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Editorial

Editorial for the Special Issue "Ultra-High-Energy Cosmic Rays"

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The origin of ultra-high-energy cosmic rays (UHECRs), with energies above $\sim$1 EeV, remains one of the most compelling open questions in high-energy astrophysics. Decades of observations from the Pierre Auger Observatory and the Telescope Array have established key features of the UHECR energy spectrum, a mixed and energy-dependent mass composition, and large-scale anisotropies that favour an extragalactic origin above a few EeV [1–4]. Nevertheless, the astrophysical sites that accelerate UHECRs are still unidentified. UHECRs are significantly deflected by galactic and extragalactic magnetic fields, which complicates direct source association. Critically, the reconstruction of primary energy and mass from ground-based extensive-air-shower (EAS) events relies heavily on hadronic interaction models that are not yet fully constrained by laboratory data [5–8]. This Special Issue brings together six contributions that address these interlinked challenges from complementary perspectives, ranging from multimessenger source modeling and shower physics to lunar radio detection, analysis methods, and distributed observational networks [9–14].

On the source side, Babur, Gugnin, and Hnatyk [9] present a multimessenger model of the Shapley Supercluster, one of the most massive large-scale structures in the nearby Universe [15,16]. Using eROSITA data for 45 X-ray-luminous galaxy clusters [17], they predict hadronic γ-ray and neutrino emission potentially accessible to CTAO-South and KM3NeT under optimistic assumptions [18,19]. Li, Min, Jin, and Guo [12] propagate UHECRs from gamma-ray bursts (GRBs) using CRPropa 3 [20] in the long-standing GRB–UHECR framework [21–23]. They show that, for a benchmark baryon loading factor $f_{\rm CR} = 1$, both high- and low-luminosity GRB populations contribute less than 10% of the UHECR spectrum. Requiring that hadronic GeV emission does not exceed the Fermi-LAT flux [24] imposes an upper limit $f_{\rm CR} \lesssim 15$. Under this constraint, GRBs are unlikely to dominate the all-sky UHECR intensity, and the resulting cosmogenic secondary γ-ray and neutrino fluxes remain below the detection thresholds of Fermi-LAT and IceCube.

Beyond the search for individual source classes, progress in UHECR astrophysics requires improved shower reconstruction, multi-station coordination, and advances in both observational strategies and analysis methodologies. Porcelli et al. [11] propose the μPPET concept to investigate the muon puzzle [8,25] using J-PET detectors for precise muon tracking, with data taking planned to begin in 2026. Wibig et al. [14] address multi-station coordination by presenting CREDO-Maze as a path toward a global muon/EAS network for cosmic-ray ensemble searches, emphasising the need for standardised, shareable data across distributed educational and research arrays. On the observational side, Chen, Zhang, Geng, and Cheng [13] propose a long-duration lunar Askaryan experiment [26–28] using two 30 m radio telescopes, estimating that a few UHE events above 10^{20} eV could be recorded with an effective observing time of about 2000 h per year over at least three years. Even such a small sample would place meaningful constraints on the extreme-energy

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spectrum and exotic neutrino scenarios near and above the Greisen–Zatsepin–Kuzmin cutoff [29,30]. On the methodological side, Calafeteanu, Isar, and Sluşanschi [10] address a computational bottleneck in air-shower simulation, namely that CoREAS [31,32] runs for AugerPrime-scale radio arrays [33,34] become prohibitively expensive when all antennas are included. Their zenith-dependent Cherenkov-ellipse pre-selection reduces simulation time by more than 50% for heavy, highly inclined showers while preserving antennas with high signal-to-noise ratios (SNRs), enabling the large Monte Carlo datasets required for radio-based composition studies and machine learning applications.

Taken together, these articles span topics from multimessenger source modeling and shower physics to lunar radio detection, analysis methods, and distributed observational networks, illustrating the breadth of current UHECR research and the value of coordinated multi-messenger and multi-technique approaches [35,36]. We are grateful to all authors and reviewers for their valuable contributions to this Special Issue.

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