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Ultra-high-energy cosmic rays / Rayons cosmiques d'ultra-haute énergie

Cosmic rays from the ankle to the cutoff

Les rayons cosmiques, de la cheville à la coupure

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ABSTRACT

Recent advances in measuring and interpreting cosmic rays from the spectral ankle to the highest energies are briefly reviewed. The prime question at the highest energies is about the origin of the flux suppression observed at $E \simeq 4 \cdot 10^{19}$ eV. Is this the long-awaited GZK-effect or the exhaustion of sources? The key to answering this question will be provided by the largely unknown mass composition at the highest energies. The high level of isotropy observed even at the highest energies challenges models of a proton-dominated composition if extragalactic magnetic fields are on the order of a few nG or less. We shall discuss the experimental and theoretical progress in the field and the prospects for the next decade.

RÉSUMÉ

Les récentes avancées des mesures et de l'interprétation des rayons cosmiques, depuis la caractéristique spectrale appelé « cheville » jusqu'aux plus hautes énergies, sont brièvement revues. Aux plus hautes énergie, la question principale concerne l'origine de la suppression du flux observée au dessus de $4 \cdot 10^{19}$ eV. Est-ce la prédiction GZK tant attendue, ou bien l'épuisement des sources ? La réponse à cette question sera fournie par la mesure de la composition des rayons cosmiques aux plus hautes énergies, qui est aujourd'hui largement inconnue. L'isotropie des directions d'arrivée observées même aux plus hautes énergies défavorise les modèles où les protons dominent la composition, si les champs magnétiques extragalactiques sont au plus de quelques nG. Nous discuterons les progrès expérimentaux et théoriques du domaine et les perspectives pour la prochaine décennie.

1. Introduction

In the last decade, a new generation of the ultra-high energy cosmic ray (UHECR) observatories has come into operation: the Pierre Auger Observatory in the Southern Hemisphere and the Telescope Array in the Northern one. Apart from a

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significant advance in size over their predecessors, both observatories have implemented, for the first time, a new hybrid technique of the UHECR detection where the same air shower is observed simultaneously by a ground array of particle detectors and by fluorescence telescopes capable of tracing the development of the air shower in the atmosphere. By now, both observatories have accumulated a significant part of their lifetime statistics. It may be time, therefore, to summarize the advances in our understanding of UHECR and formulate the remaining problems.

The Pierre Auger Observatory (Auger) [1] is located in Argentina (centered at 69°20 W, 35°20 S) at 1400 m above sea level, corresponding to 870 $\mathrm{g/cm^2}$. It consists of a Surface Detector array (SD) comprising 1660 autonomously operated water-Cherenkov detectors of 10 $\mathrm{m^2}$ area each. The tanks are filled with 12 tons of purified water and three photomultipliers are used to detect the Cherenkov light produced by charged particles. The surface detectors are spread over a 3000 $\mathrm{km^2}$ area and are placed on a triangular grid of 1.5-km spacing. The SD array is overlooked by 27 fluorescence detector telescopes (FD) distributed at five sites [2]. Stable data taking started in January 2004 and the Observatory has been running with its full configuration since 2008.

The Telescope Array (TA) is located in Utah, USA, at 39°30 N, 112°91 W at an altitude of about 1400 m above sea level. It consists of 507 plastic scintillator detectors of 3-$\mathrm{m^2}$ area each spread over approximately 700 $\mathrm{km^2}$ (for details see [3]). The detectors are placed on a square grid with a spacing of 1.2 km. The atmosphere over the surface array is viewed by 38 fluorescence telescopes arranged in three stations [4]. TA is fully operational since March 2008.

Despite similar hybrid design, the two experiments have a number of differences that should be kept in mind when comparing the results. The main one is the design of the ground array detectors. The detectors of TA are traditional two layers of 1.2-cm-thick plastic scintillators, similar to the single 5-cm-thick layers used in AGASA. The water tanks of the Pierre Auger Observatory have a thickness of 1.2 m and a large overall volume, which makes them more sensitive than the TA detectors, especially to inclined particles. At the same time, the large thickness enhances the signal due to the penetrating muonic component of a shower, which is more difficult to model.

By now, an unprecedented number of UHECR events have been detected by the ground arrays and the fluorescent telescopes of both experiments. At energies $E > 10^{19}$ eV, over 10^4 events have been recorded by the Pierre Auger Observatory, and over 2×10^3 by the Telescope Array. For each event, several observables can be reconstructed, the key ones being the energy of the primary particle, the arrival direction and, for the events detected by the fluorescence telescopes, the atmospheric depth of the air shower maximum. These and other observables allow one to shed some light on the nature of primary particles and the origins of UHECR, as discussed in the next sections.

2. Energy spectra

The all-particle energy spectrum is perhaps the most prominent observable of cosmic rays being investigated. It carries combined information about the UHECR sources and about the Galactic and/or intergalactic media in which CRs propagate. The ankle, a hardening seen in the all-particle spectrum at about $5 \cdot 10^{18}$ eV, is generally considered to mark the transition from Galactic to extragalactic cosmic rays. However, recent measurements of KASCADE-Grande [5,6] suggest that this transition may occur more than an order of magnitude lower in energy, i.e. around 10^{17} eV. At this energy, the component of light elements is subdominant, but exhibits a hardening to become dominant at the ankle. The so-called dip-model of the ankle [7] interprets the ankle as being the imprint of protons suffering e^+e^- pair-production in the CMB. Thus, it requires protons to be dominant at energies significantly above and below the ankle and the transition to occur again below the ankle energy. Obviously, models differ in their energy spectra expected for different mass groups and thereby in their cosmic ray mass composition as a function of energy. Related to this, one also expects to see different levels of anisotropies in the arrival directions, as it will be difficult to fully isotropize EeV protons in Galactic magnetic fields [8].

At the highest energy, a flux suppression due to energy losses by photo-pion production and photo-disintegration in the CMB is expected for protons and nuclei, respectively. In fact, this so-called GZK-effect [9,10] is the only firm prediction ever made concerning the shape of the UHECR spectrum. First observations of a cutoff were reported by HiRes and Auger [11,12]. However, at present we cannot be sure whether this flux suppression is an imprint of the aforementioned GZK energy losses or whether it is related to the maximum cosmic ray acceleration energy at the sources.

A first comprehensive comparison of available data was performed by a joint working group of Auger, TA, HiRes, and Yakutsk and is presented in [13]. It is found that the energy spectra determined by the Auger and TA observatories are consistent in normalization and shape if the uncertainties in the energy scale – at that time quoted for each experiment to be about 20% – are taken into account. This is a quite notable achievement and it demonstrates how well the data of current observatories are understood.

The most recent updates of the cosmic-ray energy spectra were presented at the ICRC 2013 Conference. Auger has reported an exposure of about 40 000 $\mathrm{km^2}$ sr yr in the zenith angle range up to 80°. TA, due to its later start and its more than four times smaller area, has collected about a 10th of the events. The TA collaboration restricts the analysis to zenith angles below 45°, which can be understood from the smaller vertical dimensions of the scintillator slabs compared to the 1.2-m height of the water tanks. Taking into account recent precise measurements of the fluorescence yield [17] and taking advantage of a better estimate of the invisible energy, a deeper understanding of the detector and consequently improved event reconstruction, the Pierre Auger Collaboration has recently updated their cosmic-ray energy scale and reduced its systematic uncertainties to 14% [18]. The corresponding results of the two experiments are presented in Fig. 1. The energy