AGASA Results

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Abstract

We completed successful 14-year observation of the Akeno Giant Air Shower Array (AGASA). We observed ~ 1000 ultra-high energy cosmic rays (UHECRs) above 10^{19} eV including eleven events above 10^{20} eV. The AGASA data indicate that the cosmic ray spectrum extends well beyond the predicted Greisen-Zatsepin-Kuz'min cutoff. In the arrival direction distribution of UHECRs, clusters of events are found which suggest the presence of the extragalactic UHECR point sources. The composition of UHECRs is consistent with light hadrons around 10^{19} eV, and no gamma-ray dominance has been observed.

1 Introduction

The origin of the ultra-high energy cosmic rays (UHECRs) above 10^{20} eV is one of the major interests in today's astrophysics. In last 40 years various experiments have reported observations of such cosmic rays [1]. The presence of the UHECRs above 10^{20} eV seems to be against the Greisen-Zatsepin-Kuz'min (GZK) cutoff [2]. UHECRs above 10^{19} eV are considered to originate in extragalactic sources because of their isotropic arrival direction distribution in the sky. According to the conventional '*bottom-up*' models [3], possible candidates of UHECR sources are active galactic nuclei, gamma-ray bursts and the hot-spots of radio galaxies, as demonstrated in the Hillas diagram [4]. The propagation distance of UHECRs above 10^{20} eV is limited to $30-100$ Mpc by the GZK mechanism. Then the arrival direction distribution of UHECRs can be considered as a key to search for the UHECR sources, because a relatively small magnetic deflection in and out of Galaxy is expected in such a limited propagation distance.

Up to now, however, no individual objects have been identified as a UHECR source. With no evident astrophysical sources and difficulties in accelerating particles beyond 10^{20} eV, '*top-down*' models have been proposed as an alternative [5]. They interpret the UHECRs to be generated by the decay of super heavy particles of $10^{12}-10^{15}$-GeV scale which are presumably formed in the early Universe. In these models, the gamma-ray component is predicted in UHECRs. Therefore, the composition of UHECRs is a key to discriminate the origin models.

In the following we present the important results from the Akeno Giant Air Shower Array (AGASA) experiment discussing energy spectrum, arrival direction distribution and chemical composition.

2 Experiment

AGASA was operated at the Akeno Observatory (Akeno Village about 100 km west of Tokyo; Lat. 35°47'N, Long. 138°30'E and 900 m asl.) [6]. The operation had been started in February 1990 and was closed in January 2004.

In an ~ 100 km^2 area we deployed 111 detector stations where we equipped a 2.2 m^2 surface detector with a 5 cm-thick scintillator viewed by a 5-inch photomultiplier tube. At 27 southern stations, we also built muon detectors (2.8–10 m^2) that consisted of proportional counters aligned below an absorber (0.5 GeV threshold energy for vertical incidence).

For each air shower event, the primary energy E_0 was estimated by a local charged particle density at 600 m from the core, known as $S(600)$ [8]. The relationship between $S(600)[\mathrm{m}^{-1}]$ and E_0 for vertical showers was determined to be $E_0[\mathrm{eV}] = 2.03 \times 10^{17} \cdot S(600)$ [11] by the COSMOS simulation code [9] incorporating the QCDJET interaction model [10]. For shower incident off the zenith, we corrected the atmospheric attenuation effect [7].

The error of energy determination is ±30% at $10^{19.5}$ eV and ±25% at 10^{20} eV which was evaluated by analysing artificial showers [13]. The fraction of events is only 2.4% that have more than 50% overestimated energies. The $S(600)$ intrinsic fluctuation is estimated by Monte Carlo simulation and is as small as $\sim 5\%$. The angular resolution is 1.8° at $10^{19.5}$ eV and 1.3° at 10^{20} eV from the same analysis. The overall uncertainty is $\pm 18\%$ in the energy scale, which is almost independent of energies above $\sim 10^{19}$ eV [14].

For a part of observed events, the measurement of muons is also available mainly for the chemical composition study. For technical reasons, we used the muon density at 1000 m from the core $\rho_\mu(1000)$ as a primary mass estimator to compare with simulations. The $\rho_\mu(1000)$ determination error is about 40% for hadronic showers from zenith angle $\theta \leq 36°$.

3 Results and discussions

3.1 Energy spectrum

Figure 1 shows the energy spectrum of UHECRs above $10^{18.5}$ eV (updated from [14]). The vertical axis is the differential flux multiplied by ${E_0}^3$. Poisson bounds are given at a confidence level (CL) of 68%. Upper limits are given at a 90% CL. The dashed curve represents the expected flux by the GZK hypothesis for the uniform source distribution [12]. The number of observed events is indicated in each highest bin. The exposure of AGASA is 5.8×10^{16} m^2 s sr above $\sim 7 \times 10^{18}$ eV.

The most noticeable feature is the observation of cosmic rays beyond the GZK cutoff energy. Eleven events were detected above 10^{20} eV against the expected ~ 1.9 events. This deviation corresponds to a 4σ level deviation from the model. However, if one consider the possibilities, the overdensity of nearby sources, or the discrete source distribution instead of uniform source, one can expect a variation of the model spectrum and then the estimation of the statistical significance becomes not trivial.

To confirm the observational result, we also checked the spectrum using a limited dataset with core locations well inside the array boundary. The result is in good agreement with that from the whole dataset [14]. Even if we would shift energies down by 18% within the range of systematic errors, the six most energetic events would remain above 10^{20} eV. In this case still, the data is $\sim 2.7\sigma$ deviated from the expected ~ 1.0 event. With no energy-dependent systematics above $\sim 10^{19}$ eV, the feature of the extending spectrum is unchanged and is not able to fit to the conventional GZK spectrum.

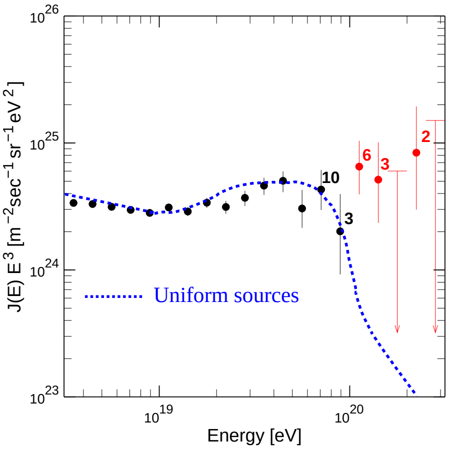

Figure 1: UHECR energy spectrum (updated from [14]). (*See text for details. For other figures as well*)

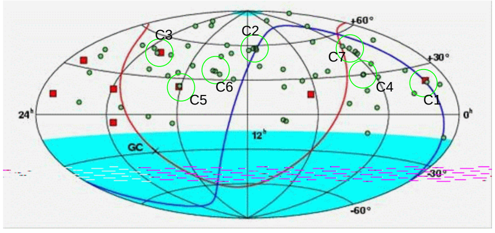

Figure 2: Arrival direction of UHECR events above 4×10^{19} eV on equatorial coordinates.

3.2 Arrival direction distribution

Figure 2 illustrates the arrival directions of 67 observed events above 4×10^{19} eV on the equatorial coordinates (updated from [15] up to 2000). Closed squares denote events above 10^{20} eV. Shaded regions are not used in the analysis due to a $\theta \leq 50°$ cut. Dashed and dotted curves represent Galactic and Supergalactic planes, respectively. Large open circles indicate event coincidences within a 2.5° cut.

Over the observed sky events distribute almost isotropically. This global isotropy is an evidence that these UHECRs are of extragalactic origin. At least, one can exclude the case of Galactic light component. However, if one look at the detail of the distribution, a fraction of events are found close to each another, referred to as event *clusters*. Seven clusters are recognised in the distribution. An energy cut of 4×10^{19} eV corresponds to the critical energy of the GZK mechanism. A 2.5° angular limit is comparable with the combined resolution for arbitrary two events from a point-like source. This coincidently yields the maximum significance on the observed clusters against the expectation for isotropy [13].

The C2 cluster is three-event coincidence (*triplet*). The number of doublets (two-event coincidences) is nine against 1.7 expected for isotropy (triplet

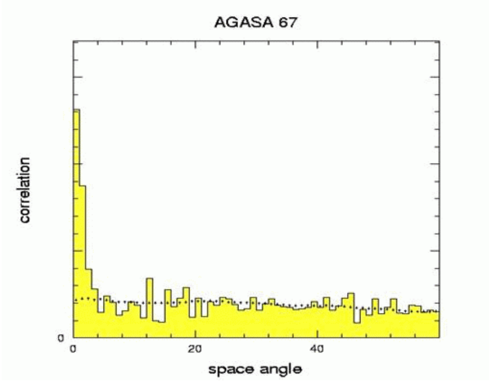

Figure 3: Event density as function of separation angle of arbitrary event pairs above 4×10^{19} eV [15, 16].

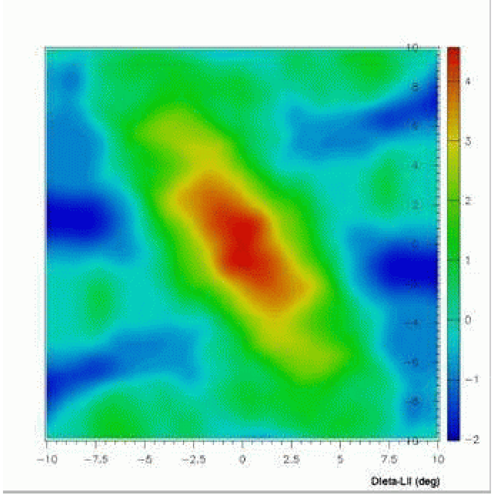

Figure 4: Event density map around UHECR events above 4×10^{19} eV on Galactic coordinates [16] (*In colour*)

accounting for three). The chance probability is less than 0.1% to observe such a significant number of doublets. As well only ~ 0.05 triplet is expected, and the corresponding probability is $< 1\%$.

Figure 3 shows the event density as a function of separation angle (self-correlation analysis) for all event combinations above 4×10^{19} eV [16]. The dashed curve corresponds to the simulated isotropic distribution.

A peak is observed near 0°, while the distribution is consistent with the isotropic distribution at large separation angles. The significance of the excess is 3.5σ against the isotropy assumption according to the Li and Ma method [17]. These peaks indicate the possible presence of point-like sources that emit UHECRs.

To extend this analysis, Figure 4 shows a two-dimensional plot on a $20° \times 20°$ frame for the same energy cuts [16]. The horizontal and vertical axes are parallel to the Galactic longitude ℓ and latitude b displacements with respect to the reference event at $(0, 0)$. The colour scale indicates a normalised significance against the isotropic background based on [17]. The dataset is limited in $\ell = 90° - 180°$ and $|b| \leq 60°$. Each event combination appears at $(\pm\mathit{\Delta}\ell_{\|}, \pm\mathit{\Delta}b_{\|})$. This region was chosen where extragalactic cosmic rays are deflected to similar direction through galactic magnetic field (GMF) modelled in [18].

The significant region orients ∼ 40° anticlockwise from the $\Delta b_{\|}$ axis, which elongates well beyond the instrumental resolution. This feature is consistent with a hypothesis of charged cosmic rays from point-like sources deflected in the GMF.

Also the spectrum of cluster component is relatively hard, and approximated to be $\propto E^{-1.8^{\pm 0.5}}$ in differential form [15]. This suggests two possible scenarios. If the cluster components are charged particles, like protons, we can interpret that the lower energy cosmic rays are the more scattered in the GMF. If they are neutral particles, their spectrum reflects the particle spectrum at nearby sources.

3.3 Chemical composition

The estimation of the chemical composition depends strongly on the hadronic interaction models used in the interpretation of the muon data. In the present work, we employed AIRES simulation [19] with QGSJET98 interaction model [20] for proton, iron and gamma-ray primaries. We took into account the detector response and analysis procedure in the simulations. An investigation is in progress using the latest interaction models and simulation codes.

In case of gamma-ray primaries, one needs to take into account the distinct effects working on showers, namely the Landau-Pomenracuk-Migdal effect [21], interaction with the geomagnetic field [22] and photonuclear interaction [23]. For the geomagnetic field effects, we used the simulation code developed in [24]. The other affect is implemented in AIRES.

Figure 5 shows $\rho_\mu(1000)$ vs. E_0 plots for the observed events (circles) [25]. The events with no muon detection are plotted at the bottom. The expected $\pm 1\sigma$ distribution bounds are indicated for proton (dashed curves), iron (dotted) and gamma-ray initiated showers (solid).

The average relationship for the data fits the proton expectation best among simulated ones and is consistent with an extrapolation from lower energies [26]. Also no significant change is observed in the lateral distribution shape of muons determined in the lower energy range [27].

In Figure 6, the fraction of iron in UHECRs is represented as a function of energy. Upper limits are given by the present work at a 90% CL. Below 10^{19} eV results are also shown from similar analyses of other experiments: A1

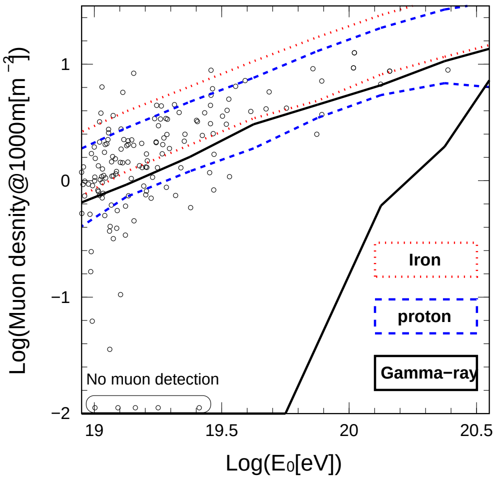

Figure 5: $\rho_\mu(1000)$ vs. E_0 plots for observed events [25].

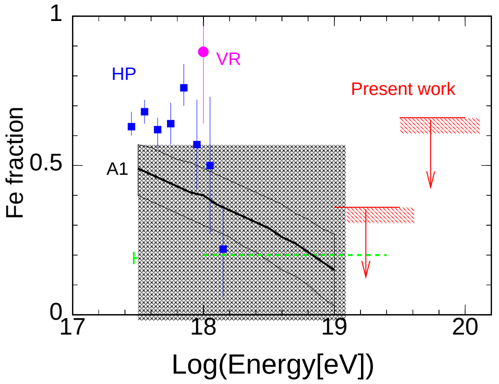

Figure 6: Iron fraction as a function of energy for proton+iron assumption.

experiment [27] (solid curves with hatch)[1], HiRes [28] (dashed line), Haverah Park [29] (squares) and Volcano Ranch [30] (circle).

In the $10^{17.5} - 10^{19}$ eV energy range, the average mass decreases gradually as energy increases. The composition is predominantly affected by light component around 10^{19} eV. The upper limit on iron fraction is given to be 40% above 10^{19} eV at a 90% CL.

We also estimated the fraction of gamma-ray initiated showers in observed events. Similarly, we assume proton plus gamma-ray two components model that is predicted by top-down models. The fraction upper limits are given at a 90% CL and are 34% above 10^{19} eV and 56% above $10^{19.5}$ eV.

The feature of gamma-ray dominance (or not) is still open around 10^{20} eV, however, we have not found any positive signature for top-down models in the data (eg. anisotropy in shower incoming direction distribution due to geomagnetic effects [25]). Although the predicted fluxes very much depend upon unknown parameters such as X-particle mass, extragalactic magnetic field, universal background radiation strength etc., these results constitute

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[1] The data from the A1 experiment (density at 600m was used) was first interpreted by Monte Carlo simulation by the collaboration. The present result is preliminary.

possible constraints against origin models.

4 Summary

Since 1990, the AGASA experiment has played a leading role in experimental UHECR physics. The operation was finished in January 2004, while the analysis is still going on. We observed nearly 1000 UHECRs above 10^{19} eV. The data quality has been well confirmed by elaborate simulations and experimental studies. We obtained many important findings to deepen our understanding of the highest energy cosmic ray origin.

The AGASA data indicates the extension of the cosmic ray spectrum beyond the GZK cutoff. This feature does not change even if one takes into account the maximum systematic error of 18% in the energy scale. This suggests that there are new components of the highest energy cosmic rays and/or other exotic physical processes behind. In coming years, excellent data will be highly anticipated by the operating Pierre Auger Observatory [31] and the planned Telescope Array (TA) Project [32].

The feature of the arrival direction distribution is consistent with the hypothesis that there exist point-like UHECR sources. Combining data from Auger, TA and the Extreme Universe Space Observatory Mission [33], the entire celestial sky will be covered by higher precision observations in near future. These results will be very likely to reveal the origin and the mystery of UHECRs along with a possibility to open the new astronomy with the UHE neutrinos.

From an analysis of muon data, the chemical composition is found to be consistent with the simulation result for light hadron components. The data from other experiments are also in good agreement at overlapping energies. As far as the existing data, there is no indications for top-down scenarios.

Based on hybrid observations, the performance of new experiments is more pronounced to enhance our knowledges not only of chemical composition but also of the better description of interaction models. As well, larger observation statistics are essentially powerful to prove or disprove gamma-ray primaries. Using the geomagnetic field effect that causes characteristic shower developments depending on incoming direction, it is potentially interesting to observe showers at various locations or on the orbit.

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