Energy Determination in the Akeno Giant Air Shower Array Experiment

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Abstract

Using data from more than ten-years of observations with the Akeno Giant Air Shower Array (AGASA), we published that the energy spectrum of ultra-high energy cosmic rays extends beyond the GZK cutoff. We have reevaluated the energy determination method used for AGASA events with respect to various factors. The currently assigned energies of AGASA events have an accuracy of $\pm 25\%$ in event-reconstruction resolution and $\pm 18\%$ in systematic errors around 10^{20}eV. This systematic uncertainty is independent of primary energy above 10^{19}eV.

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1. Introduction

From observation with the Akeno Giant Air Shower Array (AGASA), we have published that the energy spectrum of extremely high energy cosmic rays extends up to a few times 10^{20}eV without the expected GZK cutoff [2]. On the other hand, the HiRes collaboration [5] has presented their energy spectrum with the cutoff feature in the previous ICRC at Hamburg, Germany. It is quite important to examine the possibility of overestimating energies of AGASA events. We have therefore reevaluated uncertainties in the energy determination of AGASA events with respect to the lateral distribution of shower particles, their attenuation with zenith angle, shower front structure, delayed particles observed far from the core, and other factors, using data accumulated at the Akeno Observatory so far.

2. Systematic uncertainties on energy estimation in AGASA

Table 1 summarizes the major systematics and uncertainties in energy estimation. The probable overestimation of 10% due to shower front structure and delayed particles may be compensated for by the probable underestimation of the energy conversion factor by 10%, an effect resulting from the inclusion of the average altitude of AGASA and the proper definition of what is meant by a "single particle". Adding uncertainties in quadrature, the systematic uncertainty in energy determination in the AGASA experiment is estimated to be ±18% in total. Therefore, the currently assigned energies of the AGASA events are fairly

Table 1. Major systematics of AGASA.

Detector:	
detector absolute gain	± 0.7%
detector linearity	± 7%
detector response (box, housing, ...)	± 5%
Air shower phenomenology:	
lateral distribution function	± 7%
$S(600)$ attenuation	± 5%
shower front structure	− 5% ± 5%
delayed particles	− 5% ± 5%
Energy estimator $S(600)$:	
interaction models, chemical compositions (p/Fe), simulation codes, height correction, $S(600)$ fluctuation	+10% ±12%
Total	±0% ±18%

The symbol "+" means that currently assigned energies should be pushed up under a particular effect, and the symbol "−" represents a shift in the opposite direction.

good. The event-reconstruction resolution is ±25% at 10^{20}eV. The details on these uncertainties are described in *astro-ph/0209422* which is to be published in *Astroparticle Physics* [3].

3. Energy Spectrum

Fig.1 shows the energy spectrum observed with AGASA with zenith angles smaller than 45° up until the end of 2002. The exposure (the aperture × the observation time) is 5.3×10^{16} m^2 s sr above 10^{19}eV. We observed 11 events above 10^{20}eV, while 1.8 events are expected under the GZK cutoff spectrum. This corresponds to 4.5σ deviation from the GZK cutoff. The form of the GZK cut-

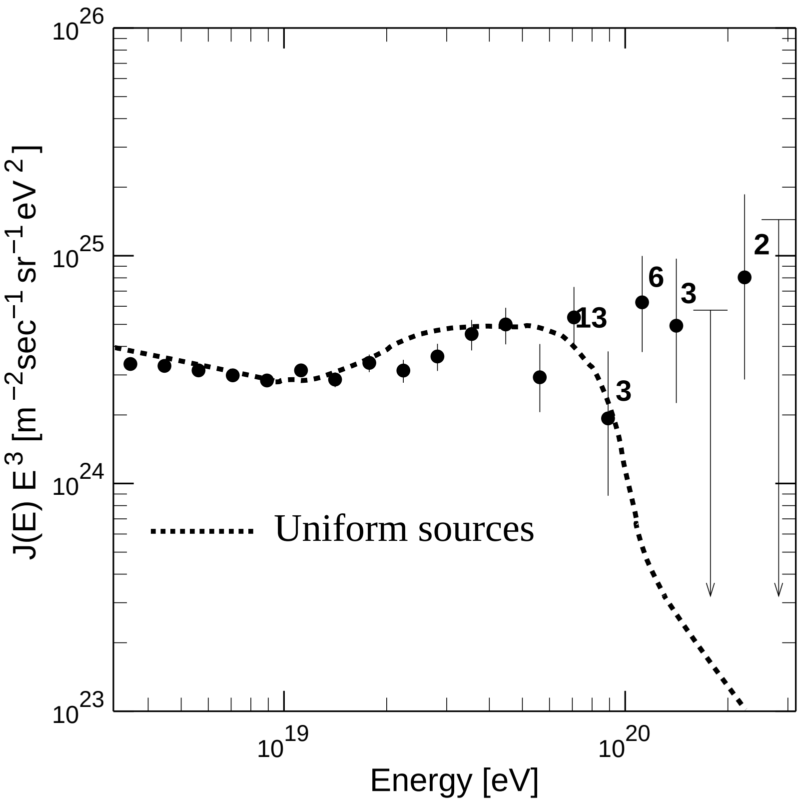

Fig. 1. Energy spectrum determined by AGASA with zenith angles smaller than 45° up until the end of 2002. The vertical axis is multiplied by E^3. Error bars represent the Poisson upper and lower limits at 68% confidence limit and arrows are 90% C.L. upper limits. Numbers attached to the points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe [4], taking account of the energy determination error. The uncertainty in the exposure is shown by the shaded region.

Table 2. Energy spectrum with zenith angles smaller than 45° up until the end of 2002. Errors represent the Poisson upper and lower limits at 68 % confidence limit.

Energy bin $\log(E[\mathrm{eV}])$	$\log(J(E)E^3$ [m^{-2} sec^{-1} sr^{-1} eV^2)	
19.65	$24.70^{+0.07}_{-0.09}$	
19.75	$24.47^{+0.15}_{-0.15}$	
19.85	$24.73^{+0.13}_{-0.14}$	
19.95	$24.29^{+0.29}_{-0.34}$	
20.05	$24.80^{+0.20}_{-0.22}$	
20.15	$24.69^{+0.29}_{-0.34}$	
20.25	< 24.76	(90% C.L. upper limit)
20.35	$24.91^{+0.36}_{-0.45}$	
20.45	< 25.16	(90% C.L. upper limit)

off spectrum depends on source emissivity and cosmological evolution of sources. According to Berezinsky et al.[1], 2.4 events are expected under the GZK cutoff spectrum, corresponding to 3.9σ deviation. The observed spectrum significantly deviates from the GZK cutoff. Even if we would shift the assigned energies on -18% of the systematic uncertainty limit, there remains 5 events above 10^{20}eV. The expected number of events is also reduced to 1.0 events and hence the observation still deviates 2.7σ from the expected GZK cutoff. Since the above systematics is independent of energy above 10^{19}eV, the cosmic-ray energy spectrum extends without any sign of cutoff.

The number of the present highest energy cosmic rays may only be limited by experimental exposure. The next generation of experiments with much larger exposures are highly anticipated.

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1. Berezinksy V. et al., 2002, in Proceedings of the 2nd International Workshop on extremely high energy cosmic rays (Universal Academy Press, Tokyo) (*astro-ph/0302483* and *hep-ph/0204357*).
2. Takeda M. et al. 1998, Phys. Rev. Letters 81, 1163 (*astro-ph/0008102*).
3. Takeda M. et al. 2003, Astroparticle Physics 19, 449 (*astro-ph/0209422*).
4. Yoshida S. and Teshima M. 1993, Prog. Theor. Phys. 89, 833.
5. The High Resolution Fly's Eye Collaboration, 2001, A series of presentations in Proceedings of the 27th International Cosmic Ray Conference (Copernicus Gesellshaft, Germany) (*astro-ph/0208301* and *astro-ph/0208243*).