Ultra-high-energy cosmic rays: Current understanding and future prospects

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Abstract. In fact, ultra-high-energy cosmic rays (UHECRs) represent the most energetic particles in the universe, thus reaching energies over a million times higher than man-made accelerators.However, even with decades of observations, their origins and acceleration mechanisms remain elusive. In virtue of which, recent data from experiments such as, the Pierre Auger Observatory and Telescope Array, have provided important insights, detecting a flux suppression at the highest energies consistent with the GZK cutoff. Besides, this suggests an extragalactic origin, though challenges remain in discriminating between galactic and extragalactic populations together with tracing arrival directions.In closing, upcoming detector upgrades and next-generation observatories aim to enhance precision and statistics, promising to unravel these astroparticle physics mysteries.

1 Introduction

Definitely, UHECRs are among the most energetic particles observed in the universe, with energies surpassing 10^{18} eV. Further, these extreme energies far exceed those achieved by human-made particle accelerators and pose significant challenges to our understanding of particle physics and astrophysical processes. Nonetheless, despite extensive research efforts over the past few decades, the sources, acceleration mechanisms, and propagation paths of UHECRs remain largely elusive [1, 2].

More to the point, observations from leading experiments, such as the Pierre Auger Observatory and the Telescope Array, have provided important insights into the energy spectrum and anisotropies of UHECR arrival directions [1, 3]. In this research, the detection of suppression in the flux is a key milestone at the highest energies, consistent with the Greisen-Zatsepin-Kuzmin (GZK) cutoff, where at UHECRs interact with the cosmic microwave background (CMB) and lose energy [1]. As consequence,these findings suggest an extragalactic origin for UHECRs, with potential sources including active galactic nuclei (AGN), starburst galaxies, and gamma-ray bursts [2, 3].

However, the task of pinpointing the sources of UHECRs is complicated by magnetic deflections that scatter their trajectories during propagation. Notwithstanding the fact that magnetic fields at lower energies cause isotropic arrival patterns, particles above $10^{19.5}$ eV, show

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hints of correlations with nearby extragalactic structures[4]. Although these advancements, open questions remain regarding the contribution of galactic versus extragalactic sources and the precise acceleration mechanisms at play [2, 4].

Most importantly, the future of UHECR research looks promising, with planned upgrades to the Pierre Auger Observatory and the development of next-generation observatories, in respect such as POEMMA and JEM-EUSO. Therefore, these instruments aim to enhance the precision of measurements, improve statistical power, and uncover new phenomena [4, 5].

2 Observational status and key findings

Certainly, the study of UHECRs has significantly advanced, over the past few decades, primarily through observations from ground-based observatories. In this respect, the Pierre Auger Observatory in Argentina and the Telescope Array (TA) in Utah are the two leading experiments contributing to our understanding of these enigmatic particles [6, 7]. Hence, these observatories have measured key properties, in respect such as the UHECR energy spectrum, mass composition, and arrival directions, offering invaluable insights and posing new questions for astroparticle physics.

2.1 Energy spectrum and flux suppression

The energy spectrum of UHECRs, spanning from 10^{18} eV, to 10^{20} eV, reveals critical features, including a flux suppression at the highest energies [6]. Above and beyond, this suppression aligns with the Greisen-Zatsepin-Kuzmin (GZK) effect, where at interactions with the cosmic microwave background (CMB) reduce the energy of particles travelling across intergalactic space [8]. Additionally, the Pierre Auger Observatory reports a statistically significant downturn in flux above $10^{19.5}$ eV consistent with the expected GZK cutoff [1, 8]. However, Telescope Array data shows a slightly different suppression, raising questions about the homogeneity of UHECR sources or regional effects in magnetic fields [7].

2.2 Mass composition

If truth be told, determining the composition of UHECRs is a major challenge. Besides, observatories measure the mass indirectly by analyzing the depth of the particle shower's maximum development (the $X_{\rm max}$) in the atmosphere. Nonetheless, current data suggests a shift from lighter elements, like protons, at lower energies to heavier nuclei at higher energies, although this conclusion remains controversial [1, 8]. In a consequence, discrepancies between results from Pierre Auger and TA indicate the need for more precise measurements and improved hadronic interaction models [2, 9].

2.3 Arrival directions and anisotropy

Indeed, understanding the distribution of UHECR arrival directions is critical for identification purpose of their sources. Besides,Auger data suggests a dipole anisotropy at energies above 8×10^{18} eV, indicating an extragalactic origin [4]. Additionally, TA data hints at potential correlations with starburst galaxies and jetted active galactic nuclei (AGN) within 200 Mpc, although these patterns have yet to be conclusive. To conclude, the reduced influence of magnetic fields provides a clearer picture at the highest energies, but identifying individual sources remains challenging due to limited statistics [1, 10].

3 Theoretical perspectives: Origins and acceleration mechanisms

Unquestionably, the origins and acceleration mechanisms of UHECRs remain highly debated, with several astrophysical scenarios proposed. Further, active galactic nuclei (AGN), with their powerful jets and strong magnetic fields, are prime candidates for accelerating particles to ultra-high energies [2, 3]. Similarly, gamma-ray bursts (GRBs) and starburst galaxies have been suggested due to their intense energy output and favourable conditions for particle acceleration [2]. In more exotic models, UHECRs could originate from topological defects or decaying super-massive particles in the early universe, representing physics beyond the Standard Model[1]. Moreover, the acceleration itself likely involves processes like diffusive shock acceleration or magnetospheric interactions within jets, providing the necessary energy over cosmic scales [3]. Nevertheless, even with these models, identifying individual sources remains challenging, with no definitive correlations yet established between UHECRs and known astrophysical objects[11].

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