# ASTROPHYSICS OF THE HIGHEST ENERGY COSMIC RAYS*

Paul Sommers

High Energy Astrophysics Institute
Physics Department, University of Utah
115 S 1400 E, Room 201, Salt Lake City, UT 84124-0830

*(Received May 7, 2004)*

The origin of the highest energy particles in the Universe is a mystery that persists despite experimental efforts that have intensified for 50 years. The issue has attracted keen theoretical interest in the last decade in response to evidence that the energy spectrum continues to energies above $10^{20}$ eV without the cutoff expected from pion photoproduction. Explanations necessarily entail new fundamental physics or some unexpected astrophysics. Observations from different experiments are presently incommensurate, and more powerful observatories are under construction to discover and study the sources of the highest energy cosmic rays.

PACS numbers: 98.70.Sa, 98.70.Vc, 95.30.Cq

## 1. Introduction

Observations of the highest energy cosmic rays pose challenging puzzles. In 1938, Pierre Auger recorded secondary particles with widely separated detectors at ground level and demonstrated that some cosmic rays have energies in excess of $10^{15}$ eV [1]. Such high energies were quite unexpected. In 1962, John Linsley recorded a cosmic ray with energy above $10^{20}$ eV at his Volcano Ranch detector [2]. That showed that the cosmic ray energy spectrum extends to phenomenal (macroscopic) energies, but the observation attracted less attention than it deserved because it predated the discovery of the cosmic microwave background (CMB) radiation by Penzias and Wilson [3]. Soon after the CMB discovery in 1965, Greisen and Zatsepin and Kuzmin [4] showed that such high energy particles cannot propagate freely but lose energy by pion photoproduction. The cosmic ray energy spectrum

* Presented at the Cracow Epiphany Conference on Astroparticle Physics, Cracow, Poland, January 8–11, 2004.

should not go as high as $10^{20}$ eV, at least not if the particles are protons from extragalactic sources. There should be a "GZK cutoff." Moreover, nuclei should photodisintegrate by collisions with cosmic photons, and gamma rays must succumb to $e^{\pm}$ pair production. Air showers with energies above $10^{20}$ eV should be highly improbable if the cosmic ray sources are extragalactic. Since there is no excess of arrival directions observed near the Milky Way band of the sky for the highest energy cosmic rays, it does seem that they must be of extragalactic origin. A continuation of the spectrum beyond $10^{20}$ eV without evidence of galactic sources constitutes a puzzle, if not a paradox.

Experiments since Volcano Ranch have yielded mixed results in regard to the GZK cutoff. At the La Jolla ICRC meeting in 1985, Fly's Eye data favored a cutoff [5], while Haverah Park results did not [6]. In 1991, the Fly's Eye recorded a remarkable event with apparent energy $3.2 \times 10^{20}$ eV [7]. AGASA recorded one nearly as energetic soon after [8]. At the Salt Lake City ICRC meeting in 1999, there was general concordance between the AGASA and HiRes spectrum results, both providing evidence for the spectrum continuing beyond $10^{20}$ eV without a strong GZK suppression [9].

A new analysis of HiRes data with improved atmospheric aerosol modeling resulted in some important discrepancies between AGASA and HiRes spectra at the Hamburg ICRC in 2001. The revised HiRes energy spectrum could be reconciled with the predicted GZK cutoff, whereas the AGASA spectrum showed no such feature [10].

## 2. Present observational status of EHE cosmic rays

HiRes and AGASA have comparable cumulative exposures at the highest energies, substantially more exposure than any previous experiment. The spectra from the two experiments in 2003 are shown together in figure 1 (Olinto [11]). There are three interesting differences:

1. AGASA finds 11 events above $10^{20}$ eV, whereas HiRes finds only 2. There is apparent conflict with regard to the GZK cutoff.

2. Near $10^{19}$ eV, where both experiments have good statistics, the AGASA flux is approximately twice the HiRes flux. In view of the steeply falling spectrum, the natural way to account for that difference is to suppose that they differ systematically in their energy assignments. A relative shift of 40% in energy brings the normalizations into agreement. Perhaps the HiRes energies are systematically 20% low, and the AGASA energies are 20% high. Both experiments admit systematic energy uncertainty of approximately that much.

3. Both spectra show a distinct flattening (ankle) structure. In the AGASA spectrum the feature is near $10^{19}$ eV, whereas it is near $10^{18.5}$ eV in the HiRes spectrum. To suppose that these are the same feature in both spectra would require a systematic energy difference of 300%, which far exceeds the combined estimated systematic errors. Moreover, a relative energy shift of that magnitude would cause the HiRes flux to exceed the AGASA flux by nearly a factor of 5. The ankle structures seen in the two spectra are incommensurate.

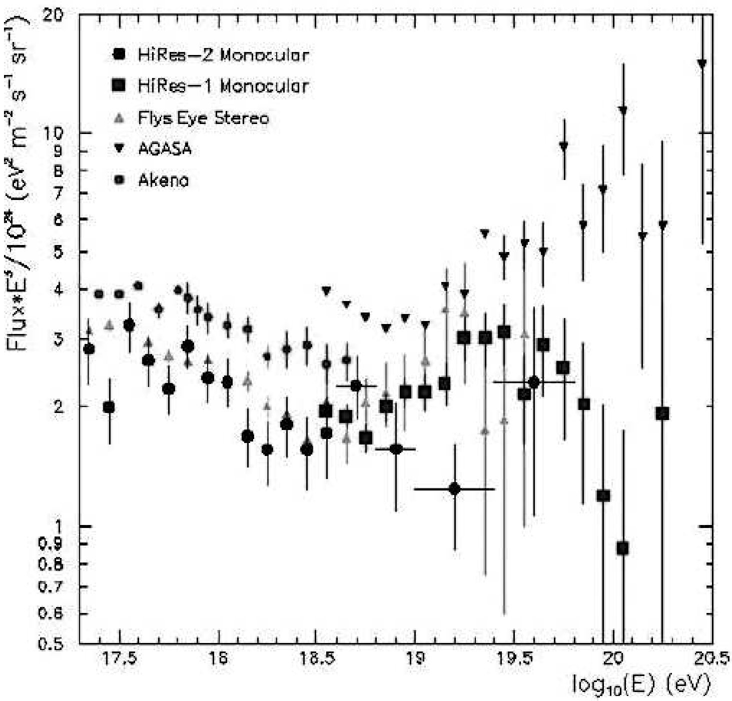


Fig. 1. Comparison of AGASA and HiRes spectrum results. There is apparent difference in the super-GZK flux at the high end where statistics are poor, difference in the overall flux near $10^{19}$ eV where both have good statistics, and difference also in the energy of the "ankle" flattening. (Figure by Olinto [11].)

The experimental results from these two experiments with greatest exposure differ not only in respect to the energy spectrum. There is an important difference also in results concerning the arrival directions. AGASA has found a significant number of event clusters on the sky [12]. The two-point correlation function has a strong excess at small angles. Analysis of HiRes arrival directions does not support that clustering [13].

AGASA and HiRes publications about the cosmic ray chemical composition may also be at odds. The Fly's Eye data suggested a transition from a heavy composition to a light composition near the spectral flattening around $10^{18.5}$ eV [14]. Analysis of HiRes/MIA data [15] and more recent HiRes data [16] support that general trend, although the composition change may start well before the spectral ankle. The AGASA muon data, however, yield a simple power law dependence on energy that does not immediately suggest any composition change [17]. Dawson *et al.* [18] have argued that the constant AGASA muon power law may result from compensating effects: enhancement of muons at the highest energies due to properties of modern interaction models (including models used in HiRes analyses) can compensate for diminished muon production due to a lighter composition.

## 3. The GZK expectation

The GZK effect on the highest energy cosmic rays is a simple consequence of special relativity, laboratory physics, and the universal microwave background radiation. In the laboratory, pion photoproduction is measured when gamma rays interact with nucleons in target material. In the restframe of a cosmic ray near $10^{20}$ eV, the cosmic microwave photons constitute a beam of gamma rays whose energies are above the pion restmass energy. Pion-producing interactions must therefore occur, and, in the universal restframe, the cosmic ray loses energy to pay for the energetic pion production. Each interaction takes roughly 20% of the cosmic ray's energy, on average, until the cosmic ray energy is below the GZK threshold.

The photoproduction cross section and CMB photon density are such that cosmic rays typically fall below the GZK energy threshold in less than about 100 million years. The present supply of super-GZK particles have therefore accumulated only over the last 100 million years. Sub-GZK cosmic rays, on the other hand, have been accumulating for at least 10 billion years. The super-GZK particles are therefore suppressed by approximately 1/100 in number compared to what would be expected without pion photoproduction. Cosmic ray experiments up to the present time have had small enough exposures that extrapolating the power-law spectrum observed just above the ankle would predict fewer than 100 particle detections above $10^{20}$ eV. Applying the 1/100 GZK suppression factor means the expected number of detections above $10^{20}$ eV is less than 1. The GZK suppression is therefore commonly regarded as an effective spectrum cutoff.

The CMB photons limit the travel time of super-GZK cosmic rays rather than how far they get from their source. The same spectral suppression feature pertains to a model with local sources if a magnetic bottle confines all the produced cosmic rays.

Although the GZK suppression is an issue that is in experimental dispute at present, there have been some carefully documented cosmic ray detections whose measured energies are well above $10^{20}$ eV [7, 8]. The existence of a measurable flux of cosmic rays with super-GZK energies has stimulated many theoretical hypotheses for why the GZK cutoff might not exist.

## 4. Scenarios without a GZK cutoff

There are three main classes of explanations for the absence of a GZK spectral suppression:

1. *All EHE particles are young (both above and below the GZK threshold).*

   "Young" here means that the average age of detected cosmic rays is not much more than 100 million years above or below the GZK energy threshold. Particles below the threshold have not been accumulating much longer than particles above. Two possible reasons are these:

   - The spectrum is dominated by sources near us. The cosmic rays escape this local region in less than about 100 million years. Candidate local sources include the galactic center, M87, and Cen A. Magnetic fields must be invoked to spread the arrival directions over the sky and mask the sources, but they must not trap the cosmic rays for billions of years.

     Strong anisotropy can be avoided without special magnetic fields if the sources are distributed throughout a halo of the Galaxy. The decay of relic massive particles can produce EHE particles without acceleration [19]. Since the sun is displaced more than 8 kpc from the galactic center, however, a very large halo is needed to avoid an excess from the side of the sky toward the galactic center. On the other hand, the halo cannot be too large. Sources distributed in extremely large halos around all galaxies would be similar to the model of homogeneous source density throughout the Universe, and the GZK suppression should then be present.
   - It is conceivable that sub-GZK EHE cosmic rays lose energy on time scales as short as approximately 100 million years. The known processes of pion photoproduction, $e^{\pm}$ pair production, synchrotron radiation, and nuclear collisions do not cause such rapid energy loss. In fact, no process is known that can explain it. Nevertheless, only 5% of the Universe's matter density is understood. There could be some interactions with dark matter or dark energy that have a very high threshold energy that is nevertheless well below the GZK energy threshold.

2. *EHE particles are old, both above and below the GZK threshold.*

   "Old" here means that the average age of detected cosmic rays is billions of years, much greater than the GZK energy loss time. Particles above the threshold have been accumulating as long as the particles below it. Two proposed reasons are these:

   - The long-lived super-GZK particles are not nucleons, nuclei, or gamma rays. They are other particles that do not interact with the CMB photons. Possibly they are neutrinos. One might imagine that they somehow interact with high cross section in the atmosphere and produce normal air showers [20]. Alternatively, they could interact with relic thermal neutrinos in the galactic halo via the "$Z$-burst" resonance, producing particles that are then responsible for the detected air showers [21]. Instead of neutrinos, the super-GZK particles might be exotic neutral particles like UHECRONS with supersymmetric components [22]. Arrival directions of long-lived neutral particles could be expected to point to very distant powerful astrophysical objects. Correlations of EHE arrival directions with distant AGN have been reported [23].
   - Lorentz invariance might be violated at extremely high energies [24]. The expectation of a GZK suppression relies on special relativity. Any reason for its failure in this untested regime can be invoked to explain old particles with super-GZK energies.

3. *Super-GZK particles are indeed much younger than sub-GZK particles, but they represent a different population of cosmic rays with a very hard energy spectrum.*

   The idea is sketched schematically in figure 2. The normal cosmic ray spectrum (dominant at low energies) is strongly suppressed above the GZK threshold. Above the threshold, the observed cosmic rays originate from a different type of source with the much harder spectrum. It is also subject to the GZK suppression, but the suppressed spectrum is approximately a continuation of the normal cosmic ray spectrum observed below the threshold. The hard spectrum is typically attributed to production of the energetic particles by a top-down process like the decay of massive relic particles rather than by any bottom-up acceleration process.

   The annihilation of topological defects was shown to produce this type of very hard spectrum even before the Fly's Eye and AGASA recorded showers well above $10^{20}$ eV [25]. That theory is tightly constrained by

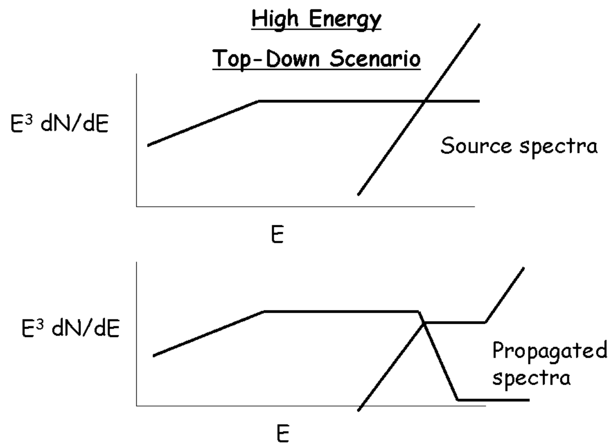


Fig. 2. Top-down scenarios with sources throughout the Universe may disguise the GZK suppression by a new cosmic ray population with a very hard spectrum that dominates at high energies. This hard new spectrum appears to continue the normal one when both are suppressed by the GZK effect.

upper limits on diffuse gamma rays near 100 MeV, however [26]. Jets from massive particle decays produce large amounts of electromagnetic radiation that (if intergalactic magnetic fields are not negligible) cascade down in energy to produce a diffuse gamma ray background near 100 MeV. If universally distributed top-down processes account for the cosmic ray observations, then this associated diffuse gamma ray background should be stronger than what is observed by satellites.

## 5. Prospects for charged particle astronomy

EHE cosmic rays have very high magnetic rigidity. Super-GZK particles should not be deflected much by expected magnetic fields before losing their energy to pion photoproduction. Observed super-GZK arrival directions should therefore point toward sources within the GZK radius (roughly 30 Mpc $\sim$ 100 million light years).

The Larmor radius of a cosmic ray is given to a good approximation by the formula

$$R_{\mathrm{kpc}} \doteq \frac{E_{18}}{Z B_{\mu\mathrm{G}}} ,$$

or

$$R_{\mathrm{Mpc}} \doteq \frac{E_{18}}{Z B_{\mathrm{nG}}} .$$

Here the cosmic ray energy $E_{18}$ is $E/10^{18}$ eV and $Z$ is the nuclear charge. If the $B$-field is measured in $\mu$G (respectively, nG), then the Larmor radius is in kpc (respectively, Mpc). The regular magnetic field near the plane of the Galaxy has a field strength on the $\mu G$ order, so a $10^{20}$-eV cosmic ray proton should have an orbit size of about 100 kpc. A transit through one kpc of galactic disk corresponds to a deflection of roughly 1/2 degree. Intergalactic magnetic fields are uncertain, but may be typically of the nG order, with coherence length roughly 1 Mpc. Over each Mpc of transit, the deflection might be on the order of 1/2 degree. A distance of 30 Mpc would produce a random walk with net deflection on the order of a few degrees. Arrival directions from a discrete source within the GZK distance limit would then not be dispersed much more than the angular resolution of a typical cosmic ray detector. A discrete source of super-GZK particles should be recognizable as a cluster of arrival directions.

In this context, it is important to note that the highest energy detected cosmic rays have arrival directions that do not correlate with directions to nearby powerful astrophysical objects that would be good candidates for sources of EHE particles. Nor do clusters identified in AGASA sky maps identify nearby sources. Charged particle astronomy has not yet been achieved. Why not? Are the highest energy particles heavy nuclei with perhaps 26 times more magnetic deflection? Measuring the chemical composition is essential. (See the paper by A. Watson in these proceedings.) Are the highest cosmic ray energies not really above the GZK threshold, so those particle trajectories have been bent over much larger travel distances? Are the cosmic rays produced diffusively rather than in discrete sources? If they originate in discrete sources, are those located in normal galaxies rather than special astrophysical objects? Are the particles exotic neutral particles whose arrival directions actually point to very distant and powerful AGNs [23]?

The vastly increased collecting power of new cosmic ray observatories (Auger, TA, EUSO) will have significantly greater sensitivity to discrete sources through higher statistics. Small clusters of 2 or 3 arrival directions will become rich clusters of 20 to 30 arrival directions when the cumulative exposure is 10 times greater. Above the GZK threshold, present sensitivity is limited by the lack of signal, and below the threshold it is limited by the background "noise" from distant sources throughout the Universe. With an order of magnitude exposure increase, nearby sources may become detectable both above and below the GZK energy threshold.

## 6. The need for a full-sky observatory

Experiments so far have not positively identified cosmic ray anisotropy at the highest energies. A conservative view is that discrete sources may not be discovered even with the next generation of observatories. There may simply be no nearby powerful source. (The number of sources at distance $r$ increases like $r^2$ while the flux from any given source decreases like $1/r^2$. If there is no nearby source, it may be that every contributing source has a flux that will still be too weak to be identified by an obvious cluster of arrival directions.) The sources may be broadly distributed or diffuse. They may be transient phenomena in normal galaxies. The trajectories may be greatly bent due to strong magnetic fields and/or particles having high atomic number $Z$. There are numerous reasons to suppose that discrete sources might not show up even when the number of arrival directions has been increased by a large factor.

The origin of high energy cosmic rays may be discoverable instead by measuring subtle large-scale patterns in the density of arrival directions. The distribution of the sources collectively leaves a fingerprint on the sky.

Multipole moments (using spherical harmonics) are the natural way to characterize a celestial fingerprint. Each coefficient is obtained by integrating the observed celestial density function against the appropriate spherical harmonic function over the full sphere. No multipole moment can be definitively determined without full-sky exposure. With full-sky exposure, however, all of the coefficients are measurable. The celestial density function is represented completely by the multipole moments, which can be conveniently tabulated [27].

## 7. Summary

It is now 66 years since Pierre Auger discovered remarkably high energy cosmic rays by their air showers and nearly 40 years since the discovery of the CMB radiation called into question the observation of cosmic rays above $10^{20}$ eV. Numerous good experiments have accelerated the growth of the cumulative EHE cosmic ray data set. Cosmic rays have now been studied extensively with air fluorescence detectors as well as ground arrays. The most fundamental questions are still with us, however. Where do EHE cosmic rays originate, how do they acquire their phenomenal energies, and what types of particles are they?

Results from the largest ground array (AGASA) and the largest air fluorescence detector (HiRes) are not easily reconciled. Their energy spectra differ in several important respects. They do not agree on the existence of arrival direction clustering on small scales. And neither experiment provides clear evidence about the particle masses at the highest energies.

New detectors should help answer the persistent basic questions. The Auger Observatory [28] is now operating with approximately 20% of its full size at the southern hemisphere site in Argentina. Auger South should be complete in 2006. It is a hybrid observatory, measuring air showers full-time with a 3000 km$^2$ surface array of water Cherenkov detectors, and at night the air shower longitudinal developments are measured in the atmosphere above the surface array by air fluorescence detectors. The design calls for a matching observatory to be built in the northern hemisphere. The combination of Auger South and Auger North will provide nearly uniform exposure to the entire sky.

The Telescope Array [29] is another hybrid observatory that will be built in Utah over the next several years. The surface array will be plastic scintillators, and part of the idea is to verify the results of the AGASA scintillator array. Air fluorescence detectors will measure the longitudinal development of air showers recorded at night.

EUSO [30] will measure cosmic ray air showers from the International Space Station. Looking down from an altitude of several hundred kilometers, it will have a giant aperture for recording air fluorescence tracks made by the highest energy cosmic rays.

EHE cosmic ray observations presently suggest a flux of super-GZK particles with seemingly random arrival directions. Whether or not the flux is much greater than expected for a universal distribution of sources is an open observational question. If so, then its explanation must entail some new fundamental physics or some remarkable astrophysics. If not, there are still vital questions about the Universe's highest energy particles: where and how are they produced, and what type(s) of particle are they? The new powerful cosmic ray observatories should resolve these primary questions. Ten years from now, will they be providing information about properties of discrete cosmic ray acceleration sites, or will cosmic ray specialists be studying properties of top-down production processes? Will cosmic rays prove to be a useful probe of cosmic magnetic fields? Stay tuned.

## REFERENCES

[1] P. Auger *et al.*, *Comptes Rendus* **206**, 1721 (1938); P. Auger, *Rev. Mod. Phys.* **11**, 288 (1939).

[2] J. Linsley, *Phys. Rev. Lett.* **10**, 146 (1963).

[3] A.A. Penzias, R.W. Wilson, *Astrophys. J.* **142**, 419 (1965).

[4] K. Greisen, *Phys. Rev. Lett.* **16**, 748 (1966); G.T. Zatsepin, V.A. Kuz'min, *JETP Lett.* **4**, 78 (1996).

[5] R.M. Baltrusaitis *et al.*, Proc. 19th Int. Cosmic Ray Conf., La Jolla, OG 2, 146 (1985).

[6] G. Brooke *et al.*, Proc. 19th Int. Cosmic Ray Conf., La Jolla, OG 2, 150 (1985).

[7] D.J. Bird *et al.*, *Astrophys. J.* **441**, 144 (1995).

[8] N. Hayashida *et al.*, *Phys. Rev. Lett.* **73**, 3491 (1994).

[9] The AGASA Collaboration, Proc. 26th Int. Cosmic Ray Conf., 3, 252 (1999); T. Abu-Zayyad *et al.*, Proc. 26th Int. Cosmic Ray Conf., 3, 264 (1999).

[10] P. Sommers, rapporteur talk, 27th Int. Cosmic Ray Conf., `http://www.physics.utah.edu/s̃ommers/publications/rapporteur2001.ps`

[11] A.V. Olinto, AAAS Symposium on Cosmic Rays, `http://astro.uchicago.edu/home/web/olinto/aaas.ppt`

[12] N. Hayashida *et al.*, *Astrophys. J.*, **522**, 225 (1999); Y. Uchihori *et al.*, *Astropart. Phys.* **13**, 151 (2000); M. Takeda *et al.*, *Astrophys. J.* **522**, 225 (1999).

[13] J.W. Belz for the HiRes Collaboration, Proc. 28th ICRC, Tsukuba HE 1.3, 425 (2003).

[14] D.J. Bird *et al.*, *Phys. Rev. Lett.* **71**, 3401 (1993).

[15] T. Abu-Zayyad *et al.*, *Phys. Rev. Lett.* **84**, 4276 (2000).

[16] G. Archbold for the HiRes Collaboration, Proc. 28th ICRC, Tsukuba HE-1.3, 405 (2003).

[17] N. Hayashida *et al.*, *J. Phys. G* **21**, 1101 (1995).

[18] B.R. Dawson, R. Meyhandan, K.M. Simpson, *Astropart. Phys.* **9**, 331 (1998).

[19] V. Berezinsky, *Nucl. Phys. Proc. Suppl.* **70**, 419 (1999); M. Birkel, S. Sarkar, *Astropart. Phys.* **9**, 297 (1998); M. Hillas, *Nature* **395**, 15 (1998).

[20] S. Nussinov, R. Shrock, *Phys. Rev.* **D59**, 105002 (1999).

[21] T.J. Weiler, *Astropart. Phys.* **11**, 303 (1999); D. Fargion, B. Mele, A. Salis, *Astrophys. J.* **517**, 725 (1999).

[22] D.J.H. Chung, G.R. Farrar, E.W. Kolb, *Phys. Rev.* **D57**, 4606 (1998).

[23] G.R. Farrar, P.L. Biermann, *Phys. Rev. Lett.* **81**, 3579 (1998); P.G. Tinyakov, I.I. Tkachev, *JETP Lett.* **74**, 445 (2001); *Pisma Zh. Eksp. Teor. Fiz.* **74**, 499 (2001).

[24] H. Sato, T. Tati, *Prog. Theor. Phys.* **47**, 1788 (1972); D.A. Kirzhnits, V.A. Chechin, *Sov. J. Nucl. Phys.* **15**, 585 (1972); L. Gonzalez-Mestres, `hep-th/0208064`; S. Coleman, S.L. Glashow, *Phys. Lett.* **B405**, 249 (1997); S. Coleman, S.L. Glashow, *Phys. Rev.* **D59**, 116008 (1999).

[25] F.A. Aharonian, P. Bhattacharjee, D.N. Schramm, *Phys. Rev.* **D46**, 4188 (1992).

[26] G. Sigl, *Ann. Phys.* **303**, 117 (2003).

[27] P. Sommers, *Astropart. Phys.* **14**, 271 (2001).

[28] See the paper by Johannes Bluemer *Acta Phys. Pol B*, **35**, (2004), these proceedings, also `http://www.auger.org/`

[29] `http://www-ta.icrr.u-tokyo.ac.jp/`

[30] `http://www.ifcai.pa.cnr.it/`