for the first time clear evidence for an extragalactic origin of EHECRs. Of course, this interpretation is challenged if the sources would happen to run out of acceleration power just at the value of the GZK threshold. However, this would be a strange coincidence and in fact is not supported by Pierre Auger data (see Sect. 5).

The shape of the energy spectrum around $10^{20}$ eV carries information about the distance distribution of CR sources and their injection spectrum [6]. However, more statistics is required before firm conclusions can be drawn. Answering the question about the origin of the ankle and discriminating the $e^+e^-$ dip-model [26] from the traditional ankle model cannot be done based on the energy spectrum alone but requires measurements of the CR composition.

4. Chemical Composition, Photon and Neutrino Limits

As noted above, the mass composition of CRs allows to discriminate models of UHECR origin and may be the only measurement allowing to answer the question about the transition from galactic to extragalactic CRs. The Berezinsky dip-model [26] predicts the transition taking place at energies significantly below the ankle but requires a proton dominant composition in the ankle region to make the Bethe-Heitler pair production process work. In the classical picture, on the other hand, the ankle itself marks the transition region and one expects a change from a heavy to light composition at the ankle. Unfortunately, the mass composition can be inferred only indirectly from EAS experiments by making assumptions about the hadronic interactions at the highest energies. In contrast to energy measurements, this model dependence is true also for fluorescence detectors. The key observable here is the position of the shower maximum, $X_{\text{max}}$, which is directly observed by fluorescence telescopes and can be inferred also from surface detector data. New results based on HiRes-Stereo and PAO hybrid data were reported at the ICRC [31, 32]. As can be seen from Fig. 5, both data sets agree very well up to $\sim 3 \cdot 10^{18}$ eV but differ slightly at higher energies. The differences between the two experiments is of the same order as the differences observed between p- and Fe-predictions for different hadronic interaction models. With these caveat kept in mind, both experiments observe an increasingly lighter composition towards the ankle. At higher energies, the HiRes measurement yields a lighter composition than Auger. Also shown are predictions of $X_{\text{max}}$ based on the QGSJET01 model for the traditional G-EG transition [33] (labelled “A”) and the Berezinsky dip-model [26] (labelled “B”). None of the two models appears to describe the preliminary data well, but they demonstrate the power of such measurements which will be particularly important in the energy range $10^{17}$-$10^{18}$ eV. The low energy upgrade HEAT with additional high elevation telescopes, infill stations and muon detectors in Auger [34], the low energy extension TALE of the TA [35], KASCADE-Grande [13, 36], and IceTop/IceCube [37] will provide powerful data in this energy range to provide a definite answer about the G-EG-Transition already in the very near future.

Primary photons are easier to separate experimentally as they penetrate deeper into the atmosphere, particularly at energies above $10^{18}$ eV. Their EAS development is also much less affected by uncertainties of hadronic interaction models due to the dominant electromagnetic shower component. They are of interest for several reasons: top-down models, invented to explain the apparent absence of the GZK-effect in AGASA data, predict a substantial photon flux at high energies [38]. In the presence of a GZK effect, UHE photons can act as tracers of the
Figure 5. \(\langle X_{\text{max}} \rangle\) as a function of energy for HiRes Stereo [32] and PAO hybrid data [31] compared to proton and Iron predictions using different hadronic interaction models and different models of EHECR origin.

Figure 6. Upper limits on the fraction of photons in the integral CR flux compared to predictions. For references see [39].

GZK process and provide relevant information about the sources and propagation. Moreover, they can be used to obtain input to fundamental physics and UHE photons could be used to perform EHE astronomy.

Experimentally, photon showers can be identified by their longitudinal shower profile, most importantly by their deep \(X_{\text{max}}\) position and low muon numbers. Up to now, only upper limits could be derived from various experiments, either expressed in terms of the photon fraction or the photon flux. Figure 6 presents a compilation of present results on the photon fraction. The most stringent limits are provided by the Auger surface detector [39]. Current top-down models appear to be ruled out by the current bounds. This result can be considered an independent confirmation of the GZK-effect seen in the energy spectrum. It will be very exciting to possibly even touch the flux levels expected for GZK-photons \((p + \gamma_{\text{CMB}} \rightarrow p + \pi^0 \rightarrow p + \gamma\gamma)\) after several years of data taking.

The detection of UHE cosmic neutrinos is another long standing experimental challenge. All models of UHECR origin predict neutrinos from the decay of pions and kaons produced in hadronic interactions either at the sources or during propagation in background fields. Similarly to GZK-photons one also expects GZK-neutrinos, generally called ‘cosmogenic neutrinos’. Moreover, top-down models predict dominantly neutrinos at UHE energies. Even though neutrino flavors are produced at different abundances, e.g. a 1:2 ratio of \(\nu_e:\nu_\mu\), results from pion decay, neutrino oscillations during propagation will lead to equal numbers of \(\nu_e, \nu_\mu, \text{ and } \nu_\tau\) at Earth. At energies above \(10^{15}\) eV, neutrinos are absorbed within the Earth so that upgoing neutrino induced showers cannot be detected anymore. Only tau neutrinos entering the Earth just below the horizon (Earth-skimming) can undergo charged-current interactions to produce \(\tau\) leptons which then can travel several tens of kilometers in the Earth and emerge into the atmosphere to eventually decay in flight producing a nearly horizontal air shower above the detector. Such showers can be searched for in ground arrays and fluorescence detectors. The absence of any candidates observed in the detectors has been used to place upper limits on diffuse neutrino fluxes. As can be seen from Fig. 7, AMANDA and the PAO provide at present the best upper limits up to energies of about \(10^{19}\) eV and, similarly to the photons discussed above, they already constrain top-down models and are expected to reach the level of cosmogenic neutrinos after several years of data taking.
Figure 7. Limits at the 90% C.L. for a diffuse flux of $\nu_\tau$ assuming a 1:1:1 ratio of the 3 neutrino flavors ([10] and references therein) and predictions for a top-down model [41].

5. Arrival Directions and Correlations with AGN

Recently, the Pierre Auger Collaboration reported the observation of a correlation between the arrival directions of the highest energy CRs and the positions of nearby AGN from the Véron-Cetty catalogue at a confidence level of more than 99% [7, 22]. Since several claims about seeing clustering of EHECRs were already made in the past with none of them being confirmed by independent data sets, the Auger group has performed an ‘exploratory’ scan of parameters using an initial data-set and applied these parameters to a new independent data-set for confirmation. With the parameters specified a priori the analysis avoids the application of penalty factors which otherwise would need to be applied for in a posteriori searches. The correlation has maximum significance for CRs with energies greater than $5.7 \cdot 10^{19}$ eV and AGN at a distance less than $\sim 71$ Mpc. At this energy threshold, 20 of the 27 events correlate within 3.2° with positions of a nearby AGN.

Observing such kind of anisotropy can be considered the first evidence for an extragalactic origin of the most energetic CRs because none of any models of galactic origin even including a very large halo would result in an anisotropy such as observed in the data. Besides this, the correlation parameters itself are highly interesting as the energy threshold at which the correlation becomes maximized matches the energy at which the energy spectrum shows the GZK feature (≈ 50% flux suppression), i.e. CRs observed above this threshold need to originate from within the GZK-horizon of $\sim 100$-200 Mpc. This number again matches (within a factor of two) the maximum distance for which the correlation is observed! Thus, the set of the two parameters suggests that the suppression in the energy spectrum is indeed due to the GZK-effect, rather than to a limited energy of the accelerators. Thereby, the GZK-effect acts as an effective filter to nearby sources and minimizes effects from extragalactic magnetic field deflections. On top of this, it is also the large magnetic rigidity which helps to open up the window for performing charged particle astronomy.

The correlation may tell us also about the strength of galactic and extragalactic magnetic fields. The galactic fields are reasonably well known and one expects strong deflections for particles arriving from nearby the galactic plane even at energies of 60 EeV. And in fact, 5 of the 7 events that do not correlate with positions of nearby AGN arrive with galactic latitudes $|b| < 12$°. The angular scale of the observed correlation also implies that the intergalactic magnetic fields do not deflect the CRs by more than a few degrees and one can constrain models of turbulent magnetic fields to $B_{\text{rms}}\sqrt{L_c} \leq 10^{-9} \text{ G} \sqrt{\text{Mpc}}$ within the GZK horizon assuming protons as primary particles [22].
6. Concluding Remarks
Remarkable progress has been made in cosmic ray physics at the highest energies, particularly by the start-up of the (still incomplete) Pierre Auger Observatory. The event statistics above \(10^{19}\) eV available by now allows detailed comparisons between experiments and indicates relative shifts of their energy scales by \(\pm 25\%\). Given the experimental and theoretical difficulties in measuring and simulating extensive air showers at these extreme energies, this may be considered a great success. On the other hand, knowing about overall mismatches of the energy scales between experiments may tell us something. Clearly, in case of fluorescence detectors better measurements of the spectral and absolute fluorescence yields and their dependence on atmospheric parameters are needed and will hopefully become available in the very near future [30]. This should furnish all fluorescence experiments with a common set of data. Differences in the calibration between surface detectors and fluorescence telescopes, best probed by hybrid experiments like Auger and TA, may then be used to test the modelling of EAS. The muon component at ground, known to be very sensitive to hadronic interactions at high energies [27], could in this way serve to improve hadronic interaction models in an energy range not accessible at man-made accelerators. In fact, several studies (e.g. [42]) indicate a deficit of muons by 30\% or more in interaction models like QGSJET.

The energy scale is of great importance also for the AGN correlation discussed in the previous section. As shown in [22], the correlation sets in abruptly at an (Auger) threshold energy of about 57 EeV. Already a downshift in energy by 17\% (the mismatch between Auger and HiRes) would weaken the signal by more than 3 orders of magnitude to make it basically disappear. Thus, verification of the correlation signal by HiRes or AGASA would need to be done for a threshold energy (on their scale) of 67 EeV and 85 EeV, respectively. In this energy range, HiRes observes a spectral slope of \(\gamma = 5.1 \pm 0.7\) [17], i.e. the number of events available for a correlation analysis would, according to Table 2, drop to about 12 (HR-I) and 4 (HR-II) when taking the rise of the apertures into account. This would amount to about half the statistics of Auger, well in agreement with the quoted exposures. Unfortunately, the angular resolution of monocular reconstruction is by far too poor for such a test. Only stereo data could provide the required angular resolution. However, in this case the expected statistics of about 5 events above threshold (based upon the numbers and exposures given above) appears too small for any verification.

In fact, the distance parameter of the correlation of 71 Mpc may indicate a mismatch of the energy scale: For protons above 57 EeV the GZK horizon would be 200 Mpc [3] but already for 20\% higher energy it would shrink by more than a factor of two to become consistent to the correlation parameter. Another puzzling feature is the observed small deflection of particles which suggests dominantly protons as primaries. Note that 90\% of the events (20/22) off the galactic plane are correlated to within \(\sim 3^\circ\) which AGN positions which is very unlikely for heavy nuclei. On the other hand, the elongation curves in Fig.5 suggests an admixture of heavy nuclei by more than 10\%. This may be related again to imperfections of the hadronic interaction models used for comparison in Fig.5.

All of this tells us that the near future will be highly exciting: The question of the energy scales will soon be settled and more detailed comparisons between experiments will become possible. The shape of the energy spectrum in the GZK region will tell us about the source evolution, the composition in the ankle region will answer the question about the G-EG transition, observations of cosmogenic photons and neutrinos are in reach and in case of neutrinos will probe the GZK effect over larger volumes, the correlations will be done with better statistics, with improved search techniques and with more appropriate source catalogues and source selection parameters to tell us about source densities, and the true sources of EHE CRs. Very important to note is that different pieces of information start to mesh and are being accessed from different observational techniques and can be cross-checked: The big picture is being painted!
Given the scientific importance of this, it would be a mistake to have only one observatory - even when operated as a hybrid detector - taking data. The TA project and its extensions will be very important particularly in the sub-GZK range but, unfortunately, will be too small to collect sufficient statistics at the highest energies. Auger-North will be imperative here and needs immediate vigorous support. The next generation experiment JEM EUSO to be mounted at the Exposed Facility of Japanese Experiment Module JEM EF will potentially reach much larger exposures but still faces many experimental challenges to be addressed.

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