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The Highest Energy Cosmic Rays, A Review and Prospects

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Abstract. The existence of extremely high energy cosmic rays (EHE-CRs) with energy above 10^{20}eV have been reported by several air shower experiments. The sources of these cosmic rays were considered to be extra-galactic. Relevant high energy astrophysical sources were searched in the arrival direction of these cosmic rays but no appropriate candidates were found. The origin of EHECRs stays unexplained. We review the present status of EHECR studies and introduce several new experiments aiming to unveil its mysterious origin.

1. Origin of Cosmic Rays

The cosmic ray is the highest energy radiation filling the universe. A large part of them are protons and nuclei with energies ranging from sub-GeV to ZeV($=10^{21}$ eV). The flux of cosmic rays, i.e. the number of particles entering the Earth per unit time, area, solid angle and energy, decreases approximately with the third power of the energy. At the highest energy, it is extremely small; one per year for 100 km^2 of area for E $>$ 10^{20} eV.

A compilation of the cosmic ray energy spectrum is shown in Figure 1 (Nagano & Watson 2000; Takeda et al. 2002). The changes of power index are observed at two energy regions; one is the change around $10^{15} - 10^{16}$ eV forming a "knee" structure and the other is around $10^{18.5} - 10^{19.5}$ eV forming an "ankle" structure.

The origin of cosmic rays below the knee energy is generally believed to be galactic supernovae. Being rebounded by the plasma shock wave produced by the supernova explosion, the energy of the charged particle increases by a certain fraction of the original energy. High energy is obtained stochastically by repeating such "rebounds" (Fermi acceleration). The power law spectrum is well explained in the Fermi's theory, and enough energy is supplied to the cosmic ray if a few % of the total energy liberated by the explosion is used to produce cosmic rays. The cosmic rays below the knee are trapped by the galactic magnetic field and propagate diffusively to the Earth.

The acceleration of charged particles by the supernova was demonstrated recently by observing TeV γ rays and X-rays from the outer rim of the SN1006 (Tanimori et al. 1998; Koyama et al. 1995). The X-rays by the synchrotron radiation of accelerated electrons and TeV gamma rays by the Inverse Compton scattering with the cosmic microwave background (CMB) are detected simulta-

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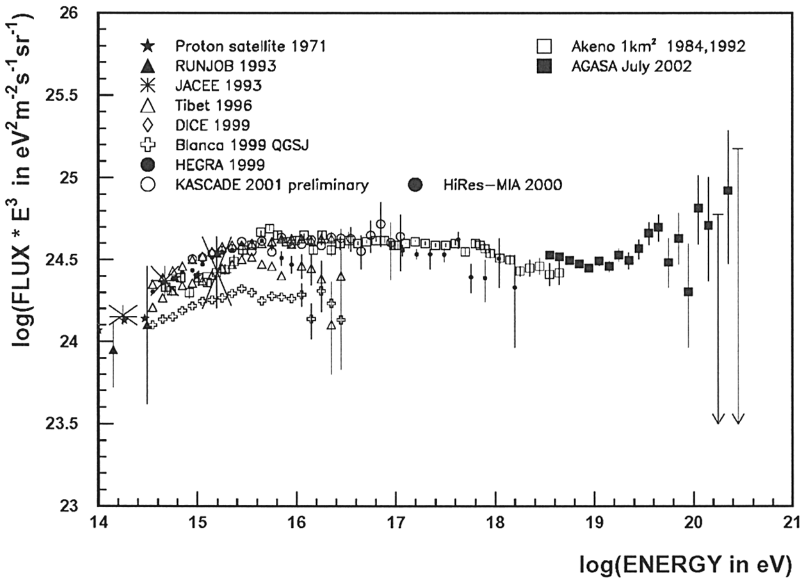

Figure 1. Compilation of cosmic ray energy spectrum. A differential flux weighted by E^3 is plotted with respect to the energy.

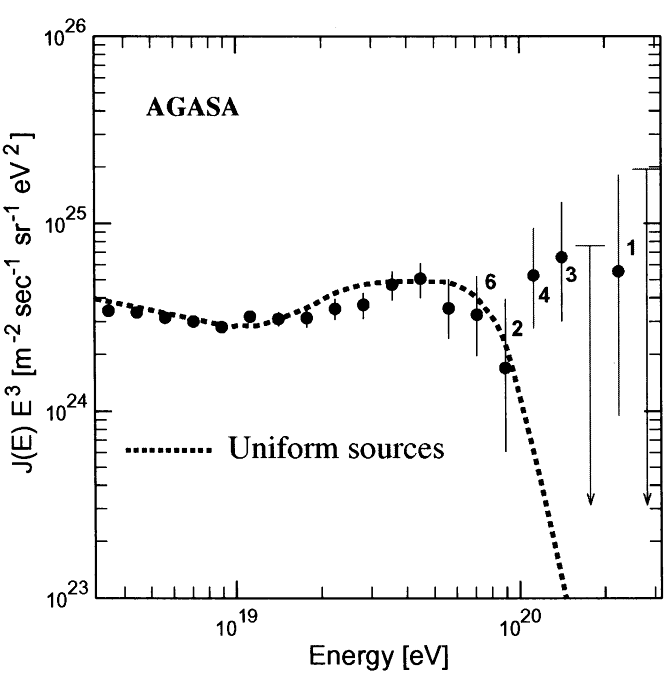

Figure 2. AGASA energy spectrum above $10^{18.5}$ eV.

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neously. The size and the duration of the supernova blast wave however limits the maximum attainable energy to $\sim 10^{15}$ eV, just below the knee structure. And little is understood theoretically and observationally how to accelerate cosmic rays beyond this energy, irrespective of their origin being galactic or extragalactic.

The modulation of power indices at the ankle structure at $\sim 10^{19}$ eV is considered to signify the onset of extragalactic cosmic rays because the energy of the ankle coincides with the limit of cosmic ray (proton) confinement by the galactic magnetic field ($\approx 3\mu$G). Two additional experimental observations support this transition from galactic to extra-galactic sources. One is the change of primary composition reported by HiRes group in this symposium; the composition changes from heavy to light nucleus in the energy region of $10^{17} - 10^{18}$ eV (Bird et al. 1993; Cao 2002). Another is the anisotropy of the arrival direction by the AGASA group; an excess of $\sim 20\%$ toward the galactic center and a deficit of similar amount in the opposite direction are observed in the energy region of $10^{18} - 10^{18.4}$ eV (Takeda et al. 1999). This can be interpreted that we are starting to see the end of the cosmic ray confinement in our galaxy, and a net flow of cosmic ray protons generated more abundantly in the galactic center is becoming prominent at these energies. The extragalactic cosmic rays take over the galactic ones above $10^{18.4}$ eV.

2. Highest Energy Cosmic Rays and GZK Cutoff

In order to accelerate particles to 10^{20} eV or more, the acceleration area must be sufficiently large and its magnetic field must be strong enough such that particles are confined in the area during the acceleration. Only a few astronomical objects are known to satisfy such conditions. They are special galaxies (AGN, radio galaxy lobe and colliding galaxies,...) and the violent explosion (GRB) in the universe. The EHECR may be produced in such "stars" and propagate through the extragalactic space toward our galaxy without suffering much deflections by the extragalactic magnetic field ($\approx$ 1 nG). Its propagation however is not without obstruction. The CMBs filling the universe are equivalent to gamma rays of energy ~ 150 MeV in the rest frame of 10^{20}eV proton. Thus the proton of this energy starts losing the energy by the pion photoproduction;

$$\gamma_{2.7K} + p_{EHE} \rightarrow \Delta(1232) \rightarrow \pi^{+}n, \pi^{\circ}p \tag{1}$$

This mechanism is first predicted by Greisen (1966) and Zatsepin & Kuzmin (1966) soon after the discovery of the CMB. Two obvious results follow;

- The energy spectrum of EHECRs arriving from the distant source should exhibit a cutoff structure at $\sim 10^{20}$ eV (e. g., Yoshida & Teshima 1993).

- If the cosmic rays above 10^{20}eV are detected, most of them should have propagated less than 50 Mpc before being detected on the Earth (e. g., Aharonian & Cronin 1994).

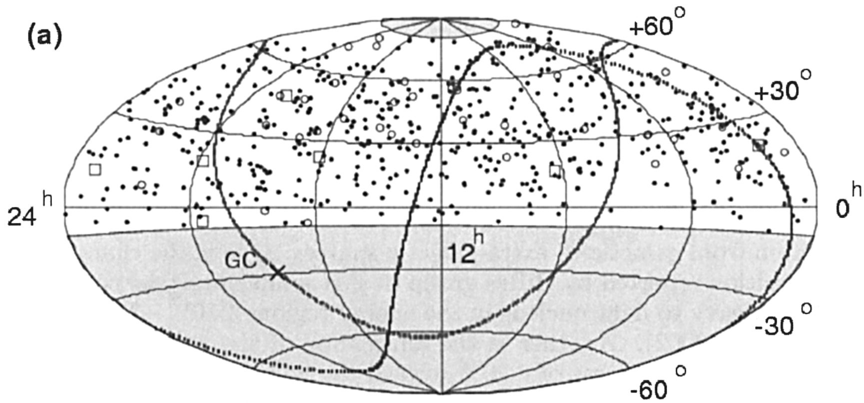

Figure 3. Distribution of cosmic ray arrival directions for E > $10^{19.0}$ eV by AGASA plotted in the equatorial coordinate.

3. Measurement by Air Shower Array

Cosmic rays with energy more than 10^{15} eV has been measured by detecting the extensive air shower on the ground because the flux is so small and the direct detection is practically excluded. The high energy cosmic rays entering the atmosphere collide with the nucleus composing the atmosphere and produce nuclear fragments and pions by the nuclear interaction. The produced π° decays into two γs and each starts electromagnetic cascading by repeating the pair creation and the bremsstrahlung. The produced $\pi^{\pm}$ decays into $\mu^{\pm}$ and ν and a large part of μs arrive at the ground surface and absorbed in the Earth. The nuclear fragments produced by the initial collision will generate further nuclear interactions and the transfer of energy to $e^{\pm}$s, γs and $\mu^{\pm}$s repeats. By the time the produced shower reaches the ground, more than 90% of the energy is carried by the low energy e$^{\pm}$s and γs below the critical energy. For the EHECRs, the diameter of the shower becomes a few km and the total number of produced particles exceeds 10^{11}. The air shower array is a network of particle detectors such as the plastic scintillator and the water Cherenkov counter, and measures the distribution of charged particles on the ground.

The Akeno Giant Air Shower Array (AGASA) was built with an aim of observing EHECRs with sufficient sensitivity (Chiba et al. 1992). A total of 111 scintillation counters is deployed in Akeno, Japan covering the ground area of ~100 km^2 (average altitude of 670 m). The size of the scintillator is 2.2 m^2 and the spacing between the counters is 1 km on average. All the counters are interconnected by the fiber optic cable for the precise timing measurement and the data transfer. The acceptance of the detector is ~160 km^2 sr for cosmic rays with energy 10^{20} eV and with zenith angles less than 45°. The AGASA has been operated since 1991.

The location of the shower core and the inclination of the shower axis is determined by fitting the measured distribution of particle density and hitting

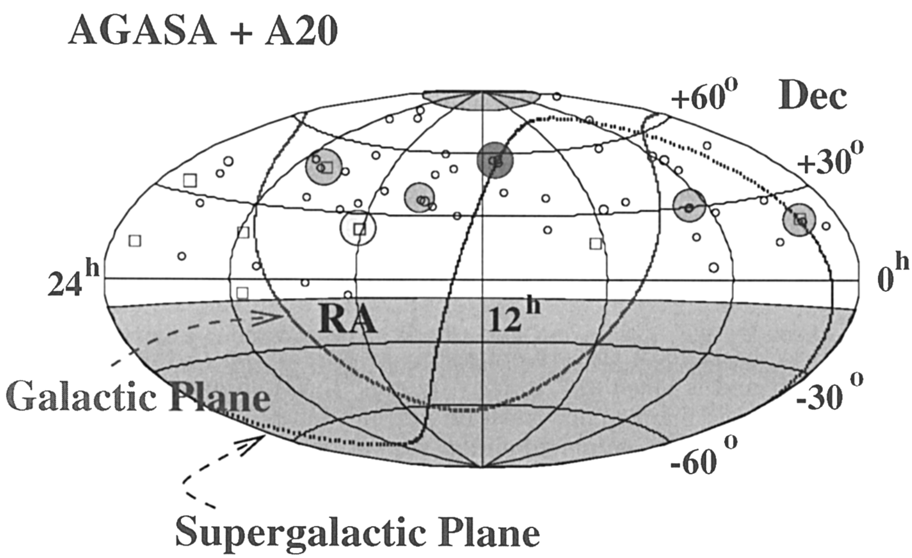

Figure 4. Distribution of cosmic ray arrival directions for $E > 10^{20.0}$ eV (square box) and for $10^{20.0}$ eV $> E > 10^{19.6}$ eV (small circle) by AGASA. The locations of the cluster are indicated by large filled circles.

time of the scintillator with the expected distribution. The primary energy E of the shower in the unit of eV is obtained by

$$E = 2.03 \times 10^{17} S_0(600) \tag{2}$$

(Takeda et al. 2002) for the vertical shower where $S_0(600)$ is the density of charged particles per m^2 at the distance of 600 m from the core. The coefficient of Equation (2) was derived from the air shower Monte Carlo simulation. For the inclined shower, a small zenith angle dependent correction is applied to obtain an equivalent value of $S_0(600)$. For a given primary energy, the parameter $S_0(600)$ is relatively insensitive to the difference of shower development, or equivalently to the position of shower maximum (Xmax), according to the simulation. The energy resolution of 25% and the angular resolution of 1.6° are estimated by the simulation for $E = 10^{20}$ eV shower.

4. Measurement by Air Fluorescence Telescopes

The nitrogen molecules in the atmosphere generate fluorescence (scintillation) light by the passage of the charged particles. Though only less than 5 UV photons are produced for 1 m passage of the charged particle (Kakimoto 1996; Nagano 2003), the fluorescence light generated by the large air shower can be detected using the telescope with the photomultiplier (PMT) readout.

The Fly's Eye (FE) is the first experiment which performed a systematic measurement of the air shower by this method (Baltrusaitis et al. 1985). The FE

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covered the whole sky with 67 telescopes each with a mirror of ~1.6 m diameter, and pictured the image of the air shower in the atmosphere by 880 PMTs with a pixel resolution of $\sim 5°$. The second measurement station with 1/8 of the full sky coverage was built 3.3 km away and a part of the measurement was made by using two stations simultaneously. The highest energy air shower to date, with the estimated energy of 3×10^{20} eV, was recorded by the FE (Bird et al. 1994).

The total energy of the event is calculated by the integration of the longitudinal shower size $N_e(x)$ at the depth x by

$$E = \epsilon_0/X_0 \cdot \int N_e(x)dx \tag{3}$$

where ϵ_0/X_0 is the ratio of the critical energy of an electron to the radiation length in the air and is taken as 2.18 MeV/(g cm^{-2}). The Equation (3) uses a near constancy of the fluorescence emission per unit length independent of the atmospheric pressure. The estimated energy resolution of FE is 27 – 36 % with a systematic energy scale uncertainty of less than 40 % for the single station measurement.

The advantage of the air fluorescence method is that the measurement of the Xmax allows the determination of primary particle species. The change of average Xmax with energy (elongation rate) was measured by FE. The predicted values of Xmax tend to differ significantly depending on the type of Monte Carlo simulation but the elongation rate itself is rather stable.

The second generation experiment (named High Resolution FE, or HiRes) started the operation in 1999 (Abu-Zayyad et al. 2000). It consists of two measurement stations separated by 12 km. The stereo determination of the shower geometry is made with much finer pixel resolution ($\sim 1°$) and the aperture is extended up to ~1000 km^2 sr. The most recent result from HiRes was reported in this symposium (Cao 2002).

5. Origin of Super-GZK Events

The energy spectrum observed by AGASA above $10^{18.5}$eV is shown in Figure 2 (Takeda et al. 1998) together with the expected spectrum for the extra-galactic protons produced uniformly in the universe. As shown, 8 cosmic rays with energy greater than 10^{20} eV (super-GZK cosmic rays) were observed whereas less than 1.6 events are expected from the uniformly distributed sources (broken line in Figure 2). The energy spectrum continues toward high energy without showing an indication of the GZK-cutoff. The arrival directions of these EHECRs are plotted in Figures 3 & 4 (Takeda et al. 1999). It seems that arrival directions are isotropic over the entire sky. It doesn't show a strong correlation with the galactic plane or the super-galactic plane of nearby galaxies.

Moreover, some of the highest energy events form a narrow angle cluster in the sky. Figure 5 shows the distribution of separation angles between any two cosmic rays with energies more than $10^{19.6}$ eV detected by AGASA (Takeda et al. 1999; Chikawa et al. 2001). The narrow angle correlation within a detector resolution of 3° stands out over a flat distribution expected from uncorrelated uniform background shown as the solid curve in the Figure. The significance of the clustering is at 5 σ level. High energy objects such as the AGN and the radio galaxy have been searched behind the super-GZK and the clustered events within $\sim$100 Mpc (Uchihori et al. 2000; Sigl et al. 2001) but no apparent candidates were found. A correlation with quasar remnants (Torres et al. 2002) and the BL Lac objects (Gorbunov et al. 2002) had been suggested, but none seem clear and definitive at this moment.

In the standard framework of astrophysics and particle physics, the existence of clustered super-GZK cosmic rays is difficult to explain. Several hypotheses, many of them rather exotic and ad-hoc, have been proposed to explain the super-GZK events and the clusters. Among proposed are

- The production of EHECRs by the decay of long-lived, super-heavy relic particles concentrated in the halo of our galaxy (e.g., Kuzmin & Tkachev 1998; Berezinsky, Blasi, & Vilenkin 1998; Hamaguchi et al. 1999; Berezinsky 2000) and with some level of clumping.
- The production of Z° by the collision of cosmological neutrino background with extremely high energy neutrinos ($E \geq 10^{21}$ eV) produced deep in the universe (e.g., Weiler 1999). The EHECR is produced as a decay product of Z°. The density of primordial neutrinos may be concentrated in the local super-cluster of galaxies by its gravitational interaction with the dark matter.
- The Lorentz invariance breaks down at a very high Lorentz factor (e.g., Sato & Tati 1972; Coleman & Glashow 1999) such that the high cross section of pion photoproduction via $\Delta(1232)$ resonance is avoided.
- The generation of EHECRs by the yet unknown dark stars which are over-populated by a factor of $\sim$10 only in the vicinity of our galaxy.

Note that the Z-burst and the violation of Lorentz invariance explain the extension of the spectrum above GZK cut off, but they leave the question of acceleration itself unanswered. It is interesting that the model with super-heavy relics and the Z-burst predict the main component of the EHECRs are gamma rays and the neutrinos rather than protons. The model of super-heavy relics also expects a concentration of the sources toward the center of the galaxy and thus a global anisotropy of EHECRs.

6. Future Experiments and Prospects

Three new projects, Pierre Auger Observatory, Telescope Array and EUSO, are being planned, or under construction, to investigate the origin of EHECRs.

Pierre Auger Observatory plans to build two large ground arrays, one in the southern hemisphere (Malargue, Argentina) and the other in the northern hemisphere (Utah, USA) each covering the ground area of 3000 km^2 (Pierre-Auger Observatory Design Report 1997). The detector to be used is the water Cherenkov counter of 3.6 m diameter and 1.2 m height. For each array, 1600 counters will be deployed in a triangular grid with a spacing of 1.5 km. The array will be connected by a hierarchical network of RF communications for the trigger and data concentration. The timing of each counter is recorded using the local GPS clock. The ground array is overlooked by the fluorescence telescopes.

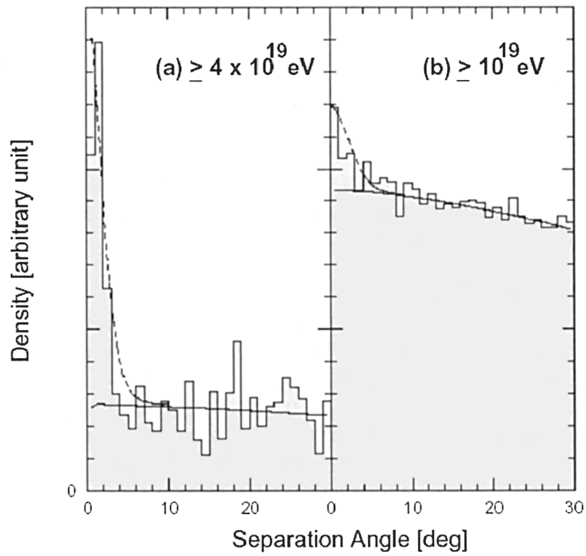

Figure 5. Distribution of separation angles for any two cosmic rays with $E > 10^{19.6}$ eV (left panel, 59 events in total) and $E > 10^{19.0}$ eV (right panel, total 775 events in total) by AGASA.

About 10% of the events will have both the ground array data and at least one telescope data taken at the same time. These events will have an excellent angular resolution and will be valuable to cross calibrate the energies obtained by two orthogonal methods. The construction of the southern Auger detector started in 1999 and the commissioning of the full detector is expected in 2005.

The Telescope Array (TA) Project plans to deploy 10 fluorescence stations in the desert of Utah, USA where the HiRes is presently located (Telescope Array Design Report 2000). Each station consists of 20 telescopes arranged in a ring structure. It monitors the night sky of 360° in the azimuth and $3° - 35°$ in the elevation with 1° pixel resolution. The 3m diameter mirror of the telescope enables the detection of EHECR up to 60 km away from the station. The total acceptance will be 6400 km^2 sr after multiplying 10% duty factor.

The TA plans to identify EHE γ rays by the Xmax measurement. At extremely high energies, the Xmax of γ ray shows a complicated behavior by the density effect (Landau & Pomeranchuk 1935; Migdal 1956) and the geomagnetic field effect. The shower originated from γ ray tends to penetrate deeper in the atmosphere above $10^{18.5}$ eV by the density effect, which is counteracted above 10^{19} eV by the pair creation and synchrotron radiation by the geomagnetic field (Kasahara 1996). The geomagnetic effect has a large north-south asymmetry depending on the transverse component of the geomagnetic field with respect to the arrival direction of EHECR. This rich modulation will be instrumental for the identification of γ rays. The TA group plans to start measurement in 2006.

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The Extreme Universe Space Observatory (EUSO) looks down the Earth from the space to measure the air fluorescence caused by the EHECR (EUSO Proposal 2000). It uses a fancy Schmidt optics with double Fresnel lenses for a wide field of view of 60° by a single telescope. A high pixel resolution ($\sim 0.1°$) and single photon counting will be used to bring the detection energy threshold down to $10^{19.6}$ eV. It was originally proposed as a free flyer but later recommended for the realization at the International Space Station. The ISS version has an acceptance of $\sim$ 50,000 km^2 sr. The EUSO will be most suited for the detection of EHE neutrinos by using its enormous aperture. The group intends to launch the detector by 2009.

All new generation detectors are designed to have at least an order of magnitude larger acceptance than AGASA to ensure enough EHECR events are collected for scrutiny. The sensitivity for identifying EHE γ rays and the neutrinos, together with the high angular resolution to determine the arrival direction, will be the key features for identifying the origin of EHECR. We keenly await the outcome of these new generation experiments.

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References

Abu-Zayyad, T. 2000, Nucl. Instrum. & Methods, A450, 253

Aharonian, A & Cronin, J. W. 1994, Phys.Rev., D50, 1892

Baltrusaitis, R. M. 1985, Nucl. Instrum. & Methods, A240, 410

Berezinsky, V., Blasi, P., & Vilenkin, A. 1998, Phys.Rev., D58, 103515

Berezinsky, V. 2000, Nucl. Phys. Proc. Suppl., 81

Bird, D. J. et al. 1993, Phys.Rev.Lett, 71, 3401

Bird, D. J. 1994, Astrophys. J., 424, 491

Cao, Z. 2002, Proceedings of this symposium

Chiba, N. et al., 1992, Nucl. Instrum. & Methods, A311, 338

Chikawa, M. 2001, Proceedings of 27th ICRC(Hamburg), HE1.4-3

Coleman, S. & Glashow, S. L. 1999, Phys. Rev., D59, 116008

EUSO Proposal, Extreme Universe Space Observatory, A proposal for the ESA F2/F3 Missions 2000

Gorbunov, D. S. et al. 2002, Astrophys. J., 577, L93

Greisen, K. 1966, Phys.Rev.Lett, 16, 748

Hamaguchi, K. et al. 1999, Phys.Rev., D60, 125009

Kakimoto, F. et al. 1996, Nucl. Instrum. & Methods, A373, 572

Kasahara, K. 1996, Proceedings of International Symposium on EHECR (Tanashi/Tokyo), pp221-230

Koyama, K. 1995, Nature, 378, 255

Kuzmin, V & Tkachev, I. 1998, JETP Lett. 68, 271

Landau, L. D. and Pomeranchuk, I. D. 1935, Dokl. Akad. Nauk SSSR, 92, 535

Migdal, A. B. 1956, Phys. Rev., 103, 1811

Nagano, M., & Watson, A. A. 2000, Rev. Mod. Phys., 72, 689
Nagano, M. 2003, astro-ph/0303193
Pierre-Auger Observatory Design Report 1997
Sato, H. & Tati, T. 1972, Prog. Theo. Phys., 47, 1788
Sigl, G. et al. 2001, Phys. Rev., D63, 081302
Takeda, M. et al. 1998, Phys. Rev. Lett., 81, 1163
Takeda, M. et al. 1999, Astropart. Phys., 10, 303
Takeda, M. et al. 1999, astro-ph/9902239
Takeda, M. et al. 2002, astro-ph/0209422
Tanimori, T. et al. 1998, Astrophys. J., 497, L25
Telescope Array Project Design Report 2000
Torres, D. F. et al. 2002, Phys. Rev., D66, 023001
Uchihori, Y. et al. 2000, Astropart. Phys., 13, 151
Weiler, T. J. 1999, Astropart. Phys., 3, 303
Yoshida, S. & Teshima, M. 1993, Prog. Theor. Phys., 89, 833
Zatsepin, G. T. & Kuzmin, V. A. 1966, JETP lett., 4, 178

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