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

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In point of fact, ultra-high-energy cosmic rays (UHECRs) represent the pinnacle of particle acceleration in the universe, with energies exceeding 1018 eV - over a million times higher than the most powerful human-made particle accelerators. However, their very existence defies our current understanding of cosmic particle accelerators and challenges the limits of nuclear and particle physics. On the other hand, this review explores the profound mysteries surrounding these incredibly rare yet immensely energetic particles bombarding Earth from all directions.
More to the point, despite decades of dedicated observations, the origins and acceleration mechanisms of UHECRs remain elusive. In virtue of which, we synthesize the latest findings from ground-based observatories like the Pierre Auger Observatory and Telescope Array, which have mapped the energy spectrum, mass composition, and anisotropic arrival directions of these cosmic messengers. In this respect, potential astrophysical source candidates, including active galactic nuclei, starburst galaxies, gamma-ray bursts, and more exotic scenarios like cosmic defects, are critically examined.
Above and beyond, key challenges encompass the discrimination between galactic and extragalactic UHECR populations, the effects of interactions with cosmic backgrounds, and the quest to increase statistics at the highest energies. In addition, upcoming upgrades and next-generation detectors promise unprecedented insights into these astroparticle physics enigmas with far-reaching implications for fundamental physics and our comprehension of the high-energy universe, as well.

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