Contribution ID: **323** Type: **Talk**

A Hierarchical Shock Acceleration Model for Ultra-High-Energy Cosmic Rays and Multimessenger Signatures

Monday 21 July 2025 13:35 (15 minutes)

Accretion shocks in the large-scale structure of the universe are promising sources of ultra-high-energy cosmic rays (UHECRs). In addition to accelerating UHECRs, these shocks should produce distinct multimessenger signatures, including synchrotron radio emission, gamma rays, and neutrinos. We investigate how a hierarchical shock acceleration framework—progressing from supernova remnant shocks to galactic wind termination shocks and ultimately to cosmic structure-formation shocks—naturally explains the full cosmic ray spectrum extending beyond the ankle. Using a hydrodynamic cosmological simulation, we compute the energy processed at cluster and filamentary shocks and predict the corresponding radio synchrotron emission. We find that microgauss magnetic fields at these shocks could explain both UHECRs and the diffuse radio synchrotron background below 10 GHz. These fields may be amplified through a combination of early-Universe galactic outflows, plasma instabilities, and small-scale turbulent dynamo action. The model also predicts a correlation between UHECR anisotropy and large-scale cosmic structure, which can be tested with Auger and future radio and gamma-ray observatories. Our results motivate a multimessenger strategy to identify UHECR sources and test whether accretion shocks dominate their acceleration.

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Session Classification: GWMS

Track Classification: Gravitational Wave, Multi-Messenger & Synergies