ULTRA HIGH ENERGY COSMIC RAYS: OBSERVATION AND INTERPRETATION

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ABSTRACT

The evidence for the existence of cosmic rays with energies in excess of 10^{20} eV is now overwhelming. There is so far no indication of the GZK cutoff in the energy spectrum at 5×10^{19} eV. This conclusion is not firm for lack of statistics. A cutoff would be expected if the sources of the cosmic rays were distributed uniformly throughout the cosmos. The sources of cosmic rays with energy above the GZK cutoff must be at a distance ≤ 100 Mpc, and if they are protons they are very likely to point to these sources. There are no easy explanations how known astrophysical objects can accelerate protons (or atomic nuclei) to these energies. This difficulty has led to speculation that there may be exotic sources such as topological defects which produce these energetic cosmic rays directly along with a copious supply of neutrinos of similar energy. The fluxes of these cosmic rays is very low and large instruments are required to observe them even with modest statistics. One such instrument, the Pierre Auger Observatory, is described. It is designed for all-sky coverage and the construction of its southern site will begin in Argentina in 1999. instrument, the Pierre Auger Observatory, is described. It is designed for all-sky coverage and the construction of its southern site will begin in Argentina in 1999.

1. The cosmic ray energy spectrum above 10^{18} eV

In recent years the interest in extremely high energy cosmic rays (EHECR), those with energy $\geq 10^{18}$ eV (EeV), has revived because of a number of discoveries. Therefore there are many excellent reviews, books, and conference proceedings to which the reader is referred [1)]. The energy spectrum of cosmic rays is quite well measured up to 10^{19} eV. Above the knee (3×10^{15} eV) it falls as a power law in energy, $\mathrm{dN/dE} \sim \mathrm{E}^{-\alpha}$, with an index α=3.

Above 10^{17} eV the cosmic ray spectrum has significant structure, which is displayed in Fig 1, where the differential spectrum has been multiplied by E^3 to better display the observed structures. These data are the contribution of four experiments which have operated over the past 20 years. These experiments observe the cosmic rays indirectly by means of the air showers they produce. They are from the Haverah Park surface array in England [2)], the Yakutsk surface array in Siberia [3)], the Fly's Eye fluorescence detector in Utah [4)], and the AGASA surface array in Japan [5)]. Before plotting, the energy scale of each experiment has been adjusted by amounts $\leq 20\%$ to show most clearly the common features. The method of energy determination in each of these experiments is quite different, and the fact that they agree within 20%

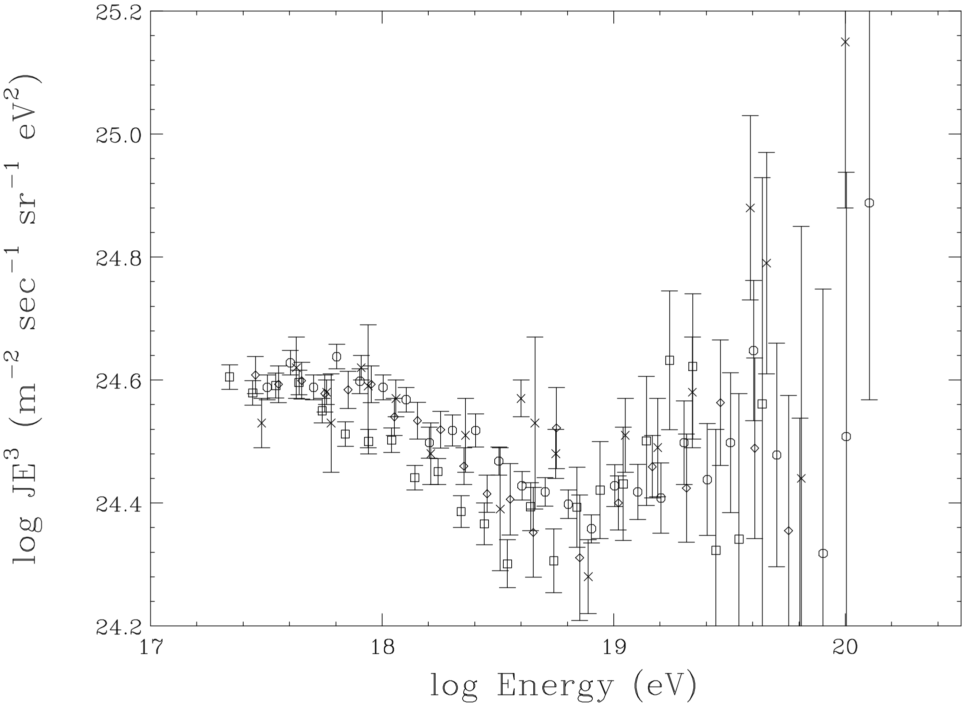

Fig. 1. Upper end of the cosmic ray spectrum. Haverah Park [2] points (crosses) serve as a reference. Yakutsk [3] points [diamonds] have been reduced by 20%. Fly's Eye [4] points (squares) have been increased by 10%. Agasa [5] points (circles) have been reduced by 10%.

is remarkable.

The spectrum continues with an index of 3.0 until about 5×10^{17} eV where it steepens with an index of about 3.3. Above an energy of 10^{18} eV it is difficult for the galaxy to contain even iron nuclei and galactic accelerators that can produce such energies cannot be imagined. If cosmic rays at these energies continue to be produced in the galaxy, they should show a strong anisotropy which correlates with the distribution of matter in our galaxy. Above this energy such a correlation is not observed probably due to lack of statistics. Above 5×10^{18} eV the spectrum hardens to a spectral index of 2.7. This hardening of the spectrum may be due to a new component that is extragalactic.

The composition of the cosmic rays is notoriously difficult to measure with the indirect air shower methods. Such evidence as does exist suggests that the composition is moving towards a lower mean atomic number as the energy increases from 10^{17} eV to 10^{19} eV [6].

2. The Difficulty of Acceleration

Above 10^{19} eV the precision of the spectrum measurement suffers from lack of statistics. There have been about 60 events recorded with energy greater than 5×10^{19}

eV. Yet it is above this energy that the scientific mystery is the greatest. There is little understanding how known astrophysical objects can produce particles of such energy. At the most primitive level, a necessary condition for the acceleration of a proton to an energy of 10^{20} eV requires that the product of the magnetic field B and the size of the region R be much larger than 3×10^{17} gauss-cm. This value is appropriate for a perfect accelerator such as might be scaled up from the Tevatron at Fermilab. The Tevatron has a BR=3×10^{9} gauss-cm and accelerates protons to 10^{12} eV. The possibility of acceleration of cosmic rays to energies above 10^{19} eV seems difficult and the literature is filled with speculations. Two reviews which discuss the basic requirements are given by Greisen [7)] and Hillas [8)]. While these were written some time ago, they are excellent in outlining the basic problem of cosmic ray acceleration. Biermann [9)] has recently reviewed all the ideas offered to achieve these high energies. Hillas in his outstanding review of 1984 presented a plot which graphically shows the difficulty of cosmic ray acceleration to 10^{20} eV. Figure 2 is a reproduction of his figure. Plotted are the size and strength of possible acceleration sites. The upper limit on the energy is given by:

$$E_{18} \leq 0.5\beta Z B_{\mu g} L_{kpc}.$$

Here the E_{18} is the maximum energy measured in units of 10^{18} eV. L_{kpc} is the size of the accelerating region in units of kilo-parsec, and $B_{\mu g}$ is the magnetic field in μgauss. The factor β was introduced by Greisen to account for the fact that the effective magnetic field in the accelerator analogy is much less than the ambient field. The factor β in the Hillas discussion is the velocity of the shock wave (relative to c) which provides the acceleration. Lines corresponding to a 10^{20} eV proton with β=1 and 1/300 are plotted. A line is also plotted for iron nuclei (β=1). With Z=26, iron is in principle easier to accelerate, but in a realistic situation it is difficult to avoid the disintegration of the nucleus during the acceleration process. Real proton accelerators should lie *well* above the solid line. The figure is also relevant for "one shot" acceleration as it represents the emf induced in a conducter of length L moving with a velocity β through a uniform magnetic field B. Synchrotron energy loss is also important. For protons the synchrotron loss rate at 10^{20} eV requires that the magnetic field be less than 0.1 gauss for slow acceleration (the accelerator analogy)[7)]. The conclusion from this figure is that the acceleration of cosmic rays to 10^{20} eV is not a simple matter. Because of this difficulty some authors have seriously postulated that the cosmic rays are not accelerated but are directly produced by "top down" processes. Defects in the fabric of space-time can have huge energy content, and can release this energy in the form of high energy cosmic rays [10)].

3. Diagnostic Tools

There are some natural diagnostic tools which make the analysis of the cosmic rays above 5×10^{19} eV easier than at lower energies. The first of these is the 2.7K Cosmic

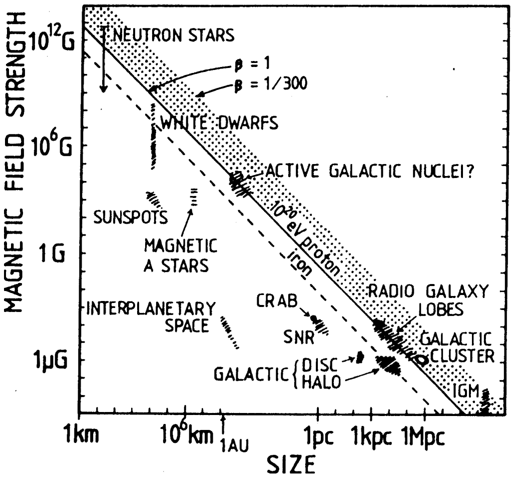

Fig. 2. Plot adapted from Hillas [8]. Size and magnetic field of possible sites of acceleration. Objects below the solid line cannot accelerate protons to 10^{20} eV.

Background Radiation (CBR). Greisen [11] and Zatsepin and Kuz'min [12] pointed out that protons, photons, and nuclei all interact strongly with this radiation (GZK effect).

The collision of a proton of 10^{20} eV colliding with a CBR photon of 10^{-3} eV produces several hundred MeV in the center of mass system. The cross section for pion production is quite large so that collisions are quite likely, resulting in a loss of energy for the primary proton. In Fig. 3 we plot the probability for selected proton energies that the source is further away than the indicated distance. This probability assumes that the sources are distributed uniformly and the spectrum has a powerlaw dependence with α=2.5.

Almost independent of the initial energy of a proton, it will be found with less than 10^{20} eV after propagating through a distance of 100 Mpc (3×10^{8} light years). Thus the observation of a cosmic ray proton with energy greater than 10^{20} eV implies that its distance of travel is less than 100 Mpc and that its initial energy at its source had to have been much greater. This distance corresponds to a red shift of $\sim$0.025 and is small compared to the size of the universe. Similar arguments can be made for nuclei or photons in the energy range considered. There are a limited number of possible sources which fit the Hillas criteria (Fig. 2) within a volume of radius 100 Mpc about the earth. The fact that the cosmic rays, if protons, will be little deflected by galactic and extragalactic magnetic fields serves as a second diagnostic tool [13]. The deflection of protons of energy 5×10^{19} eV by the galactic magnetic field ($\sim$ 2 μgauss) and the intergalactic magnetic fields ($\leq 10^{-9}$ gauss) is only a few degrees, so that above 5×10^{19} eV it is possible that the cosmic rays will point to their sources.

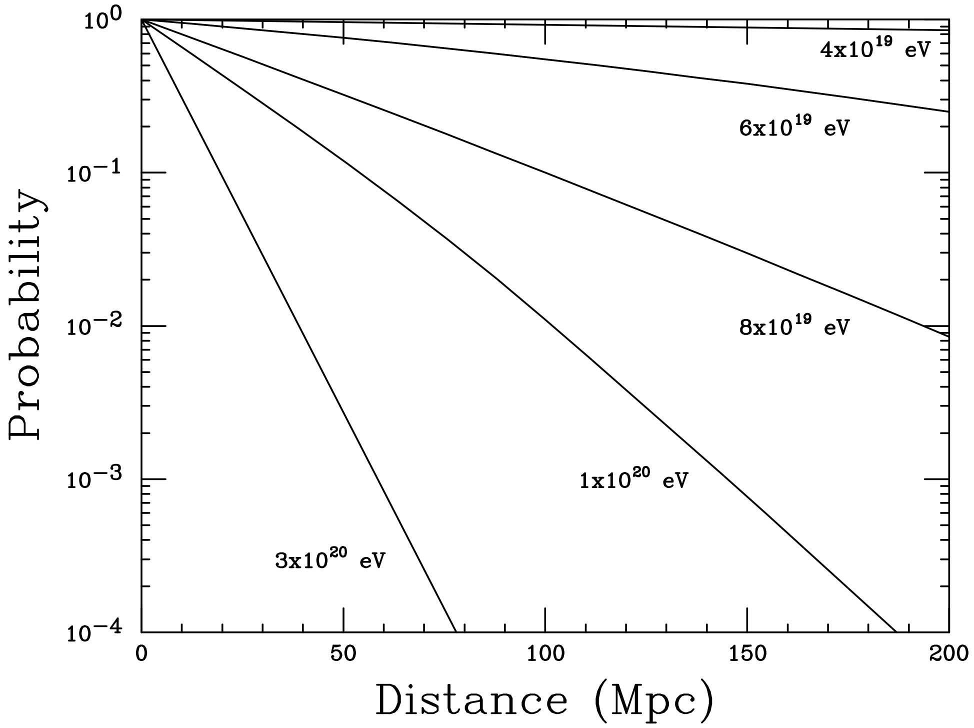

Fig. 3. Probability that cosmic ray proton has traveled further than the indicated distance. Sources are assumed to be distributed uniformly throughout space and emit cosmic rays with a differential spectral index α=2.5. This figure is based on calculations by Paul Sommers, University of Utah.

We thus approach an astronomy where the "light" consists of cosmic rays and the sources visible are dominated by those less than 100 Mpc away.

4. Cosmic Ray Astronomy

The energy 5×10^{19} eV represents a lower limit for which the notion of an astronomy of charged particles from "local" sources can be applied. For a universal distribution of sources with energy $\geq 5 \times 10^{19}$ eV, about half of the events will come from a distance of less than 100 Mpc due to attenuation of the more distant sources by the GZK effect. Above this energy the deflection of protons by galactic and extragalactic magnetic fields is expected to be no more than a few degrees. Recently the AGASA group [14)] has published the spectrum of EHECR based on seven years of operation of their 100 km^2 surface array. Their spectrum is plotted in Fig 4. There is no evidence of a GZK cutoff in this spectrum. To date about 13 events worldwide have been observed with energies in excess of 10^{20} eV. Ninty percent of these must have come from a distance less than 50 Mpc. Of these events, two particularly stand out with energies reported to be 2×10^{20} eV by the AGASA experiment [15)] and 3×10^{20} eV by the Fly's Eye experiment [16)].

The events above 5×10^{19} eV are too few to derive a spectral index. It is not

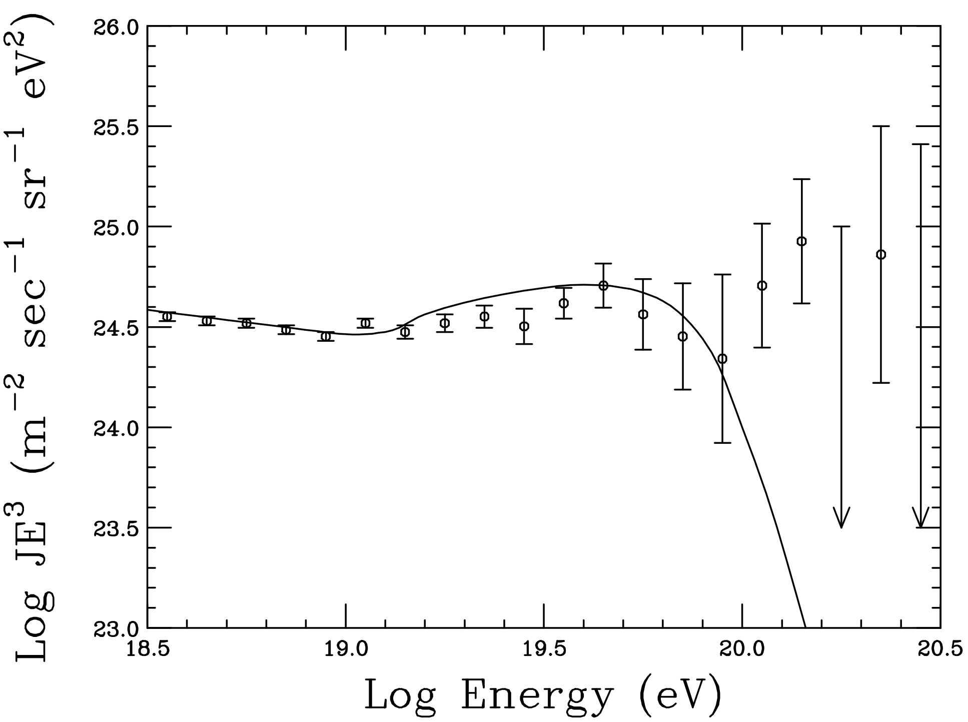

Fig. 4. Cosmic ray spectrum observed by the AGASA experiment during seven years of operation [14] [18]. The solid line is the spectrum expected for a universal distribution of sources showing the GZK cutoff, including the effects of instrument resolution.

clear that a single spectrum is even the proper way to characterize these events. Since they must come from "nearby" the actual number of sources may not form an effective continuum in space, so the spectrum observed may vary with direction. The distribution of matter within 100 Mpc is not uniformly distributed over the sky. It is probably more fruitful to take an astronomical approach and plot the arrival directions of these events on the sky in galactic coordinates.

Arrival direction data are available for the Haverah Park experiment [17)] and the AGASA experiment [18)]. In Fig. 5 we plot the arrival directions of 27 AGASA events and 16 Haverah Park events. The size of the symbols corresponds to the angular resolution. What is remarkable in this figure is the number of coincidences of cosmic rays coming from the same direction in the sky. Of the 43 events reported by AGASA and Haverah Park, there are two triplets. The probability of a chance coincidence for this occurance is about 0.1%. From astrophysical experience this small probabiliy is not sufficient to rule out chance, but the possibility that these clusters may be real cannot not be ignored. The cluster in the southern galactic hemisphere contains the largest AGASA event of 2×10^{20} eV, a Haverah Park event of about 1×10^{20} eV, and an AGASA event of 5×10^{19} eV. This cluster is particularly interesting as it contains cosmic rays separated by a factor of four in energy. The intervening magnetic fields have not separated the cosmic rays in space by more than a few degrees. This is

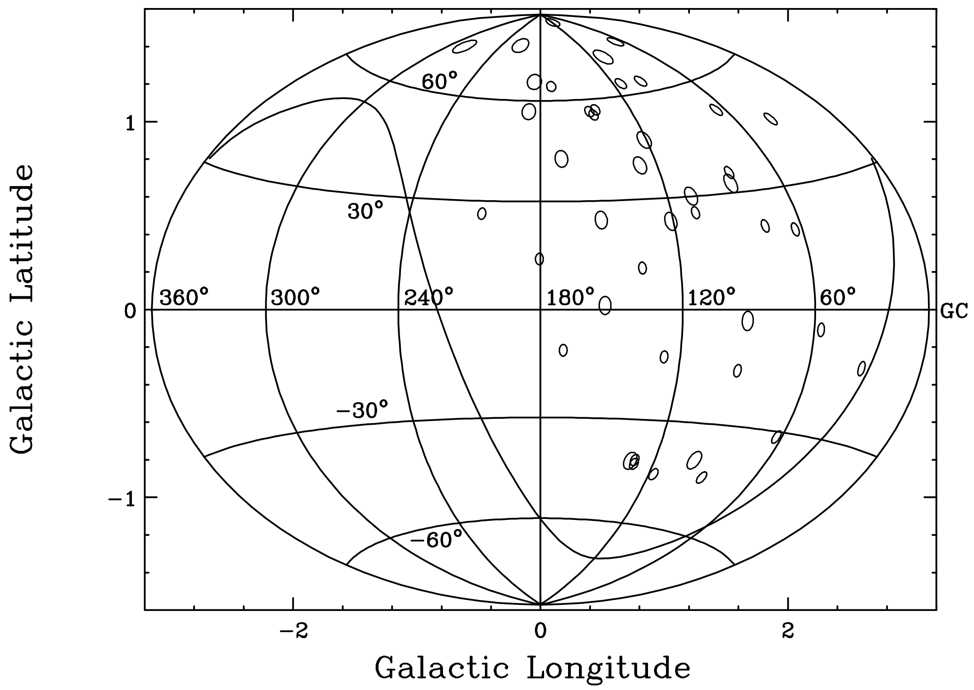

Fig. 5. Plot in galactic coordinates of arrival directions of cosmic rays with energy $\geq 5 \times 10^{19}$ eV. Large symbols, Haverah Park [17]; small symbols, AGASA [18]. The size of the symbols indicate the resolution of the experiments (63% of the events within the symbol). The empty region bounded by the solid line is the part of the sky not seen by the experiments which are located in the Northern Hemisphere.

an encouraging prospect for future experiments where, with many more events, one may observe point sources, clusters, and larger scale anisotropies in the sky. The crucial questions will be: Does the distribution of cosmic rays in the sky follow the distribution of matter within our galaxy or the distribution of “nearby” extragalactic matter, or is there no relation to the distribution of matter? Are there point sources or very tight clusters? What is the energy distribution of events from these clusters? Are these clusters associated with specific astrophysical objects? If there is no spatial modulation or no correlation with observed matter, what is the spectrum? This situation would imply an entirely different class of sources which are visible only in the “light” of cosmic rays with energy $\geq 5 \times 10^{19}$ eV. Of course there may be a combination of these possibilities. If even crude data on primary composition is available, it can be divided into catagories of light and heavy components which may have different distributions. Crucial to these considerations is uniform exposure over the whole sky. And a final and perhaps most fundamental question is: Is there an end to the cosmic ray spectrum?

5. Speculations on the nature and origin of the cosmic rays with energy $\geq 10^{20}$ eV.

When the first observation of a cosmic ray with energy $\geq 10^{20}$ eV was made some 36 years ago [19], it was considered a curiosity and attracted very little attention beyond the cosmic ray community. With the more recent results from Haverah Park, Yakutsk, Fly's Eye and particularly AGASA, the existance of these extraordinary cosmic rays cannot be ignored. There is a very rich literature that has emerged in the last few years giving a variety of explanations for these high energy particles. The fact that there is such a variety is the best evidence that we are dealing with a real mystery. We will briefly review the various categories of speculations. We cannot be exhaustive here and will refer the reader to some recent reviews that are more comprehensive.

As in all scientific mysteries it is reasonable to seek the explanation in terms of known astrophysical objects and known laws of physics. As we pointed out in section 2, acceleration by "conventional" means is difficult. The possible mechanisms for acceleration have recently been discussed by Blandford [20]. While he cannot conclude that it is impossible to accelerate cosmic rays to 10^{20} eV, he points out the extreme difficulty to achieve those energies. There is also the question of whether there are a sufficient number of qualifying sources within the distances limited by the GZK effect.

These difficulties have led to speculations that the cosmic rays are produced by direct creation at the highest energy; no acceleration is required. These sources are generally explained in terms of topological defects. These "top down" processes have been extensively discussed in several recent reviews. [21] [22] [23]. The characteristics of topological defect models are the emission of large fluxes of neutrinos and γ-rays along with the protons. The energy spectrum of the γ-rays can be degraded depending on the strength of random magnetic fields between the source and the earth. While most predictions normalize the density of defects to the observed cosmic rays, the relic densities that are required are often difficult to explain as having evolved from the early universe. One of the speculations concerns massive heavy relics which collect about the galactic center [24]. Decays of these particles will produce a spectrum of energies unaffected by the GZK effect since they are galactic in origin and there will be a prenounced enhancement towards the galactic center.

There has been extensive work on the observational consequences of bursting sources, which could be either topological defects or γ-ray bursts [25]. A time delay is expected between the most energetic cosmic ray and lower energies, with the highest energy arriving first. The scale of the time delay depends on the strength of the random magnetic fields and the distance to the source. For B=10^{-9} μ gauss and

30 Mpc distance typical time delays between the most energetic and least energetic cosmic ray in the triplet observed in southern galactic hemisphere is 2×10^5 years. The observed triplets are most likely from a continuous source or a tight cluster of independent sources.

There have been a number of speculations on how to evade the GZK cutoff. These do not address the question of how the enormous energies are produced, but seek to have the cosmic rays transported to the earth from the entire universe. Farrar and Bierman [26)] suggest that distant quasars ($z \sim 1$) produce neutral (SUSY) particles that thread their way undeflected through the CBR. A failure of Lorentz invariance can alter the kinematics of the collisions between the cosmic ray proton and the cosmic background photons so that the pion production is below threshold [27)] [28)]. It has been suggested that cosmologically produced neutrinos collide with nearby relic neutrinos producing Z bosons whose decays are the observed cosmic rays [29)]. This idea requires that at least one of the relic neutrinos have a mass of the order of a few eV. At present measurements of the electron neutrino mass give the unphysical result that the square of the mass is negative. Taking this to be the truth, an explanation of many of the observed facts concerning cosmic rays including evasion of the GZK cutoff has been crafted [30)].

Many of these speculations discussed above seem farfetched and many will be discarded when a much larger sample of data can be collected. To achieve this goal a number of new projects are underway.

6. New detectors for EHECR

The discussion so far makes clear that the EHECR's are a mystery that will require even larger detectors than the present AGASA detector which has an aperture of $\sim$ 125 km^2-sr. The rate of cosmic rays with energy $\geq 5 \times 10^{19}$ eV is about 4 km^{-2}-sr^{-1}-century^{-1} and 1 km^{-2}-sr^{-1}-century^{-1} for energies $\geq 10^{20}$ eV. Thus detectors with very large acceptances are required to gather even modest statistics.

The next improvement in the sensitivity of cosmic ray detectors will be the High Resolution Fly's Eye (HiRes) [31)]. It anticipates a time-averaged aperture of 300 km^2-sr at 10^{19} eV and 1000 km^2-sr at 10^{20} eV. The HiRes experiment is expected to begin operation at the end of 1999.

We will briefly describe a more ambitious approach to the problem, the Pièrre Auger Observatories named after the French physicist who discovered extensive air showers [32)]. In 1938 Auger demonstrated that particles were arriving from outside the earth with energies $\geq 10^{15}$ eV[33)].

The Auger project is a comprehensive experiment designed to study cosmic rays with energy $\geq 10^{19}$ eV with the least possible bias concerning theories of their origin. Since the cosmic rays are likely to point to the sources, a comprehensive study requires that the entire celestial sphere be observed.

Table 1: Events per year

Energy	HiRes	Auger
$\leq 10\ EeV$	~ 500	10000
$\geq 10\ EeV$	387	5150
$\geq 20\ EeV$	170	1590
$\geq 50\ EeV$	63	490
$\geq 100\ EeV$	15	103
$\geq 200\ EeV$	4	32
$\geq 500\ EeV$	1.4	10

Two instruments will be built at mid-latitude sites in the southern and northern hemispheres. Each instrument will observe cosmic rays at zenith angles up to 60°, so that as the earth turns the whole sky is nearly uniformly observed. Each instrument is a hybrid consisting of a surface array to measure the lateral distribution of the shower particles on the ground, and a fluorescence detector to measure the longitudinal development of the shower. The surface array consists of 1600 water tanks (10 m^2 x 1.2 m deep) spread over 3000 km^2. The configuration of the fluorescence detectors is such that when conditions permit their operation (dark, moonless nights) they will register $\geq$ 90% of the showers which trigger the surface array. Approximately 10% of the showers will be observed by both detectors. This subset of events will permit a cross check of the energy and provide the maximum possible information on the composition of the primary. In Table 1 we present the expected number of events for a single site for one year based on the AGASA spectrum [14)]. Far comparison the expected number for HiRes is also presented.

An international collaboration consisting of 19 countries is pooling resources to build two cosmic ray observatories each with an aperture of 7000 km^2-sr for energies $\geq 10^{19}$ eV. The observatories are to be built in Mendoza Province, Argentina (35.2° S, 69.2° W, altitude 1400m) and the state of Utah in the United States (39.1°, 112.6° W, altitude 1400m). Construction has begun at the southern site and is expected to be complete by 2003. Construction is expected to begin in the northern site in 2002.

7. Acknowledgements

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8. References

1) Yoshida, S. and Dai H., 1998, J. Phys. **G 24**, 905; Sokolsky, P., P. Sommers, and B. R. Dawson, 1992 Physics Rep. **217**, 225; *Proceedings of the Paris Workshop on the Highest Energy Cosmic Rays*, 1992, Nucl. Phys. lo(Proc.

Supp.) **B 28**, 213; *Proceedings of the International Symposium on Extremely High Energy Cosmic Rays: Astrophysics and Future Observations*, 1996, ed M. Nagano, (Institute for Cosmic Ray Research, University of Tokyo); Swordy, S., rapporteur talk, 1994, *Proceedings of the 23rd International Cosmic Ray Conference, (Calgary)* 243; Watson, A. A., 1991, Nucl. Phys. (Proc. Supp.) **B 22**, 116; V. S. Berezinskiĭ, S. V. Bulanov, V. A. Dogiel, V. L. Ginzburg (editor) and V. S. Ptuskin, 1990, *Astrophysics of Cosmic Rays*, North Holland, Elsevier Science Publishers, The Netherlands;Bhattachargee, P. and G. Sigl, astro-ph/9811011, submitted to Physics Reports.

2) Lawrence, M. A., et al., 1991, J. Phys. **G 17**, 773.
3) Afanasiev, B. N., et al., 1995, *Proceedings of the 24th International Cosmic Ray Conference (Rome)* **2**, 756.
4) Bird, D. J., et al., 1994, Ap. J. **424**, 491.
5) Yoshida S., et al., 1995, Astroparticle Physics **3**, 105.
6) Yoshida, S. and H. Dai , 1998, J. Phys. **G 24**, 905.
7) Greisen, K., 1965, *Proceedings of the 9th International Cosmic Ray Conference (London)* **2**, 609.
8) Hillas, A. M., 1984, Ann. Rev. Astron. Astrophys. **22**, 425.
9) Biermann, P., 1997, J. Phys. **G 23**, 1.
10) Bhattacharjee, P., C. T. Hill, and D. N. Schramm, 1992, Phys. Rev. Letters **69**, 567.
11) Greisen, K., 1966, Phys. Rev. Letters **16**, 748.
12) Zatsepin, G. T. and V. A. Kuz'min, 1966, JETP Letters **4**, 78.
13) Kronberg, P. P., 1994, Rep. Prog. Phys. **57**, 325; Kronberg, P. P., 1994, Nature **370**, 179; Cole, P., Comments Astrophys. **16**, 1992, 45.
14) Takeda, M., et al., 1998, Phys. Rev. Letters, **81**, 1163.
15) Hayashida, N., et al., 1994, Phys. Rev. Letters, **73**, 3491.
16) Bird, D. J., et al., 1995, Ap. J., **441**, 144; Elbert, J. W. and P. Sommers, 1995, Ap. J., **441**, 151.
17) Watson, A. A., 1997, University of Leeds, private communication.
18) Takeda, M. et al., 1999, astro-ph/9902239, to be published in Astrophys. J.
19) Linsley, J., 1962, Phys. Rev. Letters, **10**, 146
20) Blandford, R., *Acceleration of Ultra High Energy Cosmic Rays* 1998, paper presented at Nobel Symposium, August 1998, Stockholm, Sweden.
21) Berezinsky, V., P. Blasi, and A. Vilenkin, 1998, astro-ph/9803271.
22) Bhattachargee, P., and G. Sigl, 1998, astro-ph/9811011.
23) Hillas M., 1998, Nature, **395**, 15.
24) Berezinsky, V., 1997, Phys. Rev. Letters, **79**, 4302.
25) Waxman, E., and J. Miralda-Escudé, 1996, Astrophys. J. **473** L89; Lemoine, M., et al., 1997, Astrophys. J., **486**, L115.
26) Farrar, G. R. and P. L. Bierman, 1998, Phys. Rev. Letters, **81**, 3579.

27) Glashow, S. L. and S. Coleman, 1997, Phys. Letters, **B405**, 249; hep-ph/9703240.

28) Gonzalez-Mestres, L., 1997, in *Proceedings of Workshop on Observing Giant Cosmic Airshowers from* $\geq 10^{20}$ *eV Particles from Space: AIP conf. proc. 433* ed J. Krizmanic, et al., p 148.

29) Weiler T., 1997, astro-ph/9807324.

30) Ehrlich, R., 1998, astro-ph/9807324.

31) Abu-Zayyad, T., et al., 1997, in *Proceedings of the 25th International Cosmic Ray Conference*, Durban, edited by M. S. Potgeiter, B. C. Raubenheimer, and D. J. van der Walt (World Scientific, Singapore), Vol 5, p321; this paper and the eleven that immediately follow describe various aspects of the HiRes detector.

32) Pièrre Auger Design Report, 2nd ed. March 1997, Fermilab; Design Report and more than 200 technical notes available at Auger web site, www.auger.org.

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