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PROGRESS IN ULTRA HIGH ENERGY COSMIC RAY STUDIES*

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This is a review of the experimental data concerning the energy spectrum, the arrival distribution and the composition of cosmic rays with energies $\geq 10^{17}$ eV. We discuss conditions for production of cosmic rays and expected effects for observation. Main recent results issued by observation of cosmic ray at high and very high energy will also be presented.

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1. Introduction

After almost 90 years of research, origin of cosmic rays (CRs) is still an open question with an uncertainty increasing with energy. The energy spectrum of the CRs extends from a few hundreds MeV to above 10^{20} eV and can be approximated by a power law $dN/dE \propto E^{-\gamma}(\gamma \simeq 3)$. Up to energies to a few 10^{14} eV, the particle flux is sufficiently high to allow direct observations of the CRs using high flying balloon or satellite experiments (see Fig. 1). Above this energy, the flux drops to only one particle per square meter per year. By using large ground experiments, it is possible to indirectly observe the CRs with the detection of the shower of secondary charged particles due to interaction between CRs and earth's atmosphere. Even if spectrum of the CRs is mostly described by a regular power law, we can notice some structure with four features. At the energies of 5×10^{15} eV and 3×10^{17} eV, the spectrum bends; these 2 features are called "the first and the second knees". Because of the intensity of the galactic magnetic field, the CRs below 10^{18} eV should come from the Galaxy and "the first and the second knees" are often interpreted as the end of the galactic component of CRs. At the energy of 3×10^{18} eV, the spectrum flattens with a third break called "the ankle". The ankle is often interpreted as

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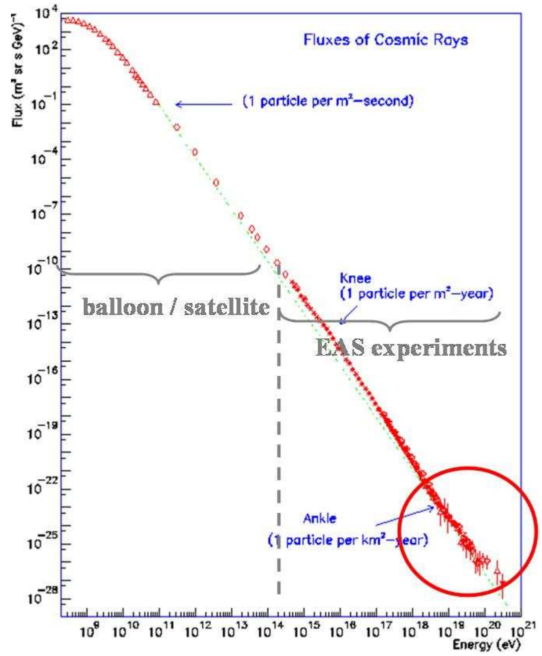

Fig. 1. Flux of cosmic ray as a function of energy.

the beginning of the extragalactic component of CRs. Above the ankle, we expected to observe a cutoff, called the Greisen–Zatsepin–Kuzmin (GZK) effect, which correspond to an energy loss due to an interaction between CRs with an energy above 8×10^{19} eV and the cosmic microwave background. The previous observations from AGASA and HiRes experiments (see Section 3) reveal a disagreement concerning this last feature (see Section 4). Different models and theories of production of CRs are also proposed and should be confirmed using the observations (see next section).

2. Origin of cosmic rays

Usually, two main processes are considered to explain the production of ultra high energy CRs ($E \simeq 10^{19-20}$ eV).

The "Top–Down" models introduce a new unstable supermassive X-particle. The source of the X-particle could be topological defect like magnetic monopoles or cosmic strings that could be produced in the early universe. Its decay produces photons, neutrinos and protons.

In the second ("bottom–up") process, charged particles are accelerated by an astronomical object. The acceleration process is believed to be a diffusive shock acceleration. The maximum energy that a charged particle can reach is related to a magnetic field of source and the size of shock region. Above 10^{20} eV, only few astrophysical objects are able to accelerate the particle. Typically, active galactic nuclei, gamma ray bursts, and neutron stars are considered as possible candidates.

Magnetic fields and especially galactic magnetic field cause a deviation of trajectory of charged CRs depending on the energy of particle. Correlations between arrival direction of CRs and position of sources are only possible at ultra high energy (typically above 10^{19} eV). On the other hand, for nuclei with energy above 10^{20} eV, the interaction of particles with cosmic microwave background causes a significant loss of energy. This GZK effect limits the distance of the production source to less than 100 Mpc (see Fig. 2).

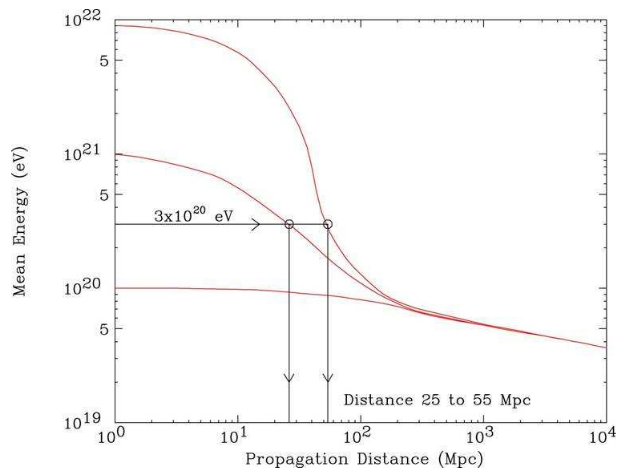

Fig. 2. Mean energy of protons as a function of propagation distance through the cosmic microwave background.

3. Extensive air shower experiments

In the last (and future) decade different experiments were launched to detect CRs with energies above "knee". We present a brief description of these experiments based on the indirect detection of CRs using extensive air shower (EAS) produced by interaction between earth's atmosphere and the CRs.

3.1. KASCADE-Grande experiment

The KASCADE-Grande experiment, located near Karlsruhe in Germany, studies cosmic radiation in the energy range $10^{14} - 10^{18}$ eV. The sensitive detection area of KASCADE-Grande is 0.5 km^2. This experiment consists of a multiple detector with an array of 252 scintillator detectors stations, a muon tracking detector, and a central detector. This design allows a separate determination of the electromagnetic and muonic components of the EAS (Ref. [5]).

3.2. Akeno Giant Air Shower Array (AGASA)

AGASA was a surface array consisting of 111 scintillator detectors spread over an area of 100 km^2. This array was complemented by 27 muon detectors. The acceptance was 1750 $\mathrm{km}^2 \times$ sr $\times$ yr. Detection of the EAS is based on the measurement of the particle distribution. AGASA was in operation from 1990 to 2004 (Ref. [12]).

3.3. HiRes experiment

The HiRes experiment is based on detection of fluorescence emitted by the EAS high in the atmosphere. Fluorescence detectors measure most directly the number of charged particles as the shower develops longitudinally.

The HiRes experiment consists of two stations/detectors separated by 12.6 km. The acceptance depends on the mode of observation ($\simeq 5000$ km^2 $\times$ sr $\times$ yr for mono mode and 2500 $\mathrm{km}^2 \times$ sr $\times$ yr for stereo mode). HiRes was in operation from 1997 to 2006 (Ref. [18]).

3.4. Pierre Auger Observatory (PAO)

The Southern PAO is located in Argentina. It is a hybrid detector with a large surface array and a fluorescence detector. The surface detector consists of 1600 water Cherenkov detectors spread over a surface of 3000 km^2 which gives a view of the lateral profile of the EAS. The fluorescence detector consists of 24 telescopes located in four stations which provides a view of longitudinal profile.

The Southern PAO started to collect data in 2004 and will be complete before the end of 2007. The actual acceptance is more than 5000 $\mathrm{km}^2 \times \mathrm{sr} \times \mathrm{yr}$. An extension of PAO should be constructed in the Northern hemisphere (Colorado (USA)). It will cover a surface of 10 000 km^2 with the same hybrid concept consisting of a surface detector and a fluorescence detector (Ref. [7]).

3.5. Neutrino experiments

Neutrino experiments constitute another aspect of the study of CRs. These experiments focus their detection on high energy neutrinos in order to give a limit on neutrino flux which is an important constraint for modelling the production of CRs. They use the interaction between high energy neutrinos and ice or water and detect the Cherenkov photons produced by this process.

Amanda is one of these experiments (Ref. [3]). It consists of 19 vertical strings with optical modules deployed to depth between 1.5 km to 2 km in ice at a South Pole station. IceCube (Ref. [4]) is the future version of this experiment with the development of the actual array and an additional surface array. Antares, Nestor or Baikal are 3 other experiments for the detection of astrophysical neutrinos (Ref. [6]) using detection in water with same design of vertical lines and optical modules at important depth.

4. The energy spectrum

The energy spectrum constitutes the first step to study CRs. Specially, the GZK cutoff is a fundamental aspect of origin of CRs due to the limitation of distance of possible source. Previous observations from AGASA and HiRes experiments which used different process of detections, revealed a disagreement concerning the existence of this feature (see Fig. 3, Ref. [18]).

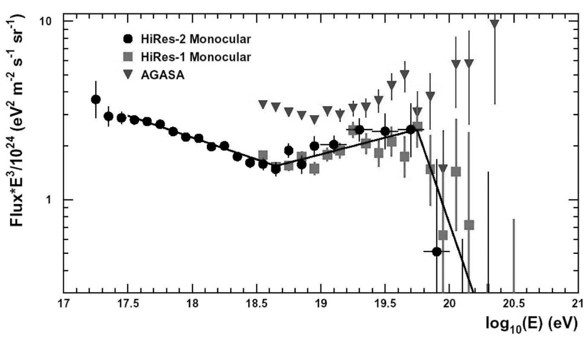

Fig. 3. Cosmic ray spectrum from HiRes experiment (monocular mode) and AGASA experiment (see Ref. in text).

The hybrid concept of PAO permits an inter-calibration of the two type of detectors (surface detectors and fluorescence detectors) and an accurate determination of energy for hybrid events (see Fig. 4). As a preliminary conclusion, the steepening of the energy spectrum observed by HiRes above $10^{19.6}$ eV would actually be confirmed by Auger spectrum (Ref. [15, 16, 20].

5. Mass composition

The question related to the mass composition of CRs at high energy has to be resolved only indirectly by making assumptions about the hadronic interactions since the observations at high energy are only based on the detection of secondary particles and concern an energy range which could not be reached by laboratory experiments.

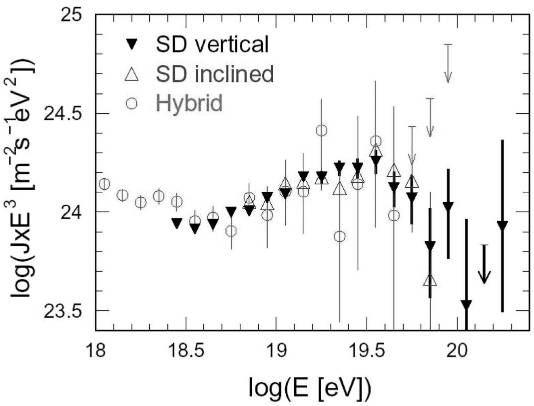

Fig. 4. Energy spectrum multiplied by E^3 (PAO) derived from surface detector data (filled triangles and opened triangles) together with the spectrum derived from the hybrid data set (red circles) (see Ref. in text).

With possibility of reconstruction both, muon and electron numbers, KASCADE-Grande experiment investigates the mass composition of primary cosmic radiation. Around the knee region ($E = 10^{17}$ eV), KASCADE-Grande data show a transition for the mass composition from light to heavy which can be interpreted by the end of galactic component (see Fig. 5, Ref. [5]).

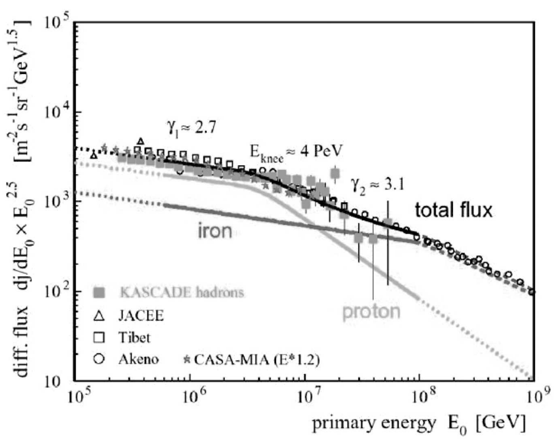

Fig. 5. Composition from KASCADE experiments (see Ref. in text).

Another method for studying the mass composition of CRs is based on the measurement of longitudinal profile of the shower. Effectively, the depth of the maximum of the shower profile, designed by $X_{\max}$, is correlated with the particle mass. $X_{\max}$ can be measured by the fluorescence telescopes.

A preliminary conclusion from the Auger data of Fig. 6 is that the mass spectrum seems to be a mixed composition at the highest energies (Ref. [13]).

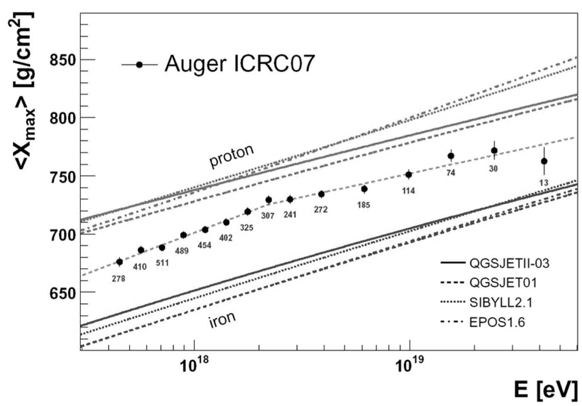

Fig. 6. $X_{\max}$ as a function of energy compared to predictions from hadronic interaction models. The dashed line denotes a fit with two constant elongation rates and a break-point. Event numbers are indicated below each data point. (see Ref. in text).

6. Anisotropy studies

6.1. Galactic center

An excess of detection of CRs was observed near galactic center and Cygnus region by AGASA and SUGAR experiments (Ref. [12]). These results make the Galactic center a very interesting place to look for localised excesses of CRs with an energy around 10^{18} eV, especially for the southern PAO. The results, issued from Auger data up to march 2007, do not reveal a significant excess of CRs flux in the region around the galactic center (Ref. [17]).

6.2. Search of clustering in the arrival directions of CRs

Significant correlations with 2.5 deg between a subset of BL lacs and CRs ($E \geq 4 \times 10^{19}$ eV) observed by AGASA and Yakutsk experiments have been claimed [10].

A similar search for clustering signals in the Auger data has been made. No strong excess of clustering is present with the same angular scale [11,14]. Auger future data will be used to check if a correlation between the arrival directions of CRs and the astronomical sources (BL lacs, active galactic nuclei . . .) is confirmed.

7. Photons flux and neutrinos limits

The measurement of flux of photon and neutrinos constitute an important part of the physic of the astroparticle. Theses values are fundamental to discriminate different models of the production and the propagation of CRs. Last results, from PAO, give a limit to the fraction of photons in the integral CRs flux of 16% above 10^{19} eV based on 29 high quality hybrid events (Ref. [2]). Neutrinos component will also be estimated by PAO (Ref. [1]) and specific experiments for neutrinos detection (IceCube, antares, km3Net ...).

8. Conclusion

Past, actual and future experiments dedicated for the EAS studies will resolve some crucial points relayed on the study of CRs specially for the energy range above 10^{18} eV. The controversial existence of GZK cutoff should be confirm by PAO. The studies for the arrival directions of CRs are actually developed. The excess at galactic center is not confirm until now, and the searches for small and large scale anisotropies are a "work in progress". The future with the development of new experiments like IceCube and the northern and southern PAO will also permit important improvements on the measurement of the photon fraction and limits of the flux of neutrinos. Improvement of the statistic at ultra high energy permit also to investigate composition of CRs at this energy range.

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