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Ultra High Energy Cosmic Rays

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Abstract. The origin of Ultra High Energy Cosmic Rays (UHECRs) is a long standing problem in Cosmic Ray Physics and Astrophysics. At the International Cosmic Ray Conference in Merida, Mexico, in 2007, significant progress in the study of UHECRs could be observed, especially in the contributions made by the Auger collaboration, the clear results showing a steeper energy spectrum above 4×10^{19}eV, and a possible small/medium scale anisotropy above 5×10^{19}eV. Together with the possible signature of a GZK cutoff (steepening above 4×10^{19}eV) and an updated flux limit for the gamma ray primary above 10^{19}eV excluded most of exotic scenario for the origin of UHECRs. The ankle position of the energy spectrum is proposed as an energy calibration parameter by V. Brezinsky et al. and demonstrated to work well. Simultaneously, the systematic errors in the energy estimation in different experiments are clearly recognized. The possible small/medium scale anisotropy observed in Auger and world data may indicate the beginning of a new astronomy with UHE particles.

Introduction

This paper will summarize the contributions to the high energy session at the 30th International Cosmic Ray Conference in Merida, Mexico, in 2007. The number of contributed papers in this session was about 250 and the activity in this field is very impressive. There were many interesting discussions focused on the energy spectrum above 10^{18}eV and the possible small/medium scale anisotropy above GZK cutoff (Greisen, Zatsepin and Kuzmin cutoff) energy or sub-GZK energy [1, 2]. There were also many contributions concerning the energy range between “Knee” and “Ankle”.

The study of UHECRs initiated at the Volcano Ranch by J.Linsley [3] was followed by the Sugar [4], Haverah Park [5], and Yakutsk experiments [6], and later by AGASA [7], Fly’s Eye [8] and HiRes [9]. There was a long discussion about the energy spectrum, especially about the existence of the GZK cutoff in the energy spectrum [10, 11]. There were also discussions of anisotropies of UHECRs, North-South asymmetry of cosmic ray arrival direction distribution [12], the enhancement of cosmic ray intensity on the Galactic plane [13], and on the Super-galactic plane [14], Clusters of events [15, 16], etc... These problems now seem to be converging, but still there are many open questions.

There are specific aspects of UHECRs compared with lower energy cosmic rays. First, interaction with microwave background photons will modify the energy spectrum of cosmic rays and will produce a dip structure by pair creation around 3×10^{18}eV and the GZK cutoff by pion production around 6×10^{19}eV [17, 18, 19]. The GZK cutoff structure depends on source distance, distribution and source evolution. The life time of UHECRs will change from several Gpc below 10^{18}eV (by the redshift energy loss) to 1.5Gpc around 3×10^{18}eV (by the pair creation) and to 30 Mpc above 10^{20}eV (by pion production).

Second, UHECRs are less deflected by the galactic and extragalactic magnetic field. The typical deflection angle of cosmic ray protons of 10^{20}eV by the galactic magnetic field becomes less than 1 degree [20, 21, 22]. We do not know well about the extragalactic magnetic field, but if we employ widely used parameters, a magnetic field strength of 10nGauss, and a coherent length of magnetic field 1 Mpc, we expect a deflection angle of a few degrees for 10^{20}eV UHECR protons after 30 Mpc propagation from sources[23, 24]. The propagation distance for 10^{20}eV UHECR protons is also limited above the mentioned GZK mechanism.

Third, we do not expect many types of sources as accelerators of UHECRs. This is very well explained by the Hillas plot [25]. The only possible sources are AGNs [26, 27], GRBs [28], hot spot of radio galaxy lobes [29], and maybe, cluster of galaxies [30] and colliding galaxies. The number of potential sources in the GZK volume is limited.

With these distinguished features, we expect a new astrophysics with hadronic particles is possible in the energy range around GZK energy or beyond GZK energy, and the study of UHECRs is very important.

UHECRs in the energy range between knee and ankle have another interest. The origin of the knee is now considered as the acceleration limit of light particles (Protons or Helium) in the Super Nova Remnants [31, 32]. The non-linear effect, the amplification of magnetic field by cosmic rays in the supernova shell boosts the maximum attainable energy of cosmic rays as high as 10^{15}eV [33]. The detailed study of the energy spectrum and the chemical composition is important for understanding the origin of galactic cosmic rays and the acceleration of cosmic rays in our galactic sources, SNRs, Pulsar Wind Nebulae, and Binaries. The average chemical composition is getting heavier above knee energy [31, 32]. The maximum attainable energy of iron nuclei can be 10^{17}eV. There is some evidence showing that above this energy the chemical composition becomes lighter toward the ankle (maybe the transition from galactic to extragalactic cosmic rays) [34, 35]. There are several experiments and near-future plans, like KASCADE Grand [36], TALE [37] in the Telescope Array site [38], and HEAP [39] and AMIGA [40] in the Auger site [41], which try to see the highest energy end of galactic cosmic rays and the transition to extragalactic components.

UHECR Energy Spectrum

The HiRes collaboration presented a final monocular energy spectrum as shown in Fig. 1 [42]. The cutoff feature above 4×10^{19}eV is observed with a significance of 4.8 sigma. The dip structure around

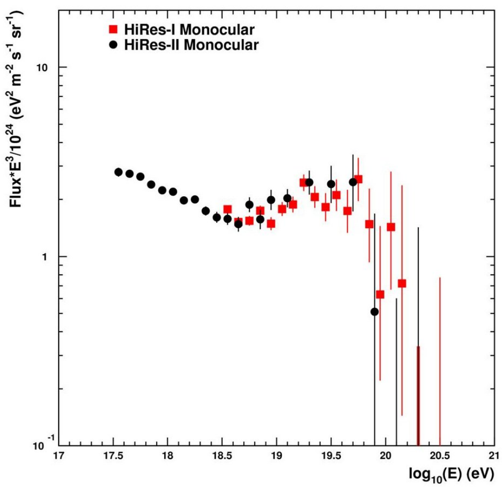

Fig. 1. HiRes Mono energy spectrum [42]. The cut off above 4×10^{19}eV is observed with a significance of 4.8 sigma.

$(3-4) \times 10^{18}$eV is also seen. These spectral structures, the cutoff and dip, can be interpreted as the effect of the propagation for the extragalactic cosmic ray protons (GZK cutoff and pair creation dip) [43]. The HiRes stereo energy spectrum [44] is shown in Fig. 2. A fiducial volume (radius) cut was carried out in each energy bin in order to only use events seen in the volume where cosmic rays can be observed with a 100% efficiency. This procedure certainly reduces the systematic errors in the aperture estimation in the Monte Carlo simulation. Furthermore, a better geometrical reconstruction, and redundant energy estimations by two eyes give us a more reliable energy spectrum than monocular data. However, the statistics is limited. The HiRes stereo spectrum is quite consistent with the HiRes monocular energy spectra, and supports them.

The Auger collaboration presented three independent energy spectra using small zenith angle Surface Detector (SD) data [45], large zenith angle SD data [46] and Hybrid data of Fluorescence Detector (FD) and SD [47]. They are all consistent within the statistical errors and allow us to combine them with proper statistical weights. The combined energy spectrum is shown in Fig. 3 [48], which shows the cutoff and dip structure. The Auger collaboration is cautious to interpret these structures as a GZK effect [49]. This is related

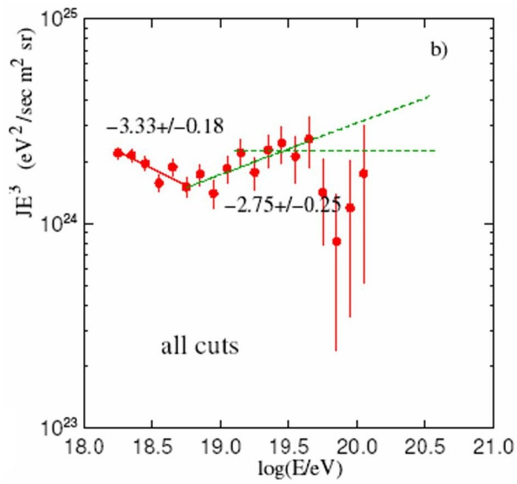

Fig. 2. HiRes Stereo Energy Spectrum [44].

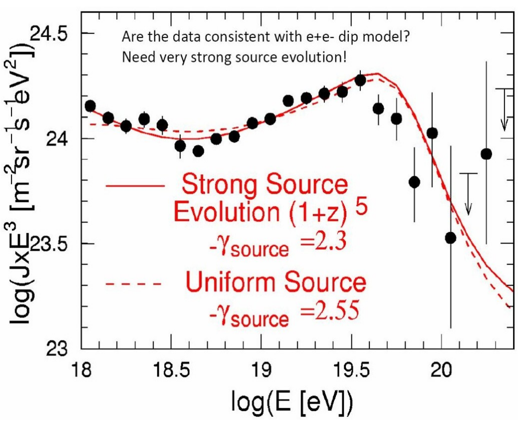

Fig. 3. Auger combined Energy Spectrum. The observed spectrum is compared to the extragalactic proton model with strong evolution [48].

to the chemical composition study by Auger [50], which will be discussed in section 4. The energy spectrum above 4×10^{19}eV can be fitted to the spectrum with the spectral slope of -4.1 ± 0.4. The deficit of events above $10^{19.6}$eV is observed with a statistical significance of 6 sigma. This spectral slope can be compared with the value 5.1 ± 0.7 obtained by HiRes monocular spectra.

Ankle in UHECR Energy Spectrum

There are two possibilities of interpretating the Ankle in the energy spectrum. One interpretation is that the ankle shows the transition from galactic cosmic rays to extra-galactic ones [51]. The other interpretation, which recently has been more widely accepted in the community, is that the ankle is the dip structure of the cosmic ray proton spectrum produced by pair creation through interaction with the microwave background radiation [52]. In any case, it is evident that there is an ankle structure around $(3-5)\times10^{18}$eV.

Berezinsky et al. proposed to use this spectral structure for calibrating the energy scales in different experiments [52]. The left panel in Fig. 4 shows E-cubed energy spectra obtained by the AGASA, Yakutsk and HiRes experiments. The fluxes of cosmic rays and the positions of the ankle are scattered. The right figure shows the spectra after this calibration. In this case, the AGASA, HiRes and Yakutsk spectra are scaled by factors of 0.9, 1.2 and 0.75, respectively. The flux is not modified. It should be noted that if we introduce a scale factor c in the expression of the E-cubed energy spectrum E^3dF/dE, E is scaled to $E' = cE$ and, consequently, the E-cubed flux is scaled to

$$E'^3\frac{dF}{dE'} = c^2E^3\frac{dF}{dE}.$$

It is amazing to see the very good agreement in the flux between three different energy spectra just by calibrating the energy scale (ankle position). Of course, there are different systematic errors in different experiments. But this good agreement of flux after energy calibration means the main source of systematic errors in deriving the energy spectra in these three experiments are the individual energy scales defined by air fluorescence yield (HiRes)[53], the conversion factor obtained by M.C.(AGASA) [54] and the calibration with Cherenkov light (Yakutsk) [55].

Berezinsky and his colleagues assumed this dip is due to the pair creation dip of the cosmological UHECR protons and defined the absolute energy scale [56]. This is a novel idea of doing an absolute energy calibration in measurements of UHECRs. If we follow this argument, the AGASA energy shall be scaled down by 10%, the HiRes one scaled up by 20%, and the Yakutsk one scaled down by 25%.

The new Auger energy spectrum is also shown in Fig. 5 in comparison with other experiments [43]. Both of the flux and ankle positions are lo-

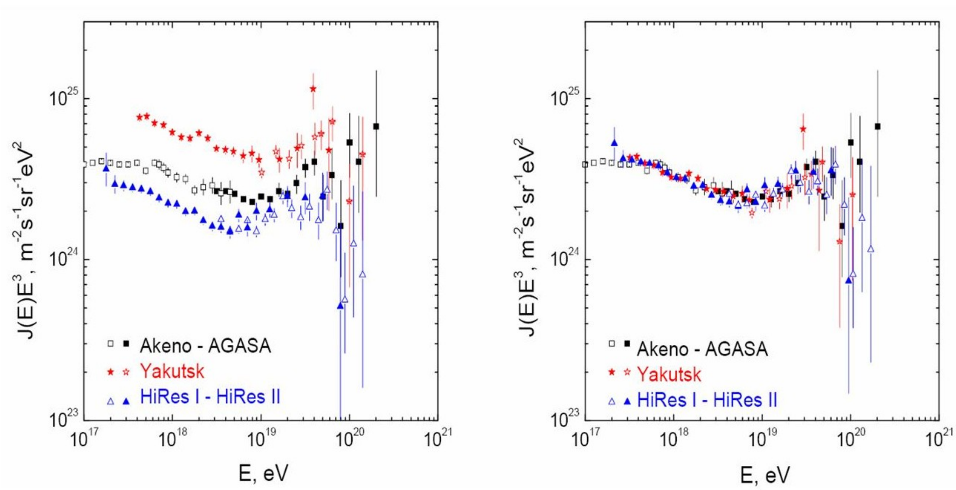

Fig. 4. Comparison of three energy spectra obtained by AGASA, Yakutsk and HiRes. The right figure shows the result after the energy calibration using ankle position [43].

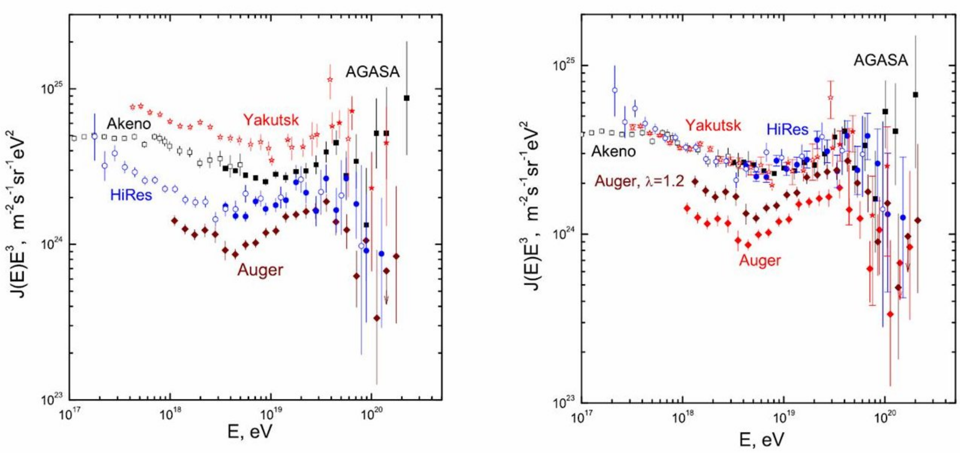

Fig. 5. Auger Energy Spectrum is compared with other energy spectra. The right figure shows the result after scaling Auger Energy by a factor of 1.2 [43].

cated at the lowest level among all experiments. The Auger collaboration estimated the systematic error in the energy determination to be about 20%. Berezinsky showed the case where the Auger energy spectrum is scaled up by a factor of 1.2, which is the maximum shift in the systematic error. It is clear, however, that the agreement with other experiments is still not excellent. We need a scale factor of 1.4-1.5 for the Auger energy spectrum to get a reasonable agreement with the expected pair creation dip or with other experiments. If the Auger energy spectrum is right, we may need to abandon the interpretation of the pair creation dip. The HiRes and Auger energy scales are based on fluorescence light yield in the air. HiRes and Auger use the yields measured by Kakimot et al. [57] and Nagano et al. [58]. The difference can be about 11-15% (HiRes uses the smaller yield). Fluorescence calibration gives us a relatively lower energy scale, and the M.C. calibration and Cherenkov calibration give us a relatively higher energy scale. Further investigation is necessary for obtaining a consistent picture of the energy scale. The chemical composition study around the ankle (mixed composition or pure proton) will give us a clear and definite answer about the ankle in the near future.

Primary Gamma-Rays and Chemical Composition

The fraction of gamma rays in UHECRs is an important parameter. The exotic models for the origin of UHECRs, so-called Top Down models, expect a higher fraction of gamma rays [59, 60, 61]. The Auger surface detector has an excellent power to discriminate gamma showers from other hadronic showers initiated by protons and heavy nuclei [62]. The gamma showers have a deeper shower maximum position, and can be identified as young showers which have a smaller radius of curvature and larger thickness in the shower front. Auger presents a new result on the flux upper limit of gamma rays in the ultra high energy regime as shown in Fig. 6 [62]. Most of the models of super heavy dark matters and topological defects are excluded by this excellent observation. The cosmogenic gamma rays produced by the GZK mechanism is estimated to be in the range of $10^{-4} \sim 10^{-2}$ of the total flux of UHECRs. Auger

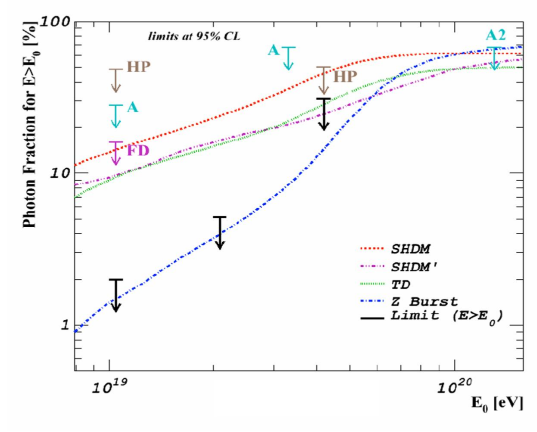

Fig. 6. Upper limit on the fraction of gamma rays among UHECRs. The thick arrows show the upper limits obtained by Auger [62].

may detect cosmogenic gammas in 20 years of operation [63].

The shower maximum depth X_{max} can be used to estimate the chemical composition of UHECRs. With relation to the interpretation/understanding of the ankle, the measurement above 10^{18}eV is important to make sure whether the chemical composition of UHECRs is dominated by protons (if the structure is due to the pair creation dip). Above 10^{19}eV, the measurement of X_{max} is extremely important to make sure the observed cutoff features around 4×10^{19}eV by HiRes and Auger are GZK cutoff for UHECR protons. In contrast, once we obtain firm evidence for the composition above 10^{18}eV or 10^{19}eV to be dominated by protons, we can also discuss the high energy interactions beyond LHC energy using cosmic rays.

Fig. 7 shows the averaged X_{max} as a function of energy. Larger closed circles with numbers of events show the Auger result [64], and the smaller circles running with slightly higher values correspond to the HiRes result [65]. Red circles with larger error bars correspond to the HiRes-MIA measurement [66]. The HiRes collaboration claims that their measurement suggests proton dominant components above 10^{18}eV by comparing their data to the expected X_{max} obtained by Monte Carlo simulation with the CORSIKA-QGSJET model. Auger observation shows almost the same X_{max} values below 3×10^{18}eV with HiRes observation, however, there is some systematic dif-

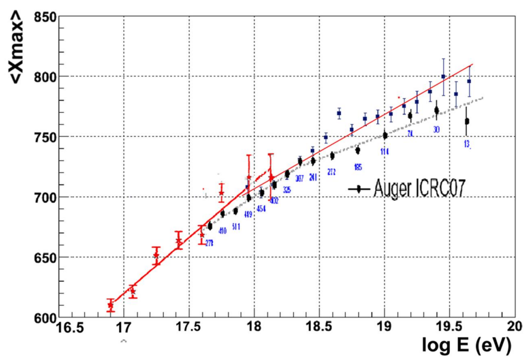

Fig. 7. Averaged Xmax as a function of energy observed by Auger Hybrid observations [64] and HiRes Stereo [65].

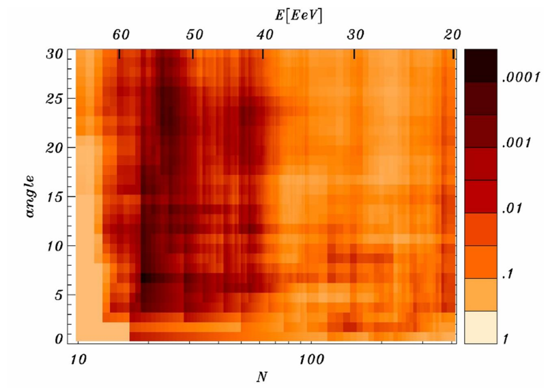

Fig. 8. Auger autocorrelation scan in the threshold energy and space angle [72].

ference of about 20g/cm^2 above 3×10^{18}eV. Auger observations may suggest mixed composition if we interpret it with the CORSIKA-QGS-JET model. At present, we can not judge which is the correct interpretation, but we can say that this difference of $20-30$g/cm^2 in X_{max} measurements in Auger and HiRes demonstrates the difficulty of experiments.

Anisotropy

The anisotropies of cosmic ray arrival direction at the energy of 10^{18}eV claimed by the AGASA collaboration [67], excess of events in the direction of the galactic center and deficit in the direction of the anti-galactic center, were examined by the HiRes [68] and Auger collaborations [69]. The Auger collaboration puts the upper limit for the excess from the galactic center direction at the anisotropy strength of 11% (10degree psf) and 5% (20 degree psf), which refutes the claim by AGASA. HiRes observed a possible deficit in the direction of the anti-galactic center. It is similar to the deficit observed by AGASA.

Concerning the small scale anisotropy at the highest energy region above 10^{19}eV., the AGASA collaboration claimed the excess of doublets and a triplet in the arrival direction of UHECRs above 4×10^{19}eV [15]. There is one more event observed by HiRes in stereo mode in the direction of the AGASA triplet [70]. The direction of this triplet/quartet is on the super-galactic plane and we can find merging galaxies and dead AGNs nearby. The MAGIC collaboration observed this sky region and put a flux limit for 200 GeV gamma rays [71].

The Auger Collaboration made a systematic study of the anisotropy of the arrival direction distribution of UHECRs above 10^{19}eV [72]. They evaluated the autocorrelation by scanning the threshold energy and space angle. The result is shown in Fig. 8 [72]. We can see dark region in a 2-D scan map at a threshold energy around $(5-6) \times 10^{19}$eV and space angles from several degrees to 30 degrees. Here the color code corresponds to the chance probability. The minimum chance probability of $P_{min} = 10^{-4}$ is obtained at a threshold energy of 5.7×10^{19}eV and an angle of 7 degrees. After taking into account the number of trials, the actual chance probability is estimated to be 10^{-2} [72].

The small/medium scale possible anisotropy observed by Auger can be slightly different from the result observed by AGASA (point source like feature) in the threshold energy and separation angles between events. If we consider the difference in the energy scales of Auger and AGASA, the threshold energies are different by a factor two. The angular resolution of Auger in its highest energy could be less than 0.5 degrees and the observed result suggests the diffuse source may be related to the large scale structure of the nearby local Universe or the small scattering by a galactic/intergalactic magnetic field. This is one of the most exciting results in this conference.

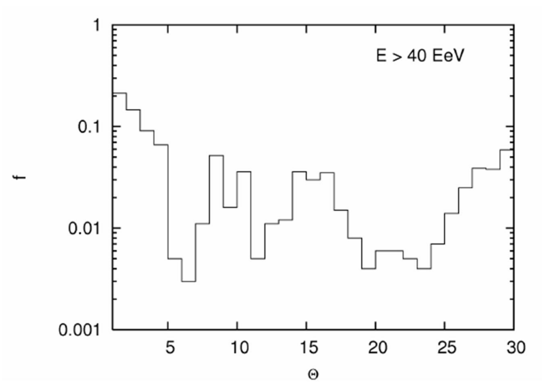

Fig. 9. Medium scale anisotropy with the world data[73].

Before the observation of the small/medium scale anisotropy by Auger, there was also an important work peformed by Kachelriess and Semikoz [73]. They analyzed the world data above a rescaled energy of 4×10^{19}eV and found a medium scale anisotropy (15-35 degrees). This work using world data and the new Auger result are quite consistent. Probably the point source like feature observed by AGASA is due to the weaker magnetic field in the northern hemisphere and or just low statistics.

There is an interesting theoretical work for the anisotropy with UHECRs by A. Olinto et al. [74]. They have assumed the intensity of UHECRs follows the matter density distribution and calculated the expected contribution to the local UHECR intensity from sources in different distances. We can expect that the maximum source distance will shrink dramatically around or beyond GZK energy, and then the inhomogeneous source distribution in the nearby volume (local structure of the Universe) becomes more visible. The realization by M.C. simulation is shown in Fig. 10. They calculated the expected anisotropy in three cases, 3×10^{19}eV, 10^{20}eV, and 3×10^{20}eV. The amplitude of anisotropy becomes higher and a large scale structure in the nearby Universe becomes more visible.

Between Knee and Ankle

There are many experimental efforts to study the UHECRs between "Knee" and "Ankle". It is impossible to review all experiments. Therefore, a few interesting results will be selected here.

The NEVOD-DECOR detector measured the muon multiplicity distribution in muon bundles in different zenith angle ranges [75]. These results are compared with the expected muon multiplicity distribution estimated with CORSIKA M.C. simulation by assuming the energy spectrum. It is surprising that their measurement is sensitive to the energy spectrum and chemical composition from the knee energy to 10^{18}eV. Of course, the interpretation is very dependent on Monte Carlo simulation, but we may use these results to test or examine the consistency of measurements and Monte Carlo simulation.

The analysis of KASCADE data was updated [31]. It was concluded that the composition gets heavier across the knee, but the relative abundance of elements strongly depends on the interaction model used in the Monte Carlo simulation. The new possible method to estimate the chemical composition is demonstrated by measuring the muon production height [76]. The muon production height is estimated using the fine muon tracking chamber of 128m^2 area. $N_e - N_\mu$ ratio has a good correlation with the muon production height. The information of muon production height may deliver a new discrimination power for the chemical composition.

KASCADE-GRANDE shows the preliminary results on shower size spectrum [77], muon size spectrum [78], and anisotropy of UHECR arrival direction in the energy range between 10^{15}eV and 10^{18}eV [79].

New Projects

Telescope Array is now in the commissioning phase, and will start full operation in autumn 2007 [38]. Telescope Array consists of 512 scintillation counters of 3m^2 size installed with the spacing of 1.2km [80] and three air fluorescence stations [81]. The acceptance of the ground array is limited at several times that of AGASA by its geometry (750km^2), but acceptance might be increased to up to 23 times of AGASA by including the monocular events observed by air fluorescence stations [82]. The Telescope Array project is completely complementary to Auger South and

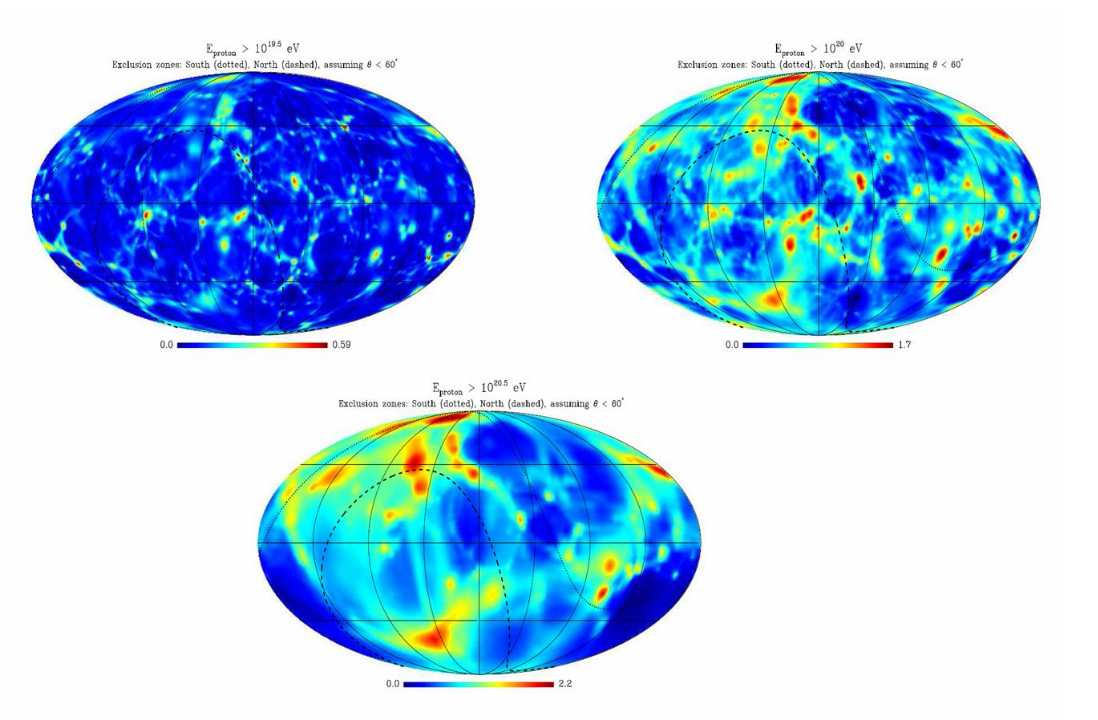

Fig. 10. The expected sky of UHECRs by A. Olinto et al. [74]. Three pictures from left to right correspond to 3×10^{19}eV, 10^{20}eV and 3×10^{20}eV threshold energies, respectively.

will provide us with the anisotropy pattern in the northern hemisphere and the flux above GZK energy in the northern hemisphere. We can expect a possible difference in fluxes above GZK energy due to the anisotropic locality of UHECR sources in the northern and southern hemispheres. The extension to low energy (TALE) is planned to see the transition from Galactic to extra-galactic components [37]. TALE consists of the surface infill and muon infill-arrays and the tower fluorescence detectors watching the high elevation angles. The acceptance can be $10 \sim 20\text{km}^2$ area and cover the energy range between $10^{16.5} \sim 10^{18.5}$eV.

The construction of Auger North is currently under discussion [83]. The site was decided to be situated in Colorado, U.S.A.. The array consists of 4000 water tanks deployed with one square mile grid covering a $10,370\text{km}^2$ area and three air fluorescence stations. It will be about 3.5 times larger than Auger South. In Auger South, the low energy extension by HEAT (High Elevation Air Fluorescence Telescopes)[39] and AMIGA (buried muon detectors) [40] is planned.

JEM-EUSO is a mission to observe air fluorescence light from gigantic air showers induced by UHECRs from the International Space Station (ISS) [84, 85, 86]. The original EUSO mission (ESA-EUSO) [87] was unfortunately frozen in 2004 by ESA due to the space shuttle accident and the uncertain future of ISS. JEM-EUSO is the new mission defined by JAXA (Japanese space agency). The phase A/B study is ongoing. To enhance the acceptance for UHECRs, tilt mode operation is planned after one or two years' nadir mode operation. The main physics target is to accumulate exposure of more than one million km^2 sr yr (one million Linsley) and collect more than 1000 events above 10^{20}eV and deliver a full-sky map of UHECRs with high statistics. JEM-EUSO may exhibit individual nearby sources. The launch is scheduled for 2013.

Conclusion

In this conference, there has been significant progress in the study of UHECRs by the new results from Auger. The cutoff or the steepening of the energy spectrum above 4×10^{19}eV was clearly seen in Auger [45, 46, 47, 48] and HiRes data [42, 44]. The energy where the spectrum becomes steeper is close to the GZK energy predicted by theoretical calculations [43, 52, 56]. Due to an incomplete understanding of the absolute energy scale and the chemical composition, the Auger collaboration has a reservation to conclude that the steepening is GZK cutoff [48, 49]. For example, the Auger X_{max} distribution favors the interpretation with a mixed composition.

The small/medium anisotropy reported by Auger above 5×10^{19}eV and the similar result reported by Kachelriess and Semikoz using the world data caused our special interest for further study of UHECRs. These analyses can be compared to the theoretical predictions. Probably we are at the dawn of new astronomy with ultra high energy particles. In this sense, the new ambitious projects, Auger North and the JEM-EUSO mission, are the right directions to firmly establish a new UHECR astronomy.

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