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Survey of the Pierre Auger Observatory

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Abstract. The question of the origin and nature of cosmic ray particles with energies exceeding the predicted GZK spectral cutoff is one of the present great challenges of astroparticle physics. The Pierre Auger Observatory (PAO), currently under construction in Province of Mendoza, Argentina, is a broadly based international effort to explore the upper-end of the cosmic ray energy spectrum. The PAO is the first experiment designed to work in a hybrid detection mode. The combination of two complementary detection techniques -water Cerenkov tank arrays overlooked by atmospheric fluorescence detectors- to observe extensive air showers guarantees high-quality and statistically significant data. An updated overview of the science prospects for the PAO is presented. The concept of the experiment as well as the current status is described.

1 Physics motivation for the Pierre Auger Observatory

The puzzle set by the existence of cosmic rays with energies above 10^{20}eV (Lawrence et al., 1991; Hayashida et al., 1994; Bird et al., 1995; Abu-Zayyad et al, 1999), which may be an indication of new physics or exotic particles, is at present one of the hot topics in high energy astroparticle physics. The underlying problem in trying to explain the origin of these extremely high energy cosmic rays (EHECR) is the well-known GZK (Greisen-Zatsepin-Kuzmin) effect: if the cosmic rays are extragalactic in origin, then a sharp cutoff at around several times 10^{19}eV in the observed spectrum is expected due to energy degradation of the cosmic ray particles through interaction with photons of the microwave background radiation (Greisen, 1965; Zatsepin and Kuzmin, 1966). This process limits the distance of the sources of particles with energies above 10^{20}eV to less than 100 Mpc from the Earth (Aharonian and Cronin, 1994; Puget et al., 1976; Stecker and Salomon, 1999; Berezinsky, 1970; Protheroe and Biermann, 1996). Since the energy loss mechanism depends on

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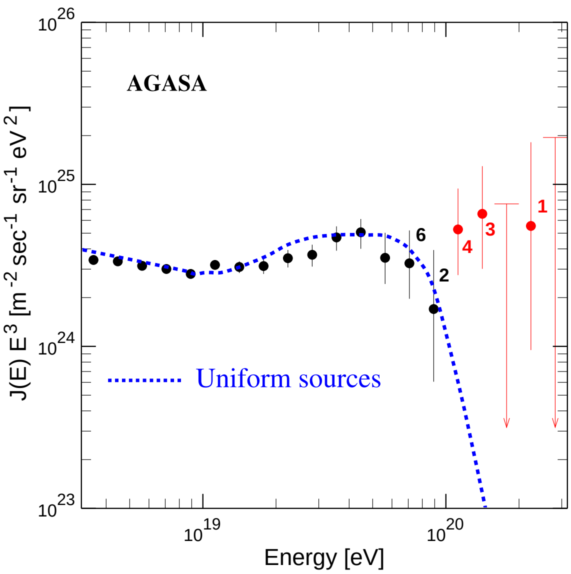

Fig. 1. Cosmic ray flux spectrum from AGASA experiment shown with the shape of the universal hypothesis spectrum (Hayashida et al., 1999)

the particle energy, the emitted spectrum will change during the propagation. Many different calculations have been performed using various techniques to study the modification of the cosmic ray spectrum (Hill and Schramm, 1985; Berezinsky and Grigoreva, 1988; Anchordoqui et al., 1997; Stanev et al, 2000; Yoshida and Teshima, 1993) and the general features are now well established.

Fig. 2 shows the updated AGASA measurement of the last end of the energy spectrum (Hayashida et al., 1999) together with the expected spectrum taking into account the detector resolution (Yoshida and Teshima, 1993), assuming the universal hypothesis (cosmological uniform distribution of sources) where the GZK cutoff is evident. However, a significant number of events is measured well beyond the

GZK energy. Observations seem to indicate that there are not enough nearby sources to provide the observed fluxes above the predicted GZK cutoff. Moreover, the distribution of matter within 100 Mpc is not uniformly distributed over the sky in contrast with the isotropic distribution of ultra high energy cosmic rays.

The information about the extragalactic magnetic fields is only known by Faraday rotation of radio signals from distant radio galaxies, providing limits at the level of about 10^{-9}G. A proton of 10^{20}eV would be deflected in such fields about 3° from a straight line over 30 Mpc. Thus, EHECR arrival directions should point back to their sources in the sky giving the possibility to do particle astronomy. Recently, the AGASA experiment has presented an analysis of events above 4×10^{19}eV (Hayashida et al., 1999; Uchihori, et al., 2000) suggesting indication of clustering on an angular scale of 2.5°. It is evident that the present statistics are not enough to make definitive conclusions concerning the observation of clusters, large scale anisotropies in the sky and point sources. Furthermore, in many senses the interpretation of data is affected by lack of knowledge of the mass composition of the primary particle. It has been emphasized the need to know the primary mass to do particle astronomy, even at the highest energies (Stanev, 1997; Harari et al., 1999).

The observation of the EHECR has motivated many studies concerning the origin and nature of particles with extremely high energy. A complete discussion of different proposed models can be found in recent reviews and references therein (Bhattacharjee and Sigl, 2000; Olinto, 2000; Weiler, 2001). In the following the observational signatures of the most popular theoretical explanations for generation of EHECR are presented.

Conventional acceleration scenarios: These models assume acceleration of ultra high energy cosmic rays in rapidly evolving processes in known astrophysical objects. i) Galactic models require heavy composition for the ultra high energy cosmic ray particles. The arrival direction may be quite isotropic. ii) Extragalactic models consider powerful objects (AGNs) as the most likely astrophysical accelerators. Strong constraints come from the spectrum they generate. As mentioned above, if sources are homogeneously distributed at cosmological distances the spectrum should end with a sharp cutoff; this effect is less pronounced for nearby sources. In the case of the origin in distant sources, only neutrinos can propagate without to Earth loosing energy. Detection of neutrinos is based on the observation of large zenith angle showers (Letessier-Selvon, 2001). There are also theories considering strongly interacting neutrinos (Nussinov and Shrock, 1999; Domokos and Kovesi-Domokos, 1999; Anchordoqui et al., 2000). The signatures of this scenario can be probed through detailed studies of shower development, leading also to constraints on the predicted neutrino nucleon cross section. An alternative possibility is the production of Z-burst from the interaction of ultra high energy neutrinos with relic massive neutrino background, the Z decay products being the source of the incident cosmic rays (Weiler, 1982). Events above the GZK cutoff could then be explained and a limit on the neutrino mass could be set.

Non-Acceleration scenarios: In these models, production mechanisms are based on speculative decaying super-massive X particles ($m_X \gg 10^{20}$eV). The sources of these X particles could be topological defects leftover from the GUT symmetry breaking phase transition in the early Universe (Hill et al., 1987). Another interesting possibility is that the X particles are superheavy metaestable relic particles (SMR) with lifetime of the order of the age of the Universe (Berezinsky et al., 1997). SMR may be produced at the end of inflationary stage of the Universe by non-thermal effects. The X particles are supposed to decay into quarks which hadronize forming jets of hadrons. The spectra of the produced particles are, therefore, essentially determined by the process of fragmentation of quarks/gluons into hadron as describe by QCD. An important point is that unlike the spectrum predicted in acceleration theories, the spectrum in non-acceleration models are not a power-law in energy. However, it can be approximated in some cases by power law segments in the high energy region, yielding to a very flat ($E^{-3/2}$) spectra. A general characteristic of top-down models is that alongside protons, many photons and neutrinos are also produced which give extra signatures to these processes. SMR could cluster as dark matter in the galactic halo, hence EHECR are expected to be produced locally and the observed spectra should be dominated by gamma rays. In addition, the arrival direction distribution should be close to isotropic but show a slight anisotropy due to the asymmetric position of the Earth in the galactic halo.

For all of these signatures to be tested it is crucial an experiment able to provide high quality and statistically significant data at the upper-end of the cosmic ray spectrum with good energy and angular resolution, high sensitivity to composition and uniform exposure over the whole sky.

2 The concept of the PAO: A hybrid detector

The Pierre Auger Observatory (PAO)(Pierre Auger Observatory Design Report, 1997) is a broadly based international effort whose primary goal is to explore the high energy region of the cosmic ray spectrum. The PAO plans to measure energy, arrival direction and primary species with unprecedented statistical precision. The completed experiment will consist of two Observatories, in the Northern and Southern hemispheres. An engineering array 1/40th-scale, expected to be completed by the end of 2001, is under construction in Mendoza Province, Argentina. This site is especially interesting since it will make possible to explore the part of the sky not explored yet, with a preferential view to the Galactic Center, potential sources or matter distributions and Galactic and extragalactic fields not available from the North. The plan is to complete the Southern Observatory by the end of 2004.

The PAO has been designed to work in a hybrid detection mode. A giant array of particle detectors will measure the lateral and temporal distribution of shower particles at ground

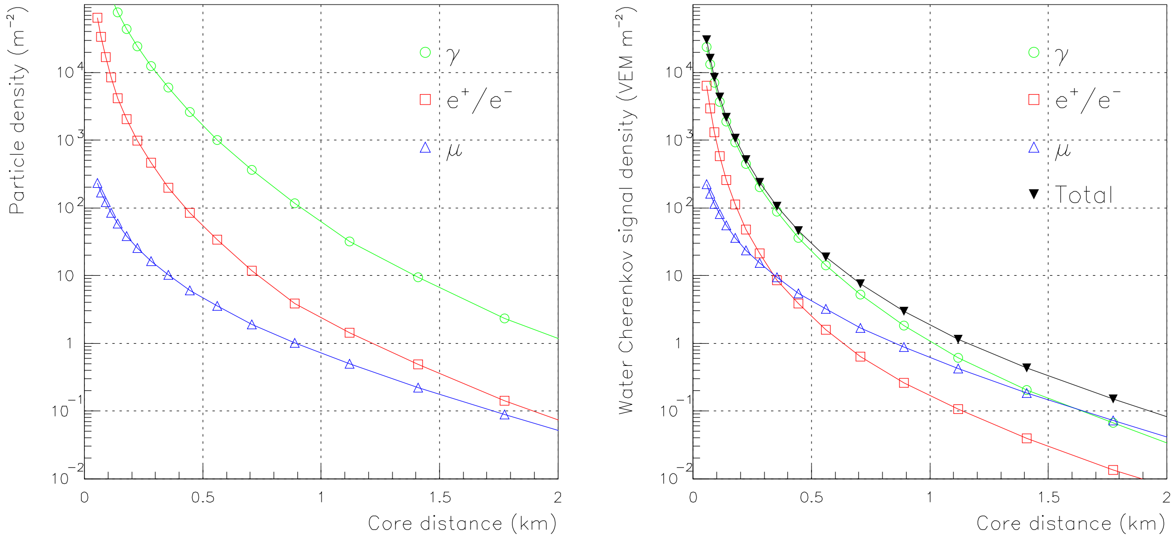

Fig. 2. Particle density distributions as a function of the distance from the core (from the Auger Project Design Report)

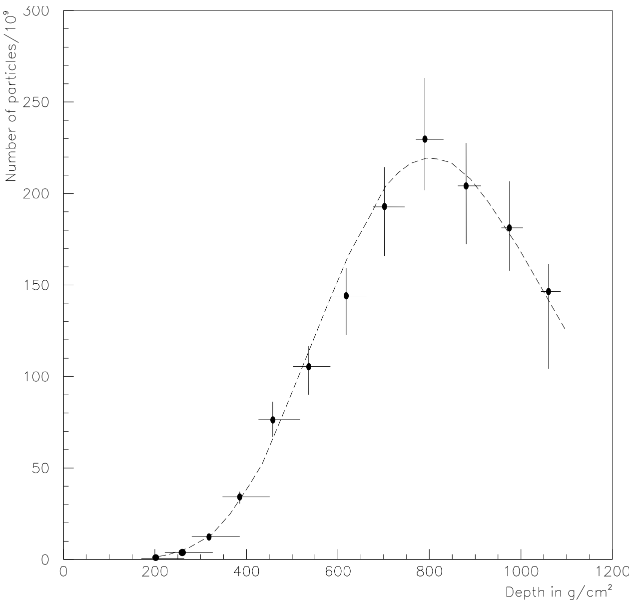

Fig. 3. Reconstructed shower longitudinal profile for the highest energy Fly's Eye event (Bird et al., 1995)

level. Air fluorescence detectors (FD) will measure the longitudinal development of the shower in the atmosphere above the surface array (SA). The combination of both techniques to measure simultaneously the shower parameters of a subset of showers will allow high precision energy and arrival direction determination as well as extremely good separation of heavy nuclei, protons, gammas and neutrinos.

The size of the Observatory is chosen in order to collect high statistics above the expected GZK cutoff, with 1600 particle detectors covering an area of 3000 km^2. Surface array stations are water Cherenkov detectors (a cylindrical tank of 10 m^2 top surface and 1.2 m height, filled with filtered water and lined with a highly reflective material, the Cherenkov light is detected by three PMTs installed on the top), spaced 1.5 km from each other in an hexagonal grid. These stations will operate on battery-backed solar power and will communicate with a central station by using wireless LAN radio links. Event timing will be provided through GPS receivers. The Observatory is completed with fluorescence detectors: three eyes (6 telescopes) will be installed at the periphery of the array and one at the center (12 telescopes). A telescope is a set of phototubes (440) mounted on a camera set at the focal plane of a mirror of 3.4 m radius of curvature. The field of view is about $30 \times 30\,°$.

The decision to use the hybrid technique is based on the following considerations: *i) Intercalibration*: Primary energy estimate using ground arrays is performed by fitting the observed particle densities to a lateral distribution function and then using the particle density at a certain distance from the core as the energy indicator. See ref. (Nagano and Watson, 2000) for experimental details. Fig 2 shows simulated lateral distribution functions of gammas, electrons and muons at ground level for a 10^{19}eV proton shower, as well as the corresponding distributions convoluted with the response of a typical PAO ground detector. When using the ground array detection technique alone, the conversion factor from density to primary energy is evaluated from Monte Carlo simulations which depend, although only weakly, on the interaction model and the mass composition (Hillas, 1970). On the other hand, fluorescence technique provides the most effective way to measure the energy of the primary particle. The amount of fluorescence light emitted is proportional to the number of charged particles in the showers allowing a direct measurement of the longitudinal development of the EAS in the atmosphere. Fig. 3 shows the reconstructed longitudinal development for the Fly's Eye 3 ×

10^{20}eV event. From this profile the position of the shower maximum X_{max} can be obtained. The energy in the electromagnetic component is calculated by integrating the measured shower profile. A further correction taking into account the amount of unmeasured energy has to be done. In the hybrid Pierre Auger Observatory, approximately 10 % of the showers will be observed by both surface and fluorescence detectors allowing intercalibration, independent of Monte Carlo results, and the control of unwanted systematics in the primary energy determination. *ii) Enhance composition sensitivity*: As mentioned above, FD can measure the depth of shower maximum X_{max} directly from the longitudinal development. The rate of change of X_{max} with energy (the elongation rate) is used to estimate the composition (Linsley, 1977), although the interpretation of this variation depends on the high energy hadronic interaction model used (Anchordoqui et al., 1999; Hinton et al., 1999). The ground array can measure the lateral distribution of the signal, the risetime, and the curvature and 'thickness' of the shower front. These shower quantities correlate with the primary mass. The hybrid data set collected by the PAO will provide a distribution function in a multidimensional parameter space consisting of all the quantities sensitive to the mass composition. In this way it will possible to constrain the choice of high energy hadronic interaction models and hence determine the primary species. *iii) Uniform exposure*: Patterns of cosmic rays arrival directions, whether isotropic or not provide the most compelling evidence for their sources. Surface arrays in both hemispheres, operating 24 hours per day year round, provide data with nearly uniform celestial exposure. This enables a straightforward search for excess from discrete sources and also a sensitive large scale anisotropy analysis. *iv)* The PAO hybrid configuration is the most economical and robust way to obtain the necessary data, including a subset with specially high reconstruction resolution and independent cross checks.

In the hybrid mode, the Pierre Auger Observatory is expected to have 10 % energy resolution and angular precision of 0.5° for energies above 10^{20}eV. For the surface array alone those numbers became 12% and 0.6°. Each observatory will have an aperture of 7400 km^{2}sr. Althought the fluxes may not be the same at the Pampa Amarilla Southern Observatory (Argentina), as the corresponding one measured from the Northern hemisphere, the expected number of events at zenith angle less than $60°$ should be $\sim$ 5100 events above 10^{19}eV and $\sim$ 60 events above 10^{20}eV per year.

In closing, the existence of the extraordinarily energetic cosmic ray particles is a puzzle, the solution of which must lead to discoveries in astrophysics and particle physics. The hybrid Pierre Auger Observatory will provide the improved observations needed to solve the ultra high energy cosmic rays mystery, allowing also the most stringent tests of extremely high energy physics.

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References

Abu-Zayyad, T. et al, (HiRes Coll.) 26th ICRC, Salt Lake City, ed. D.Kieda, M.Salamon and B. Dingus, Vol.3, p. 264

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

Anchordoqui,L.A., Dova, M.T.,Epele L.N. and Swain, J. Phys. Rev.D55, 7356, 1997

Anchordoqui,L.A., Dova, M.T.,Epele L.N. and Sciutto, S.J. Phys. Rev.D59, 094003, 1999

Anchordoqui,L., Goldberg, H., McCauley,T., Paul,P. Reucroft, S., Swain, J., Phys.Rev.D63:124009,2001

Berezinsky,V.S, Yad.Fiz 11, 339, 1970.

Berezinsky,V.S and Grigoreva, S.I., Astron. Astrophys.199,1, 1988

Berezinsky,V.S., Kachelriess,M. and Vilenkin, M., Phys.Rev.Lett. 79, 4302, 1997.

Bhattacharjee, P. and Sigl, G., Phys. Rep. 327, 109, 2000.

Bird, D.J. et al , Astrophys. J. 441, 144, 1995

Domokos, G., and Kovesi-Domokos,S., Phys. Rev Lett. 82, 1366, 1999.

Greisen, K, Phys. Rev. Lett. 16, 748, 1965,

Harari,D., Mollerach, S. and Roulet,E. JHEP, 08022, 1999

Hayashida, N.et al, Phys. Rev. Lett. 74, 3491, 1994

Hill,C.T and Schramm,D.N., Phys. Rev. D31, 5648, 1985

Hill,C.T, Schramm, D.N. and Walker,T.P. Phys. Rev D36,1007, 1987

Hillas,M., Acta Phys. Acad. Sci.Hunh 29 Supp. 3, 355, 1970.

Hinton, J.A., Proceeding of 26th ICRC. Salt Lake City, Vol. 3, p. 288, 1999.

Lawrence, M.A., Reid, R.J.O., Watson, A.A. J.Phys G17, 733, 1991

Letessier-Selvon, A., this proceeding.

Linsley,J., Proceeding of 15th ICRC. Plovdiv, Vol. 12, p. 89, 1977.

Nagano,M. and Watson,A.A., Rev.Mod.Phys, 72, 689, 2000.

Nussinov, S. and Shrock, R., Phys. Rev. D59, 105002, 1999

Olinto, A.V., Phys. Rep.,333-334,329, 2000.

Pierre Auger Project Design Report, 1997, Auger Coll., Fermi National Accelerator Laboratory. (www.auger.org/admin)

Protheroe, R.J. and Biermann, P.L., Astropart. Phys.6, 45, 1996;erratum ibid.7 ,181, 1997.

Puget, J.L., F.W.Stecker, and Bredekamp, J.H., Astrophys.J 205, 638, 1976

Stanev, T., Astrophys. J, 479, 290, 1997

Stanev,T., Engel,R., Mucke,A., Protheroe R., and Rachen,J.P.,] Phys. Rev. D62, 093005, 2000.

Stecker, F.W and Salomon, Astrophys.J 512, 521, 1999.

Hayashida, N. et al. Astrophys. J.522, 225, 1999

Uchihori,Y. et al, Astropart.Phys., 13, 151, 2000.

Weiler,T.J., hep-ph/0103023

Weiler,T.J., Phys.Rev. Lett. 49, 234, 1982.

Yoshida,Y and Teshima,M., Prog.Theor.Phys., 89, 833, 1993.

Zatsepin, G.T. and Kuzmin,V.A, JETP Lett.4, 78, 1966