FUTURE DIRECTIONS IN ASTROPARTICLE PHYSICS AND THE AUGER EXPERIMENT

MARIA TERESA DOVA
Universidad Nacional de La Plata, C.C. 67, 1900 La Plata, Argentina
E-mail: dova@fisica.unlp.edu.ar

The observation of cosmic ray particles with unexpected high energies is pushing astroparticle physics into a period of rapid progress both theoretically and experimentally. Different proposed models for the generation of these particles are constrained by the absence of the predicted GZK cutoff in the cosmic ray spectrum and by the composition and the distribution of arrival directions observed. The database increase due to the Pierre Auger Observatory will provide a clearer picture of the spectral anisotropy and properties of such high energy particles, enabling tests of their origin and nature.

1 The highest energy cosmic rays: Experimental results

Since the observation of cosmic rays with energies above $10^{20}eV$ [1], a considerable amount of studies have been performed in order to understand their origin and nature. The puzzle set by the existence of these ultrahigh energy cosmic rays (UHECR), which may be evidence of new physics or exotic particles, is nowadays one of the central subjects in high energy astroparticle physics.

The energy spectrum of cosmic rays arriving to Earth extends from $10^{9}eV$ to $10^{20}eV$ almost continuosly over ten decades with small changes in slope in a power law energy spectrum: "the knee" appears around $10^{15.5}eV$, the second "knee" at $10^{17.8}eV$ and the "ankle"at $10^{19}eV$. Above $10^{15}eV$ all the measurements are indirect, the high energy particle enters in the atmosphere and interacts with the air molecules initiating a cascade of particles which can be detected by a surface array of detectors spread over a large area or with large aperture optical telescopes since during the development of the extensive air showers (EAS), the charged secondaries excite the nitrogen molecules with a subsequent emition of fluorescence light.

Fig. 1 (left) shows the upper end of the cosmic ray spectrum where the differential flux is multiplied by an energy dependent power E^3. The compilation is from ref.[2], with data from four experiments: surface arrays (Haverah Park, Yakutsk, AGASA) and a fluorescence detector (Fly's Eye).

The arrival directions of the events with energies above $10^{19}eV$ is completely consistent with an isotropic distribution with the exception of a few small scale anisotropies in the form of multiplets of events within the exper-

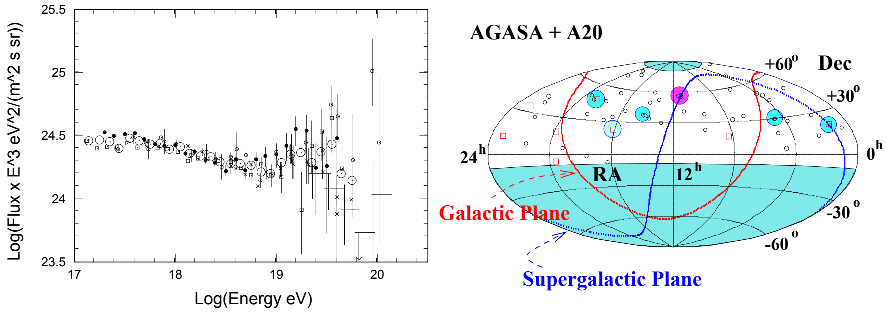

Figure 1. Left:all particle spectrum of cosmic rays for energies exceeding 100 PeV. Right: Arrival directions of UHECR above 10^{19} eV recorded by the AGASA experiment.

imental angular resolution [3,4]. Fig.1 (right) shows the arrival directions of cosmic rays collected by the AGASA experiment [3] above $4 \times 10^{19} eV$ where four doublets and a triplet is observed. Shaded in grey is the area invisible to the AGASA detector. It is remarkable that none of those clusters is on the Galactic plane suggesting that UHECR are most likely extragalactic in origin.

A crucial point in the search for the origin of UHECR is to locate their sources. The question is to which extent it is possible to do astronomy with the UHECR detected. Search for correlations of the observed multiplets with the location of candidate sources or with distribution of astrophysical objects in our neighborhood have been made with negative results. Besides, when doing this analysis it is very important to take into account the effect of the galactic and extragalactic magnetic fields [5] . Magnetic deflections can produce additional effects: galactic magnetic fields might act as giant lens magnifying the CR flux coming from a single source, or even producing multiple images of a source.

Another ingredient to consider in the search for the origin of these very energetic particles is the chemical composition of the UHECR detected. Experimentally, the composition can be determined, at least in a statistical manner, from air shower observables as the muon content of the shower at ground level and the position of the shower maximum (X_{max}) measured by fluorescence detectors. At the highest energies, the composition of the primaries seems to be consistent with nucleons, however the interpretation of data depends to some extent on the physics of the cascade included in the event generators used. Fig.2 shows simulated results for the average slant depth of maximum plotted vs. the logarithm of the primary energy for proton and iron

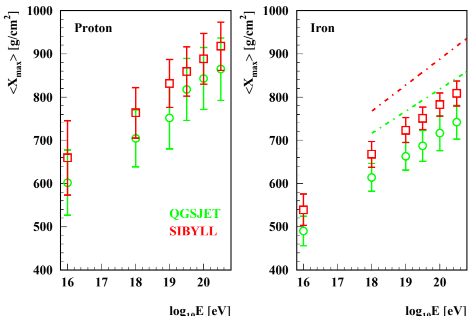

Figure 2. Average slant depth of maximum from simulated data. The error bars indicate the standard fluctiations.

induced showers using two well-known hadronic interaction models (SIBYLL and QGSJET) [6]. It is evident that SIBYLL showers present higher values for the depth of maximum, the differences increasing with rising energy. At high energies the primary chemical composition remains hidden by the hadronic interaction model.

2 Production and propagation of UHECR

The existence of UHECR has motivated many detailed studies concerning the generation of particles with extremely high energy as well as their propagation in route to Earth. A complete discussion of most of the models for the production of UHECRs can be found in some recent reviews and references therein [7,8]. Production mechanisms have been commonly classified into two groups: a) botton-up models, which consider conventional acceleration of UHECR in rapidily evolving processes in known astrophysical objects [9,10,11]. Examples are AGN radio lobes where particles can be accelerated via the first-order Fermi mechanism in the so-called hot spots, regions near neutron starts satisfying conditions to accelerate particles via direct electromagnetic acceleration; and b) top-down models suggesting that particles are not accelerated but rather they are stable decay products of supermassive particles[7]. Source of these exotic particles could be topological defects (TD) relics from early universe phase transitions associated with spontaneous symmetry breaking underlying unified models of high energy interactions. TD may survive to the present and decompose into their constituent fields. The supermassive particles (masses $\approx 10^{24} eV$) are supposed to decay into quarks which hadronize

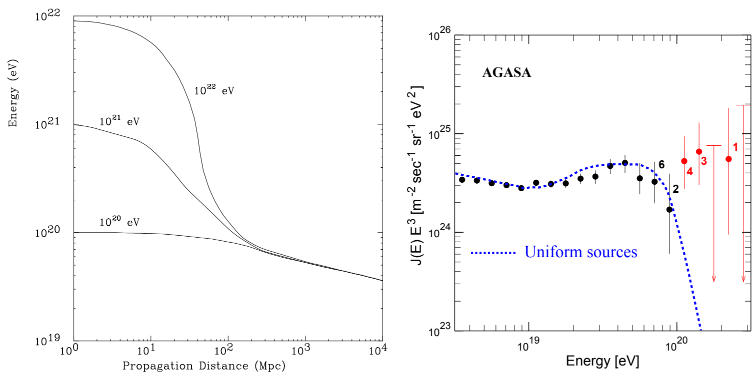

Figure 3. Left: Proton mean energy vs. propagation distance. Right: Cosmic ray flux spectrum from AGASA experiment shown with the shape of the universila hyphotesis spectrum.

forming jets of hadrons. A general characteristic of top-down models is that, alongside protons, many photons and neutrinos are also produced given an extra signature to these processes. Recently, an analysis of inclined showers recorded by Haverah Park has been published with a new method used to set a limit to the photon and iron content of the UHECR [12], setting important constraints to top-down models. Additional data, measurement of anisotropy (predicted by supermassive particles clustered as dark matter in the galactic halo [13]) and determination of composition is crucial to help solving the question of the origin of the UHECR.

There is another important issue to be considered in the search for the origin of UHECR: the opacity of the microwave background radiation to the propagation of UHECR. The first treatments [14] indicated a sharp cutoff for cosmic rays with energies above $5 \times 10^{19} eV$ due to the process $\gamma + p \rightarrow \Delta \rightarrow p/n\pi$: the GZK cutoff. A similar phenomenon of energy degradation occurs for nuclei due to process of photodisintegration which is very important in the region of giant resonances. In Figure 3(left), the energy degradation of protons in terms of their flight distance is shown[15]. It can be seen that independently of the initial energy of the nucleon, the mean energy approach to 100 EeV after a distance of $\approx$ 100 Mpc. Since the energy loss mechanism depends on the nucleon 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 [16] and the general features are now well stablished. Fig. 3 (right) shows the up-

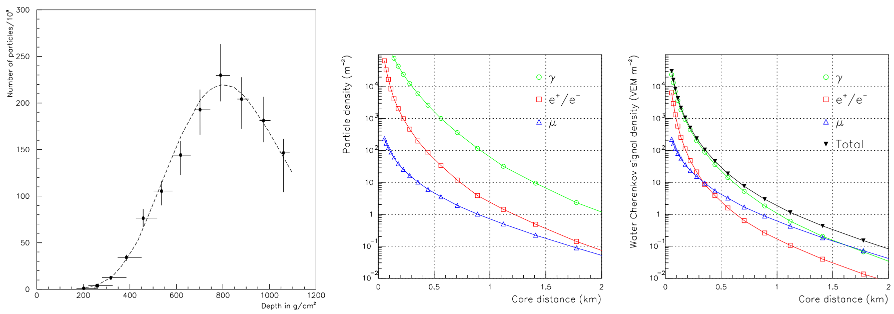

Figure 4. Left: Right: Reconstructed shower longitudinal profile for the highest energy Fly's Eye event. Left: Particle density distributions as a function of the distance from the core.

dated AGASA measurement of the last end of the energy spectrum [3] together with the expected spectrum assuming the universal hypothesis (cosmological uniform distribution of sources) where the GZK cutoff is evident. Moreover significant number of events are observed well beyond the GZK energy. It should be mentioned that the galaxies found to be in the arrival directions of the multiplets are more than 70 Mpc, too far away to be responsible for the UHECR violating the GZK mechanisms.

3 Pierre Auger Observatory: a hybrid detector

The PAO has been designed to work in a hybrid detection mode: particle showers are simultaneously observed by a ground array and fluorescence detectors [17]. The PAO is planned to measure the energy, arrival direction and primary species with unprecedente statistical precision. The observatory will be covering two sites in the Northern and Southern hemispheres. An engineering array 1/40th-scale, expected to be completed mid 2001, is under construction in Mendoza Province, Argentina. This site is specially interesting since from this part of the world, the centre of the Galaxy is visible.

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 overviewed by four fluorescence detectors. Surface array stations are water Cherenkov detectors (a cilindrical 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 will be installed at the periphery of the array and one at the centre. It is crucial that the whole array is visible by at least one of the optical detector stations.

The fluorescence technique is 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. 4 (left) shows the reconstructed longitudinal development for the Fly's Eye $3 \times 10^{20} eV$ 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. PAO optical components will measure the EAS longitudinal profile in a similar manner. The primary energy can be determine by ground arrays fitting a lateral distribution function (l.d.f), which depends on the experimental conditions, to the observed particles densities. Fig 4 (right) shows simulated l.d.f. of γ, electrons and muons at ground level for a $10^{19} eV$ proton shower, as well as the corresponding distributions convolved with the response of a typical PAO water Cherenkov detector. The particle density at a certain distance from the shower core is commonly used as an energy estimator where the conversion factor is evaluated from simulations. See ref. [18] for experimental details.

Approximately 10% of the showers detected by PAO will be observed by both surface and fluorescence detectors allowing control of unwanted systematics in the primary energy determination. The energy resolution in the hybrid mode will be $\approx 10\%$ and the angular resolution of about 0.3^0. The hybrid data set will also provide a distribution function in the multidimensional parameter space consisting of the quantities sensitive to the mass composition making possible to constrain the choice of high energy hadronic interaction models.

Acknowledgments

I would like to thank the organizers for the kind invitation as well as for the financial support and the hospitality extended to me at this conference. A special word of thanks to Jim Cronin who made possible my participation in the conference. I also would like to thank A. Etchegoyen for a careful reading of the manuscript.

References

1. M.A.Lawrence, R.J.O. Reid, A.A. Watson *J.Phys G* **17**, 733 (1991), N. Hayashida *et al*, *Phys. Rev. Lett.* **74**, 3491 (1994), D.J.Bird, *et al*, *Astrophys. J.* **441**, 144 (1995), T. Abu-Zayyad *et al*, (HiRes Coll.) 26th ICRC, Salt Lake City, ed. D.Kieda, M.Salamon and B. Dingus, Vol.3, p. 264
2. X. Bertou, M. Boratav, A. Letessier-Selvon, *Int.J.Mod.Phys* **A15**, 2181 (2000)
3. M.Takeda *et al*, *Astrophys. J.* **522**, 225 (1999).
4. Y. Uchihori *et al*, *Astropart.Phys.* **13**, 151 (2000).
5. T.Stanev, *Astrophys. J.* **479**, 290 (1997), D.Harari, S.Mollerach and E. Roulet, *JHEP* **08**, 022 (1999), G.A. Medina Tanco,*Astrophys. J. Lett.* **L71**, 495 (1998).
6. L.A. Anchordoqui, M.T.Dova and S. Sciutto, 26th ICRC, Salt Lake City, ed. D.Kieda, M.Salamon and B. Dingus, Vol.1, p. 147. L.A.Anchordoqui, M.T.Dova, L.Epele and S. Sciutto, *Phys. Rev.* D **59**, 094003 (1999), see also, D. Heck in this Proceeding.
7. P. Bhattacharjee and G. Sigl, *Phys. Rep.* **327**, (2000)
8. A.V.Olinto, *Phys. Rep.* **333-334**, 329 (2000)
9. M.Hillas, *Ann.Rev.Astron.Astrophys.* **22**, 425 (1984), P.L.Biermann *J.Phys.G:Nucl.Part.Phys* **23**, 1 (1997).
10. R.D.Blanford, *Phys.Scripta* **T85**, 191 (2000).
11. J.P.Rachen and P.L.Biermann, *Astron. Astrophys* **272**, 161 (1993).
12. M. Ave, J.A. Hinton, R.A. Vazquez, A.A. Watson, E. Zas, *Phys. Rev. Lett.* **85**, 2244 (2000).
13. V. Berezinsky, *Nucl.Phys.Proc.Suppl.* **81**, 311 (2000).
14. K.Greisen, *Phys. Rev. Lett.* **16**, 748 (1965), G.T.Zatsepin and V.A.Kuzmin, *JETP Lett.* **4**, 78 (1966)
15. F.A.Aharonian and J.W. Cronin, *Phys. Rev.* D **50**, 1892 (1994).
16. C.T Hill and D.N. Schramm, *Phys. Rev.* D **31**, 5648 (1985), V.S.Berezinsky and S.I.Grigoreva, *Astron. Astrophys.* **199**, 1 (1988), S.Yoshida and M.Teshima, *Prog.Theor.Phys.* **89**, 833 (1993), L.A.Anchordoqui, M.T.Dova, L.N.Epele and J. Swain, *Phys. Rev.* D **55**, 7356 (1997), L.A.Anchordoqui, M.T.Dova, L.N.Epele and J. Swain, *Phys. Rev.* D **57**, 7103 (1998), T.Stanev, R.Engel, A.Mucke, R.Protheroe and J.P.Rachen, *Phys. Rev.* D **62**, 093005 (2000).
17. Pierre Auger Project Design Report, 1997, Auger Coll., Fermi National Accelerator Laboratory. (www.auger.org/admin)
18. M. Nagano and A.A. Watson, *Rev.Mod.Phys* **72**, 689 (2000).