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Cosmic Ray Measurements above 1 EeV

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The Origin of the Extremely High-Energy Cosmic Rays (EHECRs) has been one of the major mystery in Astrophysics. The standard theory to bound highest energies we possibly detect in the earth, the "GZK" mechanism, is facing a serious challenge prompted by the energy spectrum extending well beyond 10^{20} eV (100 EeV) reported by AGASA group. In this conference, the HiRes collaboration, with the detector based on a totally different technique to reconstruct extensive air showers, reported their most updated spectral data and claimed that there exists the GZK cutoff feature in the way exactly expected in the standard physics scenario. Although possible sources to cause this apparent discrepancy from the AGASA results have not been well understood, the hybrid measurements by the Auger experiment would be finally able to resolve this issues as we have seen in their first preliminary data reported in this conference, showing a great potential capability of the hybrid data.

1. The AGASA era

It has been a great astrophysical problem to understand where and how particles with unbelievably high energies are produced. The conclusion made by the AGASA data on this issue indicated that they are at least coming from extragalactic space, but a straightforward picture cannot explain their findings, i.e.,

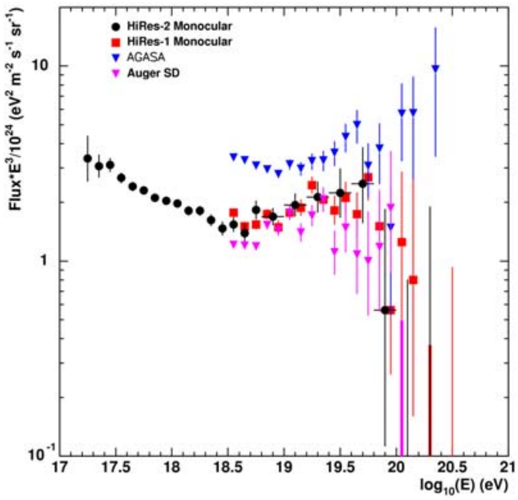
1. Event clusters above 40 EeV pointing outer space of our galaxy.
2. Large-scale isotropic distribution of the EHECR arrival directions.
3. An enhancement of cosmic rays in 1EeV range from direction of the galactic center and possibly the Cygnus region.
4. No obvious indication of changing EHECR mass composition with energies above 10 EeV.
5. Energy spectrum extending well beyond the expected GZK cutoff energy (~60EeV).

The first three items can be understood in the scenario that the galactic cosmic ray population with at least a fraction of proton component is dominated by extragalactic population in EHE range. The last two items, however, cannot be interpreted in this context, however, without fine tuning of the relevant parameters, or assuming larger experimental uncertainties than expected. An independent new data to confirm/exclude those results was definitely required.

2. The HiRes energy spectrum

The HiRes detector measures the fluorescence light profile emitted from charged particles in an extensive air shower. The quasi-calorimetric method to determine its primary energy provides relatively robust energy resolution without relying on complex particle interaction simulations. Understanding of the optical detector response and its resultant aperture requires, however, series of careful calibrations and detailed detector Monte Carlo simulations, which is never trivial. We should always be aware that the measured energy spectrum and its reliability involves these complexities.

The HiRes spectrum data consists of three population. A "monocular" spectrum either by HiRes 1 or HiRes 2, and a "stereoscopic" spectrum measured by the both eyes [1]. The HiRes 1 mono data enjoys richest statistics because of the earlier start of data taking.



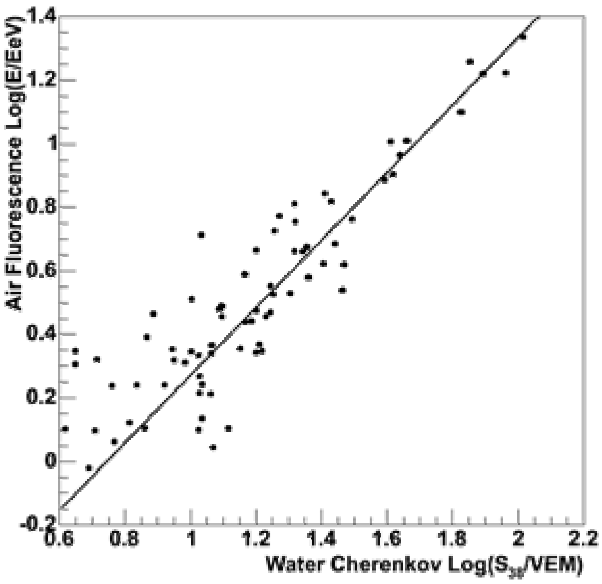
The current exposure as of this conference is approximately 5000 km^2 sr yr, a factor of three larger than that of AGASA. Its limited elevation coverage and its old-fashioned electronics increases the threshold energy in spectral measurement, however (approximately 3EeV). HiRes 2 station has a 2ring full coverage of elevation angles with the modern FADC electronics readout and the threshold energy is lower to be around 0.2 EeV. But the statistics is not good enough to reach the highest energy end of the spectrum.

The monocular spectra ("HiRes-1" and HiRes-2") are shown above. The original AGASA spectrum is also shown for comparison. One can see that the HiRes-1 mono spectrum exhibits a cutoff structure. The HiRes collaboration exercised global fitting on the integral spectrum to evaluate the cutoff energy and found that the flux attenuation starts around 60 EeV, as exactly expected in the standard GZK scenario [2]. The statistical significance of the attenuation structure was claimed to be ~5 σ.

The "stereo" spectrum, with less systematic uncertainty and finer energy resolution, has also exhibited the attenuation feature. The statistical significance is 4.8 σ [1]. Although detailed study on systematic errors and comparison with Monte Carlo simulation remains to be completed before drawing final conclusion, it is very likely that the HiRes spectrum is consistent with the GZK picture.

3. The Auger energy spectrum

A possible source to make differences of spectral results between AGASA and HiRes could be originated in their experimental method. The energy scale determined by the ground array and the fluorescence detector might explain their inconsistency. The Auger experiment is constructing both the giant ground array covering 3000 km^2 and three stations of the fluorescence detector, which allows "hybrid" measurement, viewing an extensive air shower by the both detector simultaneously. The hybrid analysis relates the energy indicator of the ground array data to energy determined by the fluorescence detector. This relation will estimate energy in an individual ground array event.



The top figure shows the correlation between the two parameters obtained by the hybrid events [3]. The surface detector of the Auger ground array is a water Cherenkov detector and they introduced "S(1000)", a local Cherenkov light intensity at 1000 m away from the shower core, normalized by signal of the vertically equivalent muons passing through the detector. Although the water tank response to secondary particles in an air shower is different from the scintillation detector, this index is conceptually similar to the AGASA' s energy indicator S(600). As seen in the figure, there is a clear correlation between S(1000) and the energy determined by the fluorescence detector. Though the statistics is not enough, yet, to finalize the energy scale factor, this is definitely an encouraging indication that the ground array data is calibrated well by the fluorescence measurement. The present energy spectrum estimated by the tentatively determined scale factor is shown above. The systematic uncertainty in energy determination is still too large (~40 %) to discuss the GZK issue, but rapidly improving statistics of the hybrid events would lead to significant reduction of the uncertainty.

On the average basis, the energy scale determined by the hybrid events would resolve issues on the absolute energy estimation. It should be remarked, however, the FLUCTUATION of S(1000) and its possible dependence on mass composition might make it difficult to evaluate the GZK effect. The present particle interaction simulation indicated that this concern would be too pessimistic : fluctuation of S(1000) due to intrinsic fluctuation of cascade development is an order of 15% and a possible systematic difference of the energy indicator values between proton and iron primaries is 10 % [4]. But the reliability of the Monte Carlo simulation has always been an issue and we should keep this point in my mind. A enough statistics of hybrid events at 10-50 EeV would be a clue to understand the shower cascade behavior in the GZK regime.

4. Anisotropy : EHE particle astronomy?

As mentioned earlier, the AGASA revealed a possibility of EHE particle astronomy - The small scale anisotropy and the galactic center enhancement. None of them have been confirmed by HiRes or Auger in this conference. The chance probability of having the triplet combining the AGASA and HiRes dataset is 0.28 [5].

The Auger southern sky exposure has not indicated an excess from the galactic center direction. Although the both group cannot EXCLUDE the AGASA' s claim by their present sensitivity, likelihood of the anisotropy in high energy cosmic rays in any form is currently in a gray zone. A near future improvement on statistics and energy resolution on the relevant data from HiRes and Auger will lead to firm confirmation/exclusion of the AGASA 's claim.

Although they are sort of tricky, there are two “positive” reports in the conference. One is the fact that a HiRes stereo event with slightly lower than 40 EeV arrives from the direction overlapping on the AGASA 's triplet region [5]. Considering a possible energy scale difference between HiRes and AGASA, it would be worth to pay attentions. Another is the claim that the arrival directions of the HiRes stereo events with energies greater than 10 EeV are correlated with BL Lacs [6]. No cuts on the BL Lac related parameters except their magnitude has led to correlation with level of 10^{-4}.

Those results were not produced in the blind analysis method – One should decide a priori what criteria will be applied to data. Therefore, the statistical significance claimed in this analysis should not be considered as it is. However, the continuous data taking by HiRes though March 2006 will yield an independent dataset with approximately 70% volume of the present data. The “frozen” analysis without changing any criteria from the present to this new data would be a real test for these interesting observations.

5. Future prospects

It will be definitely the Auger time – Their exposure will be 7 times bigger than AGASA by the next ICRC. The high statistics in the hybrid event analysis will improve the systematic uncertainty. Their results will continue to be a highlight in this field for next couple of years. The AGASA-HiRes discrepancy will be finally resolved.

I would like to draw one's attention to the trend, however, that we will see more comprehensive and complementary approach to understand the extremely high-energy universe. One is the multi-“particle types” observation. Searching for high energy neutrinos and γ-rays will provide a probe to distant sources and the cosmic diffuse radio background. The HiRes and Auger have a capability of this kind of search by looking for air showers with anomaly cascade development [7]. The km-scale neutrino observatory, IceCube, will yield a first result. The full scale IceCube detector will have sensitivity reaching to the GZK neutrino detection [8]. So as the Auger will [9]. These observations should hint physics mechanism of the EHE particle production – how and where they are produced.

While the Auger has a giant coverage in the Southern Sky, monitoring the Northern sky is also important. The Hires new dataset will be tested against the event cluster/BL lac hypothesis. Furthermore, the next generation experiment, the Telescope Array project, also with the hybrid detectors, will see its first light in the Utah [10]. With approximately 8 times AGASA acceptance, the Telescope Array will provide a picture of high energy cosmos in the Northern sky.

Finally I should mention that lots of efforts are underway in labs to reduce systematic uncertainty in energy estimation. It includes the fluorescence yield measurements and the direct detection of ultra-forward scattered particles at the LHC collision [11]. The high energy cosmic ray physics will eventually turn to level of the precise science we have not experienced, yet.

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