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# Cosmic rays around $10^{18}$ eV: Implications of contemporary measurements on the origin of the ankle feature

## *Rayons cosmiques autour de $10^{18}$ eV : Implications des observations contemporaines pour l'origine de la cheville*

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ABSTRACT

The impressive power-law decay of the energy spectrum of cosmic rays over more than thirty orders of magnitude in intensity and for energies ranging over eleven decades between $\simeq 10^9$ eV and $\simeq 10^{20}$ eV is actually dotted with small irregularities. These irregularities are highly valuable for uncovering and understanding the modes of production and propagation of cosmic rays. They manifest themselves through changes in the spectral index characterising the observed power laws. One of these irregularities, known as the *ankle*, is subject to conflicting interpretations for many years. If contemporary observations characterising it have shed new lights, they are still far from being able to deliver all the story. The purpose of this contribution is to give an overview of the physics of cosmic rays in the energy range where the transition between Galactic and extragalactic cosmic rays is expected to occur, and to deliver several lines of thought about the origin of the ankle.



RÉSUMÉ

L'impressionnante décroissance en loi de puissance du spectre en énergie des rayons cosmiques sur plus de trente ordres de grandeur en intensité et sur une échelle d'énergie balayant onze décades entre $\simeq 10^9$ eV et $\simeq 10^{20}$ eV est en fait semée de petites irrégularités riches d'enseignements quant aux modes de production et de propagation des rayons cosmiques. Ces irrégularités se manifestent par des changements de l'indice spectral caractérisant les lois de puissance observées. L'une de ces irrégularités, connue sous le nom de *cheville*, fait l'objet d'interprétations antagonistes depuis bon nombre d'années. Si les observations contemporaines la caractérisant ont permis de mieux la cerner, elles sont néanmoins encore loin de pouvoir en livrer tous les ressorts. L'objet de cette contribution est de donner un aperçu de la physique des rayons cosmiques dans la gamme d'énergie propice à une transition entre rayons cosmiques d'origine galactique et extragalactique, et de livrer plusieurs pistes de réflexion sur l'origine de la cheville.



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## 1. Introduction

The ankle is a hardening of the energy spectrum of cosmic rays in the $10^{18}$ eV energy range. Discovered in 1963 by Linsley at the Volcano Ranch experiment [1], subsequent large-aperture experiments have nevertheless been necessary to characterise accurately this feature [2–6]. The ankle is today commonly described as a *sharp* slope change of the spectral index of the cosmic ray intensity from $\simeq 3.3$ to $\simeq 2.7$ located at $\simeq 4 \times 10^{18}$ eV.

Although the existence of the ankle is beyond controversy, its interpretation is still under debate. A dedicated picture explaining this feature was already put forward by Linsley while he was reporting on this finding: "There are many possible interpretations. The one we favor is that the inflection marks a crossover between Galactic and metagalactic cosmic rays" [1]. In other words, this is nothing else but saying that the ankle may be the spectral feature marking the *transition between Galactic and extragalactic cosmic rays*. The reasons supporting this interpretation are the object of Section 2. Despite the fact that it has been popular for many years, this interpretation appears now in tension with contemporary measurements related to the mass composition of cosmic rays, the large-scale distribution of their arrival directions, and the energy spectrum for different mass group elements available around $10^{17}$ eV. The descriptions of these tensions are also the object of Section 2.

Alternatively, the ankle may be understood as the natural distortion of a proton-dominated extragalactic spectrum due to $e^{\pm}$ pair production in the collisions with the photons of the cosmic microwave background [7–10]. This requires on the one hand that the transition between Galactic and extragalactic cosmic rays takes place at lower energies and produces another spectral feature below $10^{18}$ eV [9,10], and on the other hand that the mass composition is made of protons exclusively from the transition energy up to the highest ones. This scenario, referred to as *the dip model*, is presented in Section 3.

The Telescope Array and the Pierre Auger Observatory, which are currently running, are the two largest aperture experiments ever built to study cosmic rays around $10^{18}$ eV and above. Although the dip model provides an overall satisfactory theoretical framework in interpreting data collected at the Telescope Array, a totally different picture is needed in interpreting the ones collected at the Pierre Auger Observatory. This picture, though not final, is the object of Section 4.

Hence, establishing the energy at which the intensity of cosmic rays starts to dominate the intensity of Galactic ones is still, as of today, a fundamental question in astroparticle physics. Part of the answer lies in understanding the ankle, but the whole picture will clearly appear only by revealing the origin of cosmic rays down to $10^{17}$ eV. To this end, some signatures of different scenarios that would be interesting, though challenging, to address in the future from an observational point of view are discussed in the final section.

## 2. The end of the bulk of Galactic cosmic rays

Galactic cosmic rays are thought to be retained by the Galactic magnetic field as long as the size of their Larmor orbit diameter is less than the thickness of the Galactic disk. The large confinement time of the particles in the disk is known to make the energy spectrum observed on Earth steeper compared to the one at the sources. Since the strength of the magnetic field is of the order of microgauss, Galactic cosmic rays might be confined in the Galactic disk up to energies of $Z \times 10^{17}$ eV, with $Z$ the charge of the particles. Once particles are not confined anymore – which should happen at an energy which depends on the charge $Z$, the time they spent in the disk tends to the constant free escape time due to the direct escape from the Galaxy. If cosmic rays up to the highest energies were produced by the same sources in the Galaxy responsible for the bulk of low-energy cosmic rays, the energy spectrum of each mass group element should thus show a prominent hardening (with a change of slope of $\simeq 1$) around each charge-dependent energy at which the free escape starts. Also, for energies at which particles escape freely from the Galaxy, the observed intensity should be naturally much stronger towards the disk compared to other directions. Due to their high level of isotropy, cosmic rays in excess of $\simeq 10^{18}$ eV have thus been thought to be of extragalactic origin since a long time. Because a hardening in the energy spectrum is a natural feature expected from the intersection of a steep component with a flatter one, the ankle has been widely considered as the onset in the energy spectrum marking the transition between Galactic and extragalactic cosmic rays [1,11–15].

Meanwhile, the hypothesis that supernova remnants are the sources of the bulk of Galactic cosmic rays is considered today as a standard paradigm. This is mainly because the intensity of cosmic rays observed on Earth can be produced by using $\simeq 10\%$ of the energetics of these astrophysical objects [16]; and because the diffusive shock acceleration has been shown to be a mechanism able to convert kinetic energy of the expanding supernova blast wave into accelerated particles [17–19]. In this case, the rigidity-dependent maximum acceleration energy for Galactic cosmic rays is expected to be of the order of $10^{17}$ eV for iron nuclei [20]. This makes it difficult to reach smoothly the ankle energy.

Besides this theoretical difficulty, it is worth stressing the fine-tuning required to support the hypothesis that the transition occurs at the ankle energy. Pioneer measurements were sparse, and in particular the measurement of the ankle was not very accurate. Only a smooth change of slope could be observed over a wide energy range in overall agreement with the fact that a transition from a steep spectral index ($\gamma \simeq -3.3$) to a flatter one ($\gamma \simeq -2.7$) ranges smoothly over about one decade in energy. In contrast to this natural smooth hardening, an impressive feature of contemporary measurements of the ankle is its *sharpness*. To reproduce such a feature, the end of the steep component has to *sharply cut off* at the exact same energy at which the flatter component becomes predominant, so that the overall energy spectrum appears as a continuous function. *This involves fine-tunings*, and calls into question the natural aspect of the ankle as the transition.