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

Cosmic rays from the knee to the ankle

Rayons cosmiques du genou à la cheville

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A R T I C L E I N F O

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A B S T R A C T

The shape and composition of the primary spectrum as well as the large-scale anisotropy in the arrival direction of cosmic rays are key elements to understand the origin, acceleration and propagation of the Galactic radiation. Besides the well-known knee and ankle features, the measured energy spectrum exhibits also a less pronounced but still clear deviation from a single power law between the knee and the ankle, with a spectral hardening at $\sim 2 \times 10^{16}$ eV and a steepening at $\sim 10^{17}$ eV. The average mass composition gets heavier after the knee till $\sim 10^{17}$ eV, where a bending of the heavy component is observed. An indication of a hardening of the light component just above 10^{17} eV has been measured as well. First indications of anisotropy of the arrival direction in the southern hemisphere have been reported at $\sim 10^{15}$ eV.

R É S U M É

La forme et la composition du spectre des primaires ainsi que les anisotropies à grande échelle dans la distribution d'arrivée des rayons cosmiques sont des éléments clés pour comprendre l'origine, l'accélération et la propagation du rayonnement galactique. En dehors des particularités spectrales bien connues que sont le genou et la cheville, la mesure du spectre en énergie révèle également, entre ces deux particularités, une déviation claire, bien que moins prononcée, par rapport à une loi de puissance unique : le spectre se durcit jusqu'à $\sim 2 \times 10^{16}$ eV et tombe ensuite à partir de $\sim 10^{17}$ eV. La composition en masse, quant à elle, devient plus lourde après le genou, et ce jusqu'à $\sim 10^{17}$ eV, valeur à partir de laquelle elle chute rapidement. Un durcissement de la composante légère au-dessus de 10^{17} eV a aussi été mesuré. De premières indications d'anisotropies dans les mesures des directions d'arrivée depuis l'hémisphère sud ont été rapportées à $\sim 10^{15}$ eV.

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1. Introduction

The paradigm of the origin of Galactic cosmic rays (CR) are supernovae, as their shock waves can provide the required power to explain the intensity of the CR radiation at least up to 10^{15} eV. This paradigm has been recently confirmed by the observations of AGILE [1] and FERMI satellites [2]. A continuous and steady source distribution in space and time would generate an energy spectrum with a simple power law for all elements. However, in a more realistic approach, sources are discrete and a possible non-uniform distribution in space and time could generate structures and changes in the spectral indexes of the primaries at certain energies. Moreover, different populations of sources could be responsible for the Galactic radiation at lower energies and extragalactic at the highest ones [3,4]. Those sources would be subject to a rigidity cutoff in the maximum energy at which the various elements are accelerated, as proposed originally by Peters [5]. Proton will cutoff first, followed by helium, carbon, silicon, iron, etc. according to:

$$E_{\max}(Z) = Z \times E_{\max}(Z = 1) \tag{1}$$

In this approach, the knee at $\sim 4 \times 10^{15}$ eV would represent the end of the spectrum of CR accelerated by supernova remnants in the Milky Way and the ankle at $\sim 4 \times 10^{18}$ eV the transition to particles from extragalactic sources. The ankle structure could be explained also in a completely different way, such as a consequence of the physical process of pair production by protons during propagation through the cosmic microwave background radiation, as proposed by Berezinsky et al. [6]. In this case, the Galactic–extragalactic transition occurs below 10^{18} eV.

A refined study of the CR primary spectrum and composition is, therefore, extremely important to address the above questions. As acceleration and propagation mechanisms in magnetic fields would lead to the same rigidity dependence, the study of large scale anisotropies in the arrival direction could provide relevant information to distinguish source and propagation effects.

The direct study of CRs by means of satellite or balloon-borne detectors is performed only at energies below 10^{15} eV (see [7] for a recent review of the subject). Close to the knee, the flux becomes of the order of 1 particle $\mathrm{m^{-2}\,sr^{-1}\,yr^{-1}}$. This fact prevents the possibility of a direct observation of its structure by currently planned satellite or balloon experiments. Indeed, at least hundred of events above the knee are necessary to determine its existence with enough significance.

Around the knee and at higher energies, CRs are studied by means of large arrays located at ground that measure the secondary particles produced by the primary CR cascading in the atmosphere, the so-called Extensive Air Showers (EAS). Typically, the energy is proportional to the total number of secondaries sampled at ground, while the composition is inferred either through a multi-component measurement, such as the electromagnetic and muonic components, or through the measurement of the emitted light (Cherenkov or fluorescence lights) along the longitudinal development of the shower. Despite the fact that shower arrays allow one to collect high statistics, the interpretation of the results is based on the comparison with expectations from simulation describing the EAS development in atmosphere, which are at some level inaccurate. This introduces a systematic uncertainty on the results, especially on the mass composition.

Interestingly, the TeV region allows some partial overlap between direct and indirect measurements. Several techniques have been employed recently on ground detectors that are sensitive to specific components of the CR radiation to overcome those uncertainties (for a review, see [8]). Among them, it is worth mentioning the measurement of the light component (p alone, or p+He) using hadron calorimeters [9,10], or Cherenkov light measurements in coincidence with TeV muons [11], and RPC counters at high altitude [12]. Those results are in quite good agreement with measurements by CREAM [13] balloon. In particular, the ARGO results allow one to cross-check the fluxes on an extended energy range (5–250 TeV). These results show that, when indirect measurements have the opportunity of selecting almost pure beams, their findings are in reasonable agreement with direct ones and confirm a fair representation of the EAS development in the atmosphere by simulation codes such as CORSIKA [14].

2. The knee region

The all-particle CR energy spectrum shows a distinct feature at $\sim 4 \times 10^{15}$ eV, where the power index suddenly changes from $\gamma \sim -2.7$ to $\gamma \sim -3.1$. This is the so-called ‘knee’ of the CR spectrum. Since its discovery in 1958 by Kulikov and Khristiansen [15], many theoretical works and experimental measurements have been performed; however, the origin of this feature is still under debate. From the experimental point of view, measurements indicate that such a break is observed in the hadronic, muonic, and electromagnetic components (i.e. [16–24]), as well as in Cherenkov light (i.e. [25–28]). These results give a clear indication that the knee is a peculiarity of the primary spectrum, disfavoring a hypothesis based on changes of the interaction characteristics of the primaries with air nuclei. This conclusion has been reinforced by the first comparisons of the predictions from hadronic models and LHC data [29].

The experiments operate at different altitudes, ranging from ∼4300 m of TIBET-ASγ to the sea level of KASCADE. In general, for experiments sampling EAS at the observation level, the height above sea level is crucial either for energy resolution and for sensitivity to composition. In general, near the shower’s maximum, the number of particles is almost independent of the primary particle, and the fluctuations of EAS are minimized. Therefore, high altitudes are suitable for good energy resolution. On the other hand, experiments at sea level enhance the differences in the longitudinal development of EAS of different primaries, as the shower is sampled well after its maximum. Therefore, they are more suitable for composition studies; however, fluctuations are higher.