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Review

Measurements and implications of cosmic ray anisotropies from TeV to trans-EeV energies

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ABSTRACT

Important observational results have been recently reported on the angular distributions of cosmic rays at all energies, calling into question the perception of cosmic rays a decade ago. These results together with their in-progress interpretations are summarized in this review paper, covering both large-scale and small-scale anisotropies from TeV energies to the highest ones. While the magnetic field in the Galaxy has long been considered as an external data imprinting a quasi-random walk to particles and thus shaping the angular distributions of Galactic cosmic rays through the induced average density gradient, the information encompassed in the angular distributions in the TeV–PeV energy range appear today as a promising tool to infer some properties of the local magnetic field environments. At the highest energies, the extragalactic origin of the particles has been recently determined observationally. While no discrete source of ultrahigh-energy cosmic rays has been identified so far, the noose is tightening around nearby extragalactic objects, and some prospects are discussed.

1. Introduction

The origin of cosmic rays (CRs) remains an enduring question in astrophysics. A time-honoured paradigm is that sources of the bulk of these particles could be supernova remnants in the Galaxy. This is mainly because the intensity of cosmic rays observed on Earth can be produced by making use of $\simeq 10\%$ of the energetics of these astrophysical objects [1], 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 [2–4]. However, alternative scenarios with sources related to transient events connected to the death of short-lived massive stars have also been put forward, such as in [5] for instance.

The arrival directions of these particles are highly isotropic. This is expected from the propagation of charged particles in the interstellar medium where the directions of the particle momenta are randomized over time by the effective scattering in the encountered magnetic fields. Despite the scrambling action of these fields, searches for small anisotropy contrasts at large scales have been scrutinized over many decades as reviewed for instance in [6–8]. During the past decade, multiple observatories located in both hemispheres have reported significant observations of large-scale and small-scale anisotropies in the TeV–PeV energy band. These results have challenged the long-standing description of CR propagation in terms of a typical spatial diffusion process from stationary sources located preferentially in the disk of the Galaxy, leading to a dipole moment only in the direction of the CR gradient and with an amplitude steadily increasing with the energy. The current picture is much more complex and elaborate [9].

Galactic CRs are thought to be retained by the Galactic magnetic field as long as the size of their Larmor orbit diameter is much less than the thickness of the Galactic disk. Since the strength of the magnetic field is of the order of microgauss, Galactic CRs might be confined in the Galactic disk up to energies of $100\,Z\,$PeV, with Z the charge of the particles. Once particles are not confined anymore, the time they spent in the disk tends to the constant free escape time due to the direct escape from the Galaxy. The observed intensity should then be naturally much stronger towards the disk compared to other directions. Due to their high level of isotropy, CRs with energies in excess of $\simeq 1\,$EeV have thus long been thought to be of extragalactic origin. In addition, even in the presence of efficient magnetic field amplification at the supernova remnant shock, accelerating intermediate or even heavy nuclei at EeV energies is very challenging [10]. On the other hand, Hillas pointed out the plausible classes of astrophysical objects in which Fermi acceleration could perform up to 100 EeV or so through the essential requirement that the particle Larmor radius must be smaller than the size scale of the acceleration region [11]. Thanks to the jump in statistics as well as to the improved instrumentation experienced in the past decade with the

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Pierre Auger Observatory, CRs with energies in excess of $\simeq 8$ EeV have indeed been recently observed to originate from extragalactic galaxies [12]. The exact sources remain, however, unknown since the first detection of a particle with energy in excess of 100 EeV by Linsley at the Volcano Ranch in 1963 [13].

The intervening magnetic fields in extragalactic space and in the Galaxy are uncertain, although the understanding of the magnetic fields in the Milky Way has developed over many decades and has allowed for quantitatively-constrained models to emerge [14]. The uncertainties remain however too large to firmly predict the deflections that ultra-high energy cosmic rays (UHECRs) should undergo from each line of sight outside from the Galaxy. The effect of the turbulent component of the field is particularly uncertain [15]. The expected order of magnitude for the deflections is thought to behave as $\simeq 3^\circ Z(E/100~\mathrm{EeV})^{-1}$. With such an order of magnitude, magnetic deflections could be small enough to allow for mirroring to some extent the distribution of sources in the sky. Moreover, the horizon of the highest energy particles ($\gtrsim 60$ EeV) is limited as compared to that of particles of lower energies, because the thresholds are then reached of interactions with background radiations filling the Universe and leading to large energy losses. This is the “GZK effect” [16], which allows that only the foreground sources are expected to populate the observed sky maps at these energies. But the small intensity combined to the potential absence of particles with low electric charge at these energies still prevents such a “charged-particle astronomy” with current data.

All these topics are addressed in detail in this review under the prism essentially of the results obtained during the last decade. This review is meant to be an introduction to the main analysis techniques as well as to the formalisms needed to interpret the results. In this sense, and to allow an introduction to the latest theoretical advances, many classical results are developed from the first principles by reviewing the main steps to derive them. After introducing the basic quantities of interest to decipher the underlying angular distributions of CRs from ground-based experiment data in Section 2, the guiding thread of this review is to characterize anisotropies from large to small scales, by presenting the experimental results and their interpretations as a function of energy. Thus, harmonic analysis methods in right ascension, traditionally focused on the first harmonic, are first approached in Section 3 and their astrophysical consequences discussed in Section 4. The 3D reconstruction of the intensity on the sphere and the characterization of the anisotropies in terms of power spectrum are the subject of the next two sections, reviewing the analysis techniques in Section 5 and the interpretations in Section 6. Finally, Section 7 is devoted to the highest energies, because of the specific techniques, which can in particular involve external information such as catalogs of extragalactic astrophysical objects.

2. Sky surveys from ground-based observatories

The aim of CR anisotropy studies is to reconstruct the intensity from each direction of the sky. From the all-directional flux of particles I_0, the intensity in each celestial direction, $I(\mathbf{n})$, is defined as the overall flux per steradian weighted by a directional-dependent factor characterizing the anisotropy:

$$I(\mathbf{n}) = \frac{I_0}{4\pi}(1 + \delta I(\mathbf{n})). \quad (1)$$

Ground-based observatories have access, however, to a limited part of the sky in a highly non-uniform way. This section is dedicated to introduce the basic ideas and techniques that allow for estimating the directional exposure of any experiment.

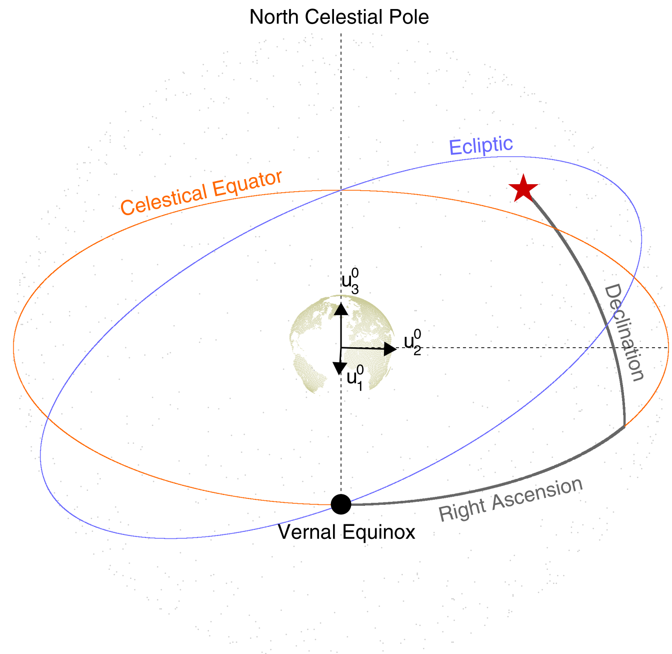

Fig. 1. Equatorial coordinate system.

2.1. Coordinate systems

Let us first define the notations used throughout this review for the relevant coordinate systems and review the rules of transformation between local and equatorial coordinates. Equatorial coordinates are the most natural ones to characterize the directional data of ground-based observatories. The projection on the celestial sphere of the equator of the Earth is used as a reference plane. This projection is the celestial equator, which divides the sky into two hemispheres, each of which has as its reference axis the projection of a terrestrial pole perpendicular to the celestial equator. From this division, the system makes it possible to establish two angular coordinates: the right ascension α and the declination δ, which are longitude-like and latitude-like coordinates. Conventionally, right ascension is measured eastward along the celestial equator from the vernal equinox to the hour circle[1] of the point in question. Declination is measured perpendicularly from the celestial equator to the observed celestial object, positive for objects in the northern hemisphere and negative for those in the southern hemisphere. The corresponding right-handed rectangular basis of unit vectors are denoted throughout this review as $(\mathbf{u}_1^0, \mathbf{u}_2^0, \mathbf{u}_3^0)$, so that any unitary vector $\mathbf{n}$ can be expressed as $\mathbf{n} = \cos\delta\cos\alpha~\mathbf{u}_1^0 + \cos\delta\sin\alpha~\mathbf{u}_2^0 + \sin\delta~\mathbf{u}_3^0$. A sketch of the considered geometry is shown in Fig. 1.

Let us now proceed to the local tracking of a point for an observer located at a geographic latitude λ and longitude l on Earth. It is then convenient to introduce the two coordinate systems depicted in Fig. 2, where the observer is located in the city of Oulan-Bator ($\lambda \simeq 47^\circ$, $l \simeq 106^\circ$) for exemplify purpose: let $(\mathbf{u}_x, \mathbf{u}_y, \mathbf{u}_z)$ be a right-handed basis of orthonormal vectors tied to the observer such that any unitary vector $\mathbf{n}$ can be characterized by a zenith angle θ and an azimuthal angle[2] φ as $\mathbf{n} = \sin\theta\cos\varphi~\mathbf{u}_x + \sin\theta\sin\varphi~\mathbf{u}_y + \cos\theta~\mathbf{u}_z$; and let $(\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3)$ be a left-handed basis of orthonormal vectors in a coordinate

[1] The hour circle is the great circle through the object and the celestial poles of the Earth.

[2] The azimuth φ is here defined relative to the geographic East direction, measured counterclockwise.