EAS Studies of Cosmic Rays above $10^{16}$ eV

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Abstract: In this rapporteur report a summary of the presentations at the 32nd ICRC dealing with studies of cosmic ray induced air showers above $10^{16}$ eV (sessions HE1.2, HE1.3 and HE1.4) is given.

Key words: cosmic rays, air showers

1 Introduction

Air shower studies above $10^{16}$ eV are of fundamental importance for the understanding of the origin of cosmic rays. If the spectral feature in the cosmic ray flux at around $4 \times 10^{15}$ eV (known as the “knee”) is due to the vanishing of galactic protons from the all-particle flux, then it would follow from a simple rigidity argument that the end of the galactic cosmic ray spectrum and a transition to extragalactic cosmic rays should take place at around $10^{17}$ eV. However, the observed hardening of the cosmic ray flux at the so-called “ankle” at around $4 \times 10^{18}$ eV may signify a later transition if it is not due to energy losses of extragalactic protons during the propagation to earth. The cosmic ray spectrum continues up to energies above $10^{20}$ eV and these ultra-high energy cosmic rays challenge our theories for both, the acceleration of these particles in astrophysical sources and hadronic interactions in air showers at center of mass energies well above the LHC.

At the 32nd ICRC of 2011 in Beijing almost 200 presentations about new detection techniques, simulations and measurements of cosmic rays above $10^{16}$ eV were given (sessions HE1.2, HE1.3 and HE1.4) which we will try to summarize in the following. In the next section, highlights of air shower measurements below $10^{18}$ eV will be reported followed by a discussion of results on the ultra-high energy cosmic ray flux. New measurements of composition sensitive observables at ultra-high energies are presented in Section 4 and recent results on the arrival directions of cosmic rays can be found in Section 5. The progress in the development of new detection techniques and future experiments is described in the last section of this report.

2 Towards the Ankle

A variety of new measurements of the all-particle flux of cosmic rays below $10^{18}$ eV were presented at this conference and they are displayed in Figure 1. The statistics and precision of these measurements are now good enough to reveal further sub-structures in the cosmic ray spectrum apart from the knee (the latter is prominently visible at around $4 \times 10^{15}$ eV in Figure 1): between 1 and $2 \times 10^{16}$ eV, a hardening of the spectrum is observed which may be followed by a steepening of the flux at around $10^{17}$ eV. For instance, the Tunka Collaboration reported a fit of their spectrum with broken power laws resulting in spectral indices of $\gamma_1 = 3.21 \pm 0.01$ until $2 \times 10^{16}$ eV, followed by $\gamma_2 = 2.93 \pm 0.01$ until $10^{17}$ eV and $\gamma_3 = 3.20 \pm 0.01$ above that energy [4]. These structures may well be the imprints of rigidity-dependent knees to the all-particle spectrum [6, 7]. The KASCADE-Grande collaboration has tested this assumption using different methods to estimate the energy evolution of the flux of individual elemental composition groups [3, 8–10]. One representative result, the deconvoluted spectra...

of three mass groups, is shown in Figure 2. As can be seen, in this analysis the “low energy ankle” at $10^{16}$ eV can be attributed to the cutoff of the intermediate mass group and the subsequent take-over of a heavy component with a hard spectrum. The latter cuts off later leading to the second spectral breakpoint at around $10^{17}$ eV, which fits well to expected extrapolated rigidity cutoff for iron at $E_{\text{Fe}}^{\text{max}} \sim 26 \cdot E_{\text{p}}^{\text{max}}$.

Fig. 2. Unfolded flux of light, intermediate and heavy primaries from KASCADE and KASCADE-Grande [3] using QGSJetII.

Further corroboration of such a scenario could be achieved by studying the energy evolution of the shower maximum with non-imaging Cherenkov detectors. The measurements from Tunka-133 [11] and Yakutsk [5] are shown in Figure 3. The average shower maximum is proportional to the average logarithmic mass of the primary particles and the calculated $\langle \ln A \rangle$ from Tunka and Yakutsk are in good overall agreement with the ones obtained for KASCADE Grande [5, 11].

Fig. 3. Measurements of the shower maximum by Tunka-133 [11] and Yakutsk [5] compared to air shower simulations.

A novel way to study composition in this energy range will soon be given by the coincident measurement of air showers in IceTop and high energy muons ($E > 500$ GeV) below the air shower array in IceCube. Different primaries at different energies can be separated in the shower size vs. muon number plane, similarly to the $N_e - N_\mu$ technique used by KASCADE but with a much higher muon energy threshold. Due
to the different phase space of the hadronic interactions responsible for high energy muons in comparison to muons with a few GeV measured on ground level, the IceTop hybrid analysis will allow for composition studies with systematics from air shower modeling that are very different from the ones of conventional arrays. In [12], a first combined IceTop/IceCube composition study was presented and preliminary results based on a neural network analysis using Sibyll2.1 indicate an increase of the average logarithmic mass of cosmic rays from 2.3 to 3.2 within an order of magnitude in energy around $10^{16}$ eV. The overall $\langle \ln A \rangle$ of this analysis is however still uncertain by about ±1, dominated by imperfections of the modeling of the IceTop and IceCube detector in simulations.

To further investigate the energy range above $10^{17}$ eV and study the transition of galactic to extragalactic cosmic rays, several planned and accomplished enhancements of existing detector setups were presented at this conference. The Yakutsk collaboration plans to modernize [13] its surface array with new scintillator detectors and improved signal timing accuracy for a better determination of the air shower front and an improved angular resolution. Moreover, wide-angle imaging Cherenkov detectors using a camera obscura design will allow for a better determination of $X_{\text{max}}$.

The Tunka Collaboration plans to deploy six additional clusters of Cherenkov detectors at 1 km distance from the core detector to increase the reconstruction accuracy for events recorded outside the central array [14] and thus increasing the effective area at $10^{17}$ eV by a factor of four. After first successful tests of coincident measurement of radio emission from air showers with one antenna, an upgrade to a network of 24 antennas is foreseen.

The Pierre Auger Collaboration showed first preliminary data from its High Elevation Auger Telescopes (HEAT) [15], which are additional fluorescence telescopes that enlarge the field of view of the standard Auger setup to allow for a detection of closely longitudinal profiles at energies below $10^{18}$ eV. This installation is complemented by additional water Cherenkov stations placed on a hexagonal grid of 750 m which lowers the energy threshold of the standard array by about an order of magnitude [16] and a first preliminary flux measurement was shown that extends the previously measured ultra-high energy spectrum smoothly down to $10^{17.5}$ eV [17]. The low energy enhancement of Auger will be completed by an array of underground scintillators and their capabilities for muon counting were demonstrated with data from prototype modules installed on site [18].

A similar program is planned with the Telescope Array Low Energy Extension (TALE) [19], which will use fluorescence telescopes from HiResII to enlarge the elevation coverage of one of the current Telescope Array fluorescence detectors and an infill of 45 additional scintillators with a spacing of 400 m.

### 3 Measurements of the UHECR Energy Spectrum

At the ultra-high energy frontier, the two largest arrays in operation are the Pierre Auger Observatory in the Southern hemisphere and the Telescope Array (TA) in the Northern hemisphere. The exposures on which the spectra presented at this conference are based on are shown in Figure 4. As can be seen, the surface detector of Auger has collected the largest exposure of about $2.1 \times 10^7$ km$^2$ sr yr. The current exposure of the scintillator array of TA is about $2.6 \times 10^3$ km$^2$ sr yr above $10^{19}$ eV and is thus approximately at the level of the HiRes mono-aperture.

![Fig. 4. Exposure of the various spectrum analyses presented at this conference, compared to previous experiments.](image-url)
measurement given by the fluorescence detectors. On average, the energy scale based on simulations was found to be 27% higher than the FD-based energy [23]. The rescaled MC is then used to correct for the trigger efficiency below saturation. In the lowest energy bin of the TA spectrum, the ratio of the simulated acceptance to its asymptotic value at saturation is at the 10% level.

The Pierre Auger collaboration presented an update of previously published spectrum analyses [24] with exposures increased by about 60% [25]. The ultra-high energy cosmic ray spectrum is determined from vertical ($\theta \leq 60^\circ$) showers detected by the water Cherenkov detectors of Auger without using air shower simulations. For this purpose, only data above trigger saturation ($10^{18.3}$ eV) are used, resulting in a purely geometrical acceptance that can be derived by integrating in time the number of active station-hexagons. The attenuation curve is determined by the constant intensity method [26, 27] and the measured shower sizes are then rescaled accordingly to a reference zenith angle of $38^\circ$. Finally, these corrected shower sizes are converted to energy by using a size-to-energy calibration curve obtained from the subset of the data for which showers were measured by both, surface and fluorescence detectors [28]. Using these techniques, the energy scale and aperture of the Pierre Auger Observatory are independent of air shower simulations.

In addition to the surface detector data, the spectrum is measured with the fluorescence detectors using the location and timing given by a single surface station for a precise reconstruction of the shower geometry. With this approach, lower energies can be reached and a combined spectrum from surface and fluorescence detector data was presented with a lower energy threshold of $10^{18}$ eV.

Auger quotes an energy scale uncertainty of 22% [28] and TA estimates it to be 21% [21]. The simple quadratic sum of the energy scale difference between TA and Auger is thus 30%, but the part of it originating from the fluorescence yield is correlated. In Auger, the yield from Nagano [29] is used together with the wavelength and pressure dependence from [30]. In the case of TA, the re-scaling of the MC energy scale was done using the HiRes energy scale, for which the yield from Kakimoto [31] together with the spectrum of Bunner [32] was used. The difference of these two yields are, however, known to be small when folded with the optical acceptance of the telescopes. Therefore, the fluorescence yield uncertainties can be considered close to 100% correlated and scale. Since the latter is expected to be less model dependent, the MC-estimates are rescaled accordingly.

The resulting spectra from TA and Auger are shown in Figure 5. As can be seen, there is an overall systematic discrepancy between the two results which is, however, within the aforementioned energy scale uncertainties. The two spectra clearly show a hardening of the spectrum at around $10^{18.8}$ eV and a flux suppression above $10^{19.5}$ eV. Both, TA and Auger, presented fits to the spectrum using broken power-laws with different spectral indices below the ankle ($\gamma_1$ below $E_1$), above the UHE flux suppression ($\gamma_2$ above $E_2$) and in between ($\gamma_2$ for $E_1 < E < E_2$). The obtained parameters are listed in Table 1. Almost perfect agreement about the measured spectral indices from the two experiments can be stated and also the energies of the ankle and flux suppression agree within the energy scale systematics.

Thus the data from Auger and TA, together with earlier data from HiRes [22], univocally support the existence of a flux suppression at ultra high energies with large statistical significance. However, the systematic uncertainties of the energy scale of either of these experiments do not allow for a stringent test of theoretical predictions (e.g. [33]) related to the GZK-scenario [34, 35] in which the flux suppression is due to the interaction of protons with the cosmic microwave background radiation.

| Table 1. Parameters of a broken power-law fit to the ultra-high energy cosmic ray spectrum as presented by TA [23] and Auger [25] (uncertainties are statistical only). |
|---------------------------------|------|------|
| $\gamma_1$  | $3.33 \pm 0.04$ | $3.27 \pm 0.02$ |
| $\gamma_2$  | $2.68 \pm 0.04$ | $2.68 \pm 0.01$ |
| $\gamma_3$  | $4.2 \pm 0.7$ | $4.2 \pm 0.1$ |
| $\log(E_1/\text{eV})$ | $18.69 \pm 0.03$ | $18.61 \pm 0.01$ |
| $\log(E_2/\text{eV})$ | $19.68 \pm 0.09$ | $19.41 \pm 0.02$ |

One of the dominating factors in the energy scale uncertainty is the fluorescence yield in air. A new precise measurement of this important ingredient to the energy calibration of ultra high energy cosmic ray observatories was presented by the AIRFLY collaboration [36]. Using two independent methods to determine the overall normalization of their laboratory measurement, they could achieve a measurement of...
the absolute fluorescence yield with an unprecedented precision of 4%. The presented yield of $5.7 \pm 0.1\text{(stat.)} \pm 0.2\text{(syst.)}$ photons/MeV at 337 nm would result in lowering the energy scales of the experiments (e.g. by about -10% for the Pierre Auger Observatory). This new measurement is consistent with the world average of previously published data as presented by Arqueros et al. [37], who found a combined value of $5.5 \pm 0.2$ photons/MeV at 337 nm.

Further improvements in the energy scale systematics can be achieved by a better calibration of the optical systems and monitoring of atmospheric conditions during data taking. The Pierre Auger Collaboration reported on plans to use Raman LIDARs to measure the optical depth of the atmosphere [38]. In comparison to currently used laser systems, this technique has the advantage of being able to determine the light attenuation in the atmosphere independent of assumptions of the scattering properties of aerosols in the air. The Telescope Array Collaboration presented a new method for an end-to-end calibration of their fluorescence telescopes [39]: They installed an electron linear accelerator at a distance of 100 m in front of one of the fluorescence buildings that can achieve a pulse rate of 0.5 Hz with electron bunches of about 40 MeV $\times 10^9$. One bunch is thus equivalent to an upgoing air shower with $4 \times 10^{16}$ eV and given the beam charge per bunch measured with a Faraday cup, TA will be able to cross-check the fluorescence yield, atmospheric transmission (though only in a very short piece of the atmosphere) and response of their fluorescence telescopes.

4 UHECR composition studies

4.1 Nuclear Primaries

The study of the cosmic ray composition at ultra high energies is important to establish the nature of the observed features in the cosmic ray spectrum. For instance, the ankle and the flux suppression can both be explained by propagation effects, if most of the cosmic rays are protons [33–35]. On the other hand, the ankle could also be the signature of a transition of a soft galactic component to a hard extragalactic component [40–42] and the flux suppression at ultra-high energies could be either due to energy losses of nuclei during propagation [34, 35, 43] or due to the maximum energy of the accelerators [43–45].

Since UHECRs can only be studied indirectly via air showers, the determination of the primary mass composition is difficult and very susceptible to uncertainties of the modeling of hadronic interactions that drive the air shower development [46–49].

The most straightforward composition-sensitive observable is the atmospheric depth at which the size of the electromagnetic part of the shower reaches its maximum, $X_{\text{max}}$, which can be directly observed by fluorescence and non-imaging Cherenkov detectors. Showers initiated by light primaries penetrate deeper into the atmosphere than the ones from heavy nuclei and the latter are moreover expected to exhibit smaller shower-to-shower fluctuations.

At this conference, the Pierre Auger collaboration presented an updated $X_{\text{max}}$ measurement [50].
with 80% more data than previously published [51]. The measurements of the energy evolution of the average shower maximum, \( \langle X_{\text{max}} \rangle \), and its fluctuations, RMS(\( X_{\text{max}} \)), are shown in the two lower panels of Figure 6. As can be seen, the comparison of the Auger data to predictions from air shower simulations [53–56] for proton and iron primaries suggests a transition from a light or mixed composition at around \( 10^{18} \text{ eV} \) to a mixed or heavy composition at highest energies. Similar conclusions can be drawn from the full \( X_{\text{max}} \) distributions that were presented as well.

Preliminary \( X_{\text{max}} \) measurements were also shown by the Telescope Array Collaboration from a data set of 35 months of stereo observation of showers with two of their three fluorescence sites [57]. The resulting \( \langle X_{\text{max}} \rangle \) data are displayed in Figure 7. Unfortunately, these data points cannot be directly compared to the Auger measurements from Figure 6, since they are not corrected for detector effects. Instead, air shower predictions that are folded with the simulated detector response are provided that differ by up to 25 g/cm\(^2\) from the original input values depending on the energy and primary particle. At low energies, the comparison with these modified predictions leads to the same conclusions as in case of Auger, namely a predominantly light composition below \( 10^{19} \) eV. At the highest energies, the low statistics do currently not allow for a stringent discrimination between proton and iron primaries. For instance, the measured \( X_{\text{max}} \) distributions above \( 10^{19.4} \) eV are compatible with air shower predictions for both, proton and iron primaries, using a two-sample Kolmogorov-Smirnov test even without taking into account the systematics in the \( X_{\text{max}} \) and energy scale.

Further insight into the shower development can be obtained with ground level measurements of particle densities using surface detectors. Auger presented first data on longitudinal muon production depths [58] that were inferred from a geometrical interpretation [59] of the time structure of signals recorded in the water Cherenkov stations of the observatory. The results on the average depth of muon production, \( \langle X_{\mu\text{max}} \rangle \), as a function of energy are displayed in the upper panel of Figure 6. A second method employed by Auger uses the rise-time of the surface detector signals as a proxy for the muon-to-electron fraction of particles in the detector. For non-vertical
showers, the rise-time can be measured at different longitudinal depths by comparing signals in stations located up- and down-stream of the incoming shower direction. The zenith angle at which the corresponding rise-time asymmetry is maximal can be used as an estimator for the average longitudinal development of air showers [60]. The measured energy evolution of this estimator, $\Theta_{max} = \sec \theta_{max}$, was presented in [52] and is shown in the second panel from above in Figure 6. When compared to predictions of air shower simulations, both, $\Theta_{max}$ and $\langle X_{max}\rangle$, favor a mixed or heavy composition at ultra-high energies.

![Fig. 8. Ratio of underground muon density and surface detector scintillator signal at 600 m as measured in Yakutsk compared to QGSJetII simulations [61].](image)

The Yakutsk collaboration measured the energy evolution of the ratio of the number of muons determined with underground scintillators to the total shower size at 600 m [61]. As can be seen in Figure 8, this ratio exhibits interesting features and could be interpreted by comparison to air shower simulations as a predominantly heavy composition at low energies followed by an increase of the contribution from light elements between $10^{18}$ eV and $10^{19}$ eV and a subsequent increase of the fraction of heavier nuclear primaries above that energy. Note that for a comparison to other experiments the energy scale difference of Yakutsk must be taken into account (e.g. about a factor of two with respect to Auger [62]).

Whereas all these new results presented at this conference constitute a significant increase of high-quality measurements of the energy evolution of air shower characteristics, their interpretation in terms of the evolution of the average primary mass relies on the modeling of hadronic interactions in air showers. A significant deficit of the simulated muon number at ground level with respect to surface detector data was reported by the Auger Collaboration at this meeting [63–65]. Therefore, the interpretation of observables that depend on absolute measures (as opposed to e.g. the longitudinal position) of muon production for the study of primary mass composition may be considerably biased towards heavy primaries. It will be interesting to see how these estimates of the muon number from Auger can be combined with the more direct measurements from Yakutsk. At around $10^{18}$ eV, the muon studies from Yakutsk are clearly at odds with the $\langle X_{max}\rangle$ results from Auger and Telescope Array that favor a light composition and thus fit well to the muon deficit in simulations reported by Auger. However, at higher energies the Yakutsk data are well bracketed by air shower predictions if one allows for a systematic shift in the energy scale of the experiment.

Given the uncertainties of the predictions of muons in air showers, measurements of the longitudinal development of air showers seem to be a more reliable way to estimate the primary composition. Unless a drastic change of hadronic interactions takes place at around $10^{18.5}$ eV, the longitudinal air shower development is already quite constrained by recent data from the LHC [66] as well as by proton-air cross section measurement with air showers like the one from Auger presented at this conference [67]. Once the models have been tuned to the LHC data, a significant decrease of the model differences is to be expected. For instance, as discussed in [68], the LHC-tune of the QGSJetII model will result in a $\langle X_{max}\rangle$ which is very similar to the one from the current Sibyll2.1 model.

### 4.2 Photons

A further aspect of composition studies at ultra-high energies is the search for primary photons. Luckily, these investigations are not hampered by uncertainties of hadronic interactions since the electromagnetic interactions that are relevant for the development of photon induced air showers are well understood. Primary photons are inevitably produced by the decay of neutral pions that are created in interactions of charged cosmic rays with the photons of the cosmic microwave background radiation at the $\Delta$ resonance. Since the production threshold depends on the energy per nucleon, a much higher photon flux is to be expected if ultra-high energy cosmic rays are protons rather than nuclei. New experimental limits on the integral photon flux as a function of energy were presented at this conference. The experimental signature of a photon induced shower is a deep $X_{max}$ and muon-poor particle densities at ground.
The Pierre Auger Collaboration used events detected in hybrid mode to improve the photon discrimination power at low energies. Limits are obtained from a linear discriminant analysis of the $X_{\text{max}}$ measurement and the sum of radially weighted surface detector signals [69]. The Telescope Array Collaboration presented an analysis in which the shower front curvature measured with the surface detector is used as a measure of the shower age to discriminate photons from nuclear primaries [70]. The resulting flux limits are shown in Figure 9 together with a new calculation of GZK photon fluxes from [71]. As can be seen, the sensitivity of current experiments is unfortunately not yet close to the predictions for guaranteed flux of GZK-photons produced by an all-proton primary spectrum at the source. Exotic scenarios for the production of photons, such as decay of super-heavy dark matter (SHDM) or Z-boson production by interactions of extremely high energy neutrinos with the relic neutrino background can however be already excluded.

Fig. 9. 95% C.L. upper limits on the integral photon fraction from TA [70] and Auger [69] compared to previous measurements [72–75] and theoretical flux predictions [71, 76].

5 Arrival Directions

The potentially most direct access to the origin of cosmic rays is given by their arrival directions. At the end of the galactic cosmic ray spectrum, the possible escape from the magnetic confinement in the galaxy could manifest itself in a dipolar large-scale anisotropy. Furthermore, the movement of our galaxy with respect to the isotropic extragalactic cosmic ray frame could cause a detectable anisotropy due to the Compton-Getting effect [77]. At ultrahigh energies, when deflections in the galactic and extragalactic magnetic fields are negligible, one may hope to identify close and bright sources individually. But even if the source density is large and their luminosities low, the arrival directions should follow the anisotropic distribution of nearby matter, since the propagation distance of particles is limited to within the GZK-sphere of about 100 Mpc.

The Pierre Auger Collaboration presented a number of anisotropy studies at this conference. They searched for a dipolar anisotropy in a wide energy range starting from $2.5 \times 10^{17}$ eV [78]. Since this threshold is way below the saturation of the Auger surface detector trigger, a novel method [79] to control for spurious variation in the acceptance due to e.g. weather effects was applied, in which the amplitude in right ascension is calculated from the difference of counting rates in east- and westwards direction for energies below $10^{18}$ eV. The obtained limits on the equatorial component of a dipole component of the arrival directions of cosmic rays are shown in Figure 10. As can be seen, the low energy limits exclude already certain models (e.g. drift escape of a heavy galactic component in an antisymmetric magnetic halo [80], labeled as A in Figure 10). In addition to the amplitudes, the Auger Collaboration studied the energy evolution of the phase of the dipole and found an interesting smooth transition from $-270^\circ$ below $10^{18}$ eV to $+100^\circ$ above $5 \times 10^{18}$ eV, for which, however, only a posterior chance probability could be given and new data with the recently installed Auger infill array are needed to confirm this observation.

Fig. 10. 99% C.L. upper limits on the equatorial component of a dipole component of the arrival directions of cosmic rays from Auger and previous experiments as well as theoretical predictions ([78] and references therein).

Further low-energy anisotropy studies can be performed with neutrons, which should be inevitably
produced in hadronic interactions of cosmic rays with matter during acceleration. Since neutrons are not deflected in the galactic magnetic field, they constitute suitable messengers for the search of galactic cosmic ray sources above $10^{18}$ eV at which energy their decay length reaches about the distance from the galactic center to Earth. Auger reported blind and targeted searches for neutron sources in [81]. No significant statistical excess over the background expectation was found even when stacking events from brightest gamma ray sources reported by H.E.S.S..

At ultra-high energies, the Pierre Auger Collaboration gave an update on the correlation of cosmic rays with extragalactic sources as previously reported in [82]: Events above 56 EeV and arrival directions within 3.1° to the positions of nearby ($d < 75$ Mpc) objects from the catalog of quasars and active galactic nuclei (AGNs) of Véron-Cetty and Véron [83] (cf. Figure 11(a)) are compared to the expectation from isotropy. 28 out of 84 events were found to correlate as of June 2011 [86]. The fraction of correlating events is thus $0.33 \pm 0.05$ with a 1% chance probability of being a random fluctuation of the isotropic background expectation of 0.21. The intrinsic clustering properties of this data set was translated to a limit on the density of equal-luminous sources in [87]. Assuming that deflections in magnetic fields do not wash out the clustering at scales below $5^\circ$ a source density limit of $10^{-4}$ Mpc$^{-3}$ could be set at 95% C.L..

The ultra-high energy data set of Auger shows an overdensity of events from the region of Centaurus A, which was found, however, to be not statistically significant ($P_{\text{chance}} = 0.04$) [86]. Under the hypothesis that the overdensity is real, strong constraints [88] on the injection index and fraction of heavy nuclei from this source can be derived from the lack of an overdensity in the same direction but at lower energies $E/Z$ from light nuclei as presented in [89]. In [90] it was argued, that taking into account the bending of charged nuclei in galactic magnetic fields, the events from the Centaurus A region could in fact constitute a deflected image of nuclei from the Virgo cluster.

The Telescope Array Collaboration presented anisotropy studies in the Northern hemisphere [85, 91] and their sky maps of arrival directions is shown in Figure 11(b). At energies above 40 EeV, the arrival directions from TA are compatible with both isotropy and the large scale matter distribution. The latter was determined using the 2MASS catalog of galaxies and allowing for interaction and redshift losses of cosmic rays during propagation from source to Earth. At a lower energy threshold of 10 EeV a compatibility with the matter distribution could only be achieved by assuming a large angular smearing from the galactic magnetic field. Furthermore, the Telescope Array Collaboration reported a correlation analysis using the same event selection parameters and cataloger as used by Auger in [82]. At the conference a correlating event fraction of 8 out of 20 was reported, which has been recently updated to 11 out of 25 [92] and has a 2% chance probability of being caused by a random fluctuation of the isotropic expectation of 0.24. It is interesting to note that the combined chance probability of the Auger and TA correlation result is only one permille.

6 New Techniques and Future Experiments

Radio Detection of Air Showers

A large number of contributions at this conference was devoted to the detection of cosmic rays using the MHz emission from air showers due to either geomagnetic synchrotron radiation or the Askaryan effect in solids. The principal feasibility of this technique in terms of the measurement of the arrival direction, energy estimate and self-triggering is already established and the presentations focused on the better understanding of the signal and the way towards physics measurements with radio arrays.

The CODALEMA detector reported on its operation mode of a standalone antenna array [93] and on systematic shifts within the east-west direction between the reconstructed cores from the radio array and the ones determined with a scintillator array. Using simulations these shifts could be explained as a signature of radio emission from the charge excess in air showers which is superimposed to the dominant geosynchrotron emission [94].

Self-triggered events were also reported by the Auger Engineering Radio Array (AERA) [95] and the TREND Collaboration [96]. AERA furthermore presented the first 'super-hybrid' detection [97] of radio signals in coincidence with the Auger surface detector and three fluorescence detector stations. Moreover, using the measured polarization of the signals along the east-west and north-south direction, they were able to determine the contribution of the electric charge excess in the shower to the overall signal in good quantitative agreement to predictions from event simulations with REAS [98] and MGMR [99].

A first step towards a composition sensitivity with radio arrays was presented by the LOPES Collaboration. Both, the shape of the radio wave front [100]
and the steepness of the lateral signal strength \citep{101} can be measured and related to the position of the shower maximum. Using REAS simulations the correlation between $X_{\text{max}}$ and the wave front shape and the lateral steepness can be established. The resulting $X_{\text{max}}$ values derived from the measurements were found to be encouragingly close to the ones of proton and iron, cf. Figure 12 for the distribution of shower maxima using the lateral steepness.

First events from the core of the LOFAR radio telescope were presented in \citep{102}. The LOFAR cosmic ray program can detect showers either in self-triggering mode or with an external trigger from a small air shower array \citep{103}. The central core is the most densely instrumented of all current radio arrays and the fine-grain detail with which the signals can be sampled laterally will help to get a detailed understanding of the MHz-LDFs. An example of an event measured by LOFAR is shown in Figure 13.

Apart from 'standard' cosmic ray measurements LOFAR will also conduct searches for extremely high energetic neutrinos impacting on the moon \citep{104, 105}. The ANITA Collaboration presented results from two flights over Antarctica with a balloon-borne radio detector. Searching for radio emission from neutrino interactions in ice, they found only one candidate event consistent with background estimates \citep{106}. However, they detected 16 events which they can attribute to direct or ice-reflected radio emission from ultra-high energy cosmic rays with an estimated mean energy of about 15 EeV. Using a dedicated trigger for the next flight in 2013, about 400 UHECRs are expected to be detected which may open the path for large aperture detection of cosmic rays from long duration balloon flights or from space using radio detectors.

**Microwave Emission from Air Showers**

A further technique for air shower measurements may be given by the detection of microwave radiation created in collisions of low energy electrons with the neutral molecules of the atmosphere as suggested by recent laboratory measurements performed at ANL and SLAC \citep{107}. If the emission is isotropic and strong enough to be detected over large distances, then the GHz-detection of air showers could be an attractive alternative to e.g. fluorescence telescopes allowing for the observation of the longitudinal air shower profile with a high duty cycle. Several groups are currently operating detectors to measure this radiation in the field. GHz-detectors were set up at Auger \citep{108}, KASCADE-Grande \citep{109} and in Japan \citep{110, 111} and additional laboratory measurements are being performed at ANL and LNF \citep{112}. At the time of this conference, no signals have been reported, but the reader is referred to the presentations at UHECR 2012 \citep{113–115} at which first coin-
incident measurements of GHz signals with air showers and new laboratory results were reported. These preliminary results suggest that the microwave signal is smaller than stated in [107] and potentially forward beamed similar to Cherenkov light which would make a stand-alone use of this technique for the detection of ultra-high energy cosmic ray showers less attractive (the potential of a hybrid detection together with surface detectors is currently evaluated by the Pierre Auger Collaboration).

Radar Detection of Air Showers

Yet another current field of research and development for new detection techniques is the “active” detection of cosmic rays via radar detection. The Telescope Array Radar Project (TARA) [116, 117] is currently operating a 2 kW decommissioned television transmitter at 54 MHz and log-periodic receiver antennas to detect radar signals scattered off air showers measured in TA. Simulations were presented that showed that with the upgrade to a 20 kW transmitter, the signal of an $10^{19}\text{eV}$ air shower may be detectable over the galactic noise at a distance of 50 km between transmitter and receiver.

Observation of Air Showers from Space

Over 30 years after the first proposal of observing ultra-high air showers via fluorescence light in a huge atmospheric volume from space [118], the first realization of such a project may actually happen in a few years from now. Realistic estimates about the potential duty cycle of a fluorescence detector in space are now possible due to the in situ measurements of the UV background light from the Universitetsky-Tatyana satellite [119, 120] yielding a conservative lower bound of 18.4% in good agreement with previous estimates. The first pathfinder mission for the detection of extremely high energy cosmic rays will be the TUS (Tracking Ultraviolet Setup) detector on board the “Mikhail Lomonosov” satellite to be launched in 2013 [121]. The detector will consist of a 1.8 m$^2$ Fresnel mirror read out by 256 PMT pixels which will be able to monitor an area of 6400 km$^2$ from an orbit height of 500 km [121].

The JEM-EUSO project [122] is a large spaceborne fluorescence detector proposed to be installed on the ISS. Its main science objective is the search for the sources of ultra-high energy cosmic rays above the GZK-threshold with a near uniform all-sky coverage and, depending on the actual source density within the GZK-sphere, the study of the energy spectrum of individual sources [123]. It will consist of a large aperture Fresnel lens system (2.5 m diameter) and camera composed out of over $3 \times 10^5$ pixels each of which will cover a tile of only 550 m on ground. The detector design is in a very advanced stage and details...
on the performance and prototype tests were given in over 30 contributions to this conference. The expected annual exposure of JEM-EUSO in nadir observation mode (i.e. downward looking without tilt) for different levels of quality cuts is shown in Figure 14. As can be seen, JEM-EUSO will be able to collect 6×10^4 km^2 sr yr within one year with the full field of view. Restricting the accepted shower geometries to zenith angles of < 60°, an angular and energy resolution of ≤2.5° and ≤30% respectively can be achieved with an annual exposure that is still about a factor of 1.5 larger than the one of the Pierre Auger Observatory. With further restrictions on the distance of the shower, the acceptance threshold can be lowered to a few tens of EeV, which will allow JEM-EUSO to compare its results with the ones from ground based detectors. The largest exposure would be possible if the detector views the atmosphere with a tilt of 35° in which case an annual exposure of 2×10^5 km^2 sr yr could be achieved (more than ten times the value the data presented by Auger at this conference are based on). The performance of the apparatus in tilted mode in terms of energy and angular resolution is, however, still under study.

7 Summary

The study of cosmic rays above 10^{16} eV is a vibrant field of astroparticle physics. At this conference, a lot of new high quality air shower data have been presented. Below the ankle, sub-structures in the all-particle flux as well as estimates of the contribution from different mass groups fit well to a rigidity dependent knee scenario. At ultra-high energies, the Telescope Array Collaboration presented first physics results and the Auger Collaboration confirmed many of its earlier findings with increased statistics. The spectrum measurements of the two experiments agree well within systematics but more statistics from the TA fluorescence detectors are needed to cross-check the observations of the longitudinal development from Auger. Both collaborations reported on the correlation of the arrival directions of cosmic rays with extragalactic objects and matter distributions. It is encouraging that both found more correlating events as would be expected from isotropy, though the individual chance probabilities of this being a random fluctuation are 1% and 2% respectively. New techniques, the observation of cosmic rays from space or a ground based large aperture world observatory will hopefully allow for a successful identification of the sources of ultra-high energy in the near future.

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