AGASA results and the Telescope Array Project

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The existence of Super-GZK particles, cosmic rays above $10^{20} eV$, was well established by the AGASA experiment. Recent data from AGASA also suggests the existence of compact sources. These two experimental evidences seem to be contradictory each other and are difficult to be explained by a simple theoretical model. The origin of the highest energy cosmic rays became more mysterious with the increase of statistics. We will review the experimental results of AGASA and discuss the origin of the highest energy cosmic rays. The status of the telescope array project is also reported.

1 Introduction

Since the discovery of the cosmic rays by Hess in 1912, their origin is one of the most important issues. After the discovery, extensive efforts for the measurement of cosmic rays have been carried out with various methods. At present, we know their energy extends over more than 13 decades from 10^7 eV up to 10^{20} eV.

At present, the most interesting topic in the cosmic ray physics is the study of the highest energy cosmic rays. Experimental data accumulated so far show increasing inconsistency with the conventional models for cosmic ray origin based on acceleration of charged particles. We expect to see an end of the high energy cosmic ray spectrum at 6×10^{19} eV, due to the resonance production of hadrons with the cosmic microwave background radiation (CMBR), what is called the Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen 1966, Zatsepin and Kuzmin 1966). Most striking, however, is the clear evidence for the extension of the cosmic ray energy spectrum above the GZK cutoff discovered by AGASA, and recently confirmed by preliminary data from HiRes. Furthermore, the propagation length of cosmic ray particles above the GZK cutoff energy is limited to within 50 Mpc from our Galaxy. The magnetic field of the Galaxy and of inter-galactic space is not strong enough to bend the trajectory of these particles more than a few degrees. Sources for particles with energies above the GZK cutoff energy should thus

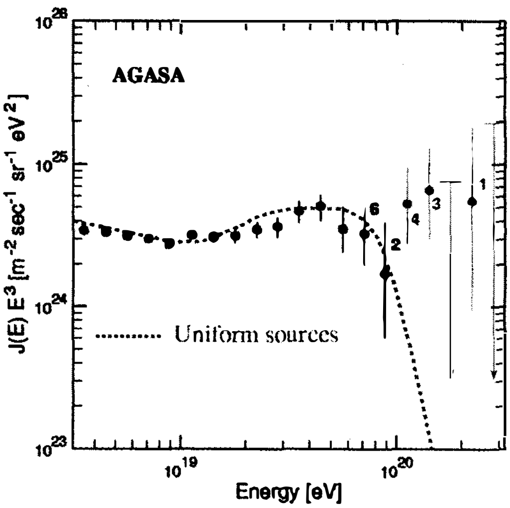

Figure 1: The energy spectrum observed by AGASA. The vertical axis is multiplied by E^3. Error bars represent the Poisson upper and lower limits at 68% and arrows are 90% C.L. upper limits. Numbers attached to points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error. The primary spectrum is assumed $\propto E^{-2.3}$.

be relatively close by and particles will point back to these sources. Recently, AGASA data shows the strong evidence for the existence of compact sources. However, no possible nearby astrophysical sources (accelerators) at the arrival direction of these particles were identified.

Here, we will discuss the results obtained by AGASA, the Akeno Giant Air Shower Array, covering over 100km^2 area in operation at Akeno village about 130km west of Tokyo.

2 The Highest Energy Cosmic Rays

Figure 1 shows the energy spectrum above $10^{18.5}$ eV observed by AGASA experiment (Takeda et al. 1998, Hayashida et al 2000). For reference, we have superposed the expected GZK energy spectrum assuming the uniform source distribution in the Universe. Eight events are observed above 10^{20} eV. The energy of giant air showers observed by AGASA is estimated by the particle density $S(600)$ at a distance of 600m from the shower axis. This is known to be a good energy estimator after the detail Monte Carlo simulation. The conversion factor from S(600) [m^{-2}] to primary energy E_0 [eV] is derived from the simulation to be

$$E_0 = 2.0 \times 10^{17} \times S(600)^{1.0}.$$

We can conclude that the energy spectrum clearly extends beyond 10^{20} eV with no GZK cutoff. However, it is not clear with present statistics whether there is any structure in the spectrum (for example, a GZK dip around 10^{20} eV).

The arrival direction distribution of the highest energy cosmic rays above 4×10^{19} eV is shown in Fig. 2 in the equatorial coordinates(Takeda et al. 1999). Small dots and squares show events between 4×10^{19} eV and 10^{20} eV and above 10^{20} eV, respectively. The events above 10^{20} eV correspond to the pure super-GZK particles, and if they are hadrons, their sources should

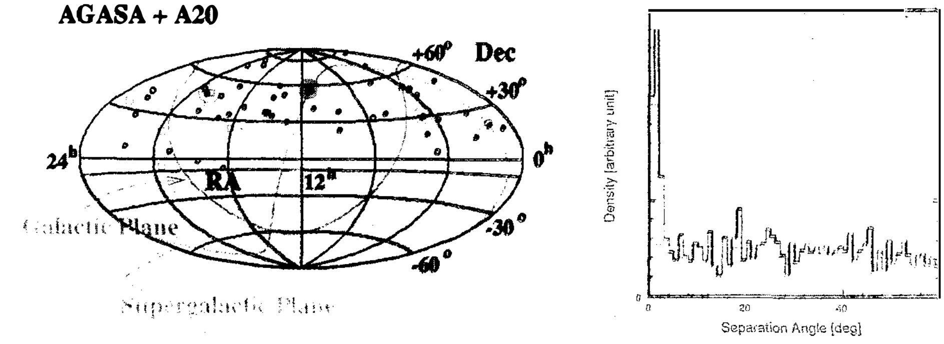

Figure 2: The arrival direction of the highest energy cosmic rays above $4 \times 10^{19} eV$ on the equatorial coordinates observed by AGASA. Right pannel shows the space angle distribution between arbitrary two events. The prominet peak at small space angle region can be seen.

be closer to the Earth than 50 Mpc. The energy 4×10^{19} eV is the lower threshold energy of the expected pile produced by the GZK mechanism. Events above this energy may still come from the same sources as the super-GZK events. Their energies have been decreased by inelastic interactions. If we assume an $E^{-2.3}$ source energy spectrum, we expect 50 % or more of these event have energies above the GZK cutoff at the source and the source could be close.

They appear to be distributed uniformly over the observable sky. We have carried out several tests for global anisotropy but could not find any large scale structures in this distribution. However, we found one triplet and six doublets of events clustering within an angular resolution (2.5° circle) as indicated shadowed circles. The chance probability for this clustering effect was evaluated by Monte Carlo simulation and found to be $P_{ch} \sim 0.1$ % . No outstanding astronomical objects have been found in the directions of these clusters, although an colliding galaxy called VV141 was found to lie in the direction of the triplet at 100 Mpc away.

In the right pannel of Fig. 2, we have shown the space angle distribution between events(some kind of auto-correlation). We can see an clear peak at small angles(≤ 2 degrees). This peak distribution could be explained by the angular resolution of AGASA. This result strongly suggests the existence of point sources (compact sources). The primary particles should be neutral or the intergalactic magnetic field must be very weak.

Futhermore, we can estimate the number of point sources from the number distribution of triplets, doublets, and singlets by assuming the same intensity sources and event distribution follows the poisson distribution. We can estimate 100-300 compact sources in the AGASA viewing sky.

3 Evidence for Galactic Cosmic Rays at 10^{18} eV

In order to explore the origin of galactic cosmic rays, a harmonic analysis in Right Ascension was carried out using about 216,000 events observed by AGASA (Hayashida 1999). This is a reliable method to search for global anisotropy of the cosmic-ray arrival direction distribution. A Rayleigh power $k \sim 14$ was found at energy bin $1.0 - 2.0 \times 10^{18} eV$. This value is surprisingly high, corresponding to a chance probability of 2.5×10^{-6}.

In Fig. 3 the arrival direction distribution in the equatorial coordinates obtained by AGASA is shown. The figure shows the statistical significance of the deviations from isotropic expectation. Here, the energy region of 10^{18} eV $\sim 10^{18.4}$ eV is selected which corresponds to the

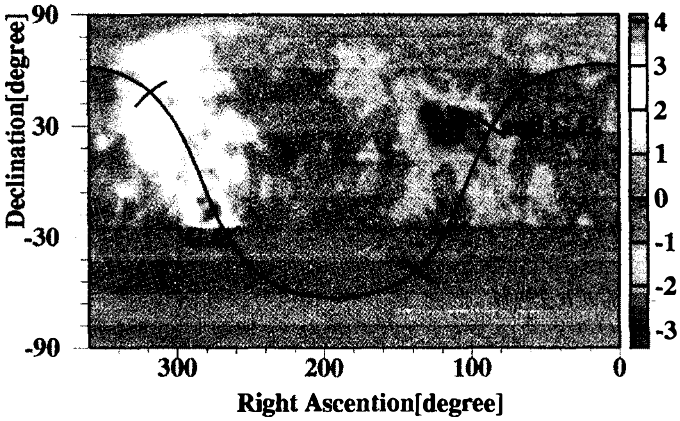

Figure 3: The statistical significance of the deviations of the arrival direction distribution of the cosmic rays above 10^{18} eV on the equatorial coordinates (obtained by AGASA, Hayashida et al. 1999).

maximum Rayleigh power k-value. Note that we cannot observe events with declination less than $-25°$, as long as we use showers with zenith angles less than 60°. In this figure, we have chosen a circle of 20° radius to evaluate the excess. In the significance map, a 4.5 σ excess (obs./exp. = 506/413.6) near the Galactic Center region can be seen. In contrast, near the direction of anti-Galactic Center we can see a deficit in the cosmic ray intensity (-4.0σ). An event excess from the direction of the Spiral Inn or Cygnus region is also seen with 3.9σ (obs./exp. = 3401/3148). This anisotropy can be considered as clear evidence for the existence of galactic cosmic rays up to 10^{18} eV.

4 Discussions

4.1 Astronomical sources

Hereafter, we will discuss the origin of the super-GZK particles with bottom up models and top down models.

According to the discussion by Hillas(1984), in the Fermi acceleration or one shot acceleration models, we always meet with the minimum condition for the attainable maximum energy: $R_g < R_{obj}/2$, i.e., the Gyro radius of accelerated particle should be smaller than the object size.

Since gyro radius is proportional to the particle momentum, this equation give us the maximum acceleration energy at the astronomical objects. At the same time, we need to consider the cooling or energy loss process of cosmic ray particles in these objects, for example, synchrotron radiation, and photo-pion production. In compact sources (or in the strong magnetic field case), synchrotron radiation becomes important, because the energy loss rate is proportional to B^2. On the other hand, in large acceleration systems ($\geq$ Mpc), the acceleration time becomes relatively larger and we need to consider photo-pion production process with CMBR. With these arguments, we can rule out neutron stars (extremely high B condition), and galactic clusters (photo-pion cooling becomes dominant) as candidates for sources of the highest energy cosmic rays.

The GRBs, AGNs, and radio galaxy lobes are possible source candidates. Most promising source is the GRB (Waxman 1999, Totani 1999). Since we could not see clear cross-correlation between the arrival direction of the highest energy events and AGNs and radio galaxies, AGNs and radio galaxy lobes may not be sources.

GRBs on the other hand, can solve this problem (no counterpart). There is a constraint on GRB models from the arrival direction distribution of super-GZK particles. The GRB rate in our Universe is estimated $\sim$ 2/day from BATSE gamma ray detector observations. This value can be rewritten as 0.0013–0.0026/(100 Mpc)^3 yr. The typical propagation delay of charged cosmic ray with respect to light is 100–1000 yrs due to the scattering by the magnetic field in the inter-galactic space. Therefore, we will see the GRBs occurred in the last 100–1000 yrs within the GZK horizon (50–100 Mpc). The number of GRBs contributing to the cosmic ray flux is thus estimated to be at most, 5 $\sim$ 10 in this space-time volume and we expect only several independent GRBs (arrival direction) for cosmic rays. This estimated number will contradict with the number of 500-1000 compact sources estimated from the event cluster distributions. If we consider the beaming effect in the GRB fireball model, there is a possibility to save this contradiction, since we can significantly increase the number of independent GRBs in the GZK horizon.

4.2 Beyond the Standard Model

There is another set of models with completely different approaches to explain the super-GZK particles. These are the so-called Top Down models in which EHE CR are produced in decays of superheavy particles (X-particles) (Bhattacharjee et al. 1992, Sigl et al. 1994, Sigl et al. 1995, Sigl et al. 1997, Berezinsky et al. 1997, Sigl et al. 1999). These new particles have to decay into ordinary particles during present era, and they have to be heavy enough and their number density and life time sufficient to explain the present EHE CR flux.

For example, the decay of cosmic strings may produce X particles (GUT gauge bosons), through the intersection of cosmic strings, cusp evaporation, self-intersection, or collapse of closed loops. Then X-particles decay into quarks and leptons while quarks give hadron jets. We expect a photon and neutrino dominant composition in the final products. Another possible source of X-particles is the annihilation of primordial monopole-antimonopole pairs (monopolonia, Hill 1983) or cosmic strings with monopoles (so-called necklace, Bereznsky 1997).

Another proposed concept is long-lived primordial X-particles. The X-particle must have a sufficient life time to survive until the present epoch and must decay at some finite rate in the present. These possibilities are discussed in the literatures(Kuzmin and Tkachev 1999, Chung et al. 1998, Hamaguchi et al. 1998). Probably we require clumping heavy relics in the universe or in our halo to explain the AGASA clusters.

Another possible scenario is that the primary particles are not ordinal particles. The possibility of neutrino(Weiler 1999) and supersymmetric hadrons have been discussed.

A different approach is to assume that the special relativity is violated. This has been discussed by S.Coleman and S.L.Glashow(1999). In deriving the GZK cutoff, Lorentz invariance is assumed for $\gamma = 10^{11}$, however, there is no independent experimental confirmation that special relativity is valid at such high γ factor.

Two experimental results, no GZK cutoff and existence of compact sources, naturally deny the hadronic primary particles from distant sources and favor the neutral particles, gamma ray primary or neutrino primary. In case of gamma ray primary, we expect the attenuation by the interaction with background photons(2.7K and radio). It is similar with the GZK mechanism for hadrons, however, the attenuation length of gamma rays has no strong energy dependence. It is reasonably smooth as a function of energy around $10^{20}eV$. Gamma ray primary will not show GZK cutoff. In the next generation experiment, the capability to distinguish the primary composition is highly required to obtain clear results on the origin of the highest energy cosmic

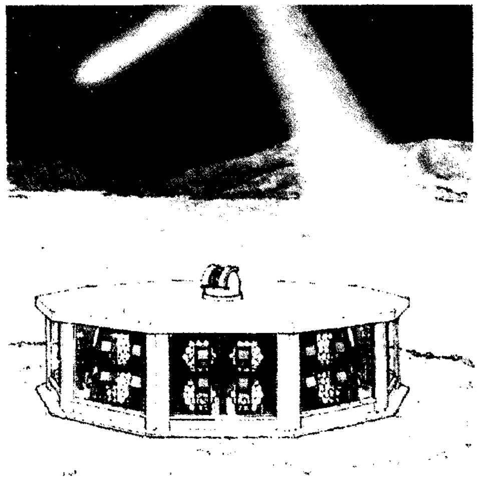

Figure 4: The artist view of a telescope array station. It consists of 40 units of fixed telescopes covering the field of view, the entire azimuthal angle and the elevation angle of $3° - 34°$. At the roof of the station, the laser doom is installed for the atmospheric monitoring and the telescope alignment calibration.

5 Telescope Array Project

The Telescope Array (TA) detector has been planned in order to draw a clear conclusion on the mysterious origin of the extremely high energy cosmic rays by Japan-US collaboration. For this purpose, the detector is required to have much larger aperture for super-GZK particles than the present detectors. Also it should provide a particle identification as well as an accurate detemination of energy and arrival direction for primary cosmic rays. The detail of telescope array project is described in the design report.

In Fig. 4, the artist view of a telescope array station is shown. It consists of 40 units of fixed telescopes each covering an independent region of the sky. The field of view (FOV) of one telescope unit is 18.0° in azimuth and 15.5° in elevation. The upper ring composed of 20 telescope units covers the entire azimuthal angle and the elevation angle of $3° - 18.5°$. The lower ring covers 18.5° – 34° in elevation. The telescope has a main dish with a diameter of 3.3m which is composed of 18 hexagonal shape segment mirrors. The location of the central mirror is made empty and is reserved for the optical alignment system and PMT calibrations system. At the roof of the station, the laser doom is installed, which is used for the atmospheric monitoring and the telescope alignment calibration.

The Telescope Array will be installed in the West Desert of USA, near Salt Lake City, Utah. Each station is separated by 30-40km. Three out of 10 TA stations cover the planned northern hemisphere Auger detector, forming a large hybrid detector each having about the same effective acceptance for the EHE cosmic rays. The effective aperture of TA is approximately $5,000km^2sr$ for $10^{20}eV$ particles assuming a 10% observation duty factor. It is 30 times larger than the existing AGASA ground array, and is an order of magnitude larger than HiRes. The shower images can be observed by multiple stations with this configuration. The detail detector performance was examined by Monte-carlo simulations. The energy, arrival direction and shower maximum position X_{max} are determined with an acuracy of 6%, 0.6° and $20g/cm^2$, respectively.

As mentioned above, the most important parameter to descriminate models is the portion of primary gamma rays in the super-GZK particles. For gamma rays above $10^{19}eV$, LPM effect start to work gradually. It suppresses pair creation and bremthstralung interaction in the electromagnetic cascade. Eventually, the gamma ray shower has a deeper X_{max} and larger fluctuation in the shower development. However, above $3 \times 10^{19}eV$ parimary gamma ray start to interact with geomagnetic field and produce pair electrons. Pair electrons emit high energy photons($10^{17}eV \sim 10^{18}eV$) throgh synchrotron radiation process in the geomaganetic field. These processes start to occure at high altitude, around the altitude of 2-3 Re(earth radious) and the interaction is governed by the parameter $\chi = \epsilon(B_{\perp}/B_c)/mc^2$, where ϵ is gamma ray energy, m is electron mass and $B_c = 4.41 \times 10^{13}G$. $B_{\perp}$ is a magnetic field strength perpendicular to the gamma ray track. If $\chi > 0.1$, geomagnetic pair creation occur with significant probality.

In Fig 5, the geomagnetic pair creation probabilities are shown for four different parimary energies in coordinates of zenith and azimuthal angles. These calculation were carried out assuming the geographical position of Utah. We can see strong north-south anisotropy at the energy of $10^{20}eV$. The atmospheric depth of the shower maximum X_{max} is also depend on the primary energy and arrival direction. We expect north-south asymetry of the average X_{max}, and abrupt change of X_{max} as a function of energy between $3 \times 10^{19}eV and 3 \times 10^{20}eV$ for primary gamma rays. The telescope array have an enough sensitivity to detect such X_{max} anisotropy, and X_{max} phase transition.

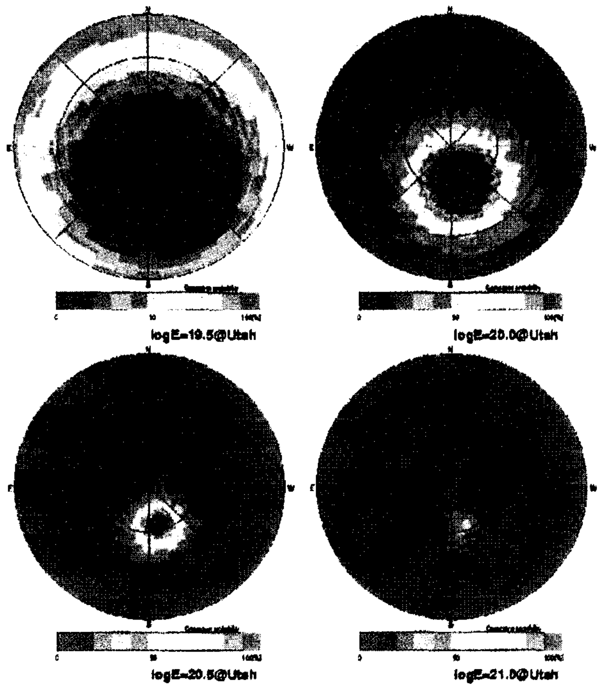

Figure 5: The geomagnetic pair creation probabilities as a function of energies and directions at Utah.

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