Journal of Physics Research and Applications

Editorial

A SCITECHNOL JOURNAL

Astrophysics of Cosmic Rays

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Received date: May 09, 2021; **Accepted date:** May 16, 2021; **Published date:** May 30, 2021

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The origin of the highest energy cosmic rays is still unknown. The discovery of their sources is expected to reveal the workings of the most energetic astrophysical accelerators in the Universe. Current observations show a spectrum consistent with an origin in extragalactic astrophysical sources. Candidate sources range from the birth of compact objects to explosions related to gamma-ray bursts or to events in active galaxies. We discuss the main effects of propagation from cosmologically distant sources, including interactions with cosmic background radiation and magnetic fields. We examine possible acceleration mechanisms leading to a survey of candidate sources and their signatures. New questions arise from an observed hint of sky anisotropies and an unexpected evolution of composition indicators. Future observations may reach the necessary sensitivity to achieve charged particle astronomy and to observe ultrahigh-energy photons and neutrinos, which may further illuminate the workings of the Universe at these extreme energies. In addition to fostering a new understanding of high-energy astrophysical phenomena, the study of ultrahigh-energy cosmic rays can constrain the structure of the Galactic and extragalactic magnetic fields as well as probe particle interactions at energies orders of magnitude higher than achieved in terrestrial accelerators.

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After many decades of efforts to discover the origin of cosmic rays, current observatories are now reaching the necessary exposure to begin unveiling this longstanding mystery. The first detection of UHECRs dates back to Linsley, but it was only during the 1990s that an international effort began to address these questions with the necessary large-scale observatories.

The largest detectors operating during the 1990s were the Akeno Giant Air Shower Array (AGASA), a 100 km^2 ground array of scintillators in Japan, and the High Resolution Fly's Eye (HiRes), a pair of fluorescence telescopes that operated in Utah until 2006. During their lifetimes, AGASA reached an exposure of 1.6×10^3 km^2 sr year (or 1,600 L; in honor of UHECR pioneer John Linsley, we use the exposure unit L = 1 km^2 sr year), whereas HiRes reached twice that. To date, the highest energy recorded event was a 320 EeV fluorescence detection by the pioneer fluorescence experiment Fly's Eye.

Completed in 2008, the Pierre Auger Observatory (Auger) is the largest observatory at present. Constructed in the province of Mendoza, Argentina, by a collaboration of 18 countries, it consists of a 3,000 km^2 array of water Cherenkov stations with 1.5 km spacing in a triangular grid overlooked by four fluorescence telescopes. The combination of the two techniques into a hybrid observatory maximizes the precision in the reconstruction of air showers, allowing for large statistics with good control of systematics. The largest observatory in the northern hemisphere, the Telescope Array (TA), is also hybrid. Situated in Utah, it covers 762 km^2 with scintillators spaced every 1.2 km overlooked by three fluorescence telescopes.

The confirmed presence of a spectral feature similar to the predicted GZK cutoff settles the question of whether acceleration in extragalactic sources can explain the high-energy spectrum, ending the need for exotic alternatives designed to avoid the GZK feature. However, the possibility that the observed softening of the spectrum is mainly due to the maximum energy of acceleration at the source, E_{max}, is not as easily dismissed. A confirmation that the observed softening is the GZK feature awaits supporting evidence from the spectral shape, anisotropies, and composition at trans-GZK energies and the observation of produced secondaries such as neutrinos and photons.

In this case, the maximum energy of the accelerators is likely to be below GZK energies for protons, and the spectrum cutoff is likely to be a combined effect of the maximum iron energy and the GZK effect. This coincidence is not an elegant solution, but it is a clear possibility. A heavy composition at injection is more natural for models based on magnetars, whereas scenarios based on AGN and GRBs need to be modified to account for the suprisingly heavy composition. In this scenario, cosmogenic neutrinos and photons will not be easily detected, leaving only the hope of observing a nearby source or of major technological advances to reach down orders of magnitude in flux.

Great progress in the UHECR frontier may lead to a completely different outcome than our speculative exercise above, but that will require a significant increase in statistics at trans-GZK energies. Current data suggest that watershed anisotropies will only become clear above 60 EeV and that very large statistics with good angular and energy resolution will be required. Auger will add 7×10^3L per year in the South, whereas TA will add about 2×10^3L per year in the North. Current technologies can reach a goal of another order of magnitude if deployed by bold scientists over very large areas (e.g., Auger North). New technologies may ease the need for large numbers of detector units to cover similarly large areas. Future space observatories (e.g., JEM-EUSO, OWL, and Super-EUSO) promise a new avenue to reach the necessary high statistics, especially if improved photon detection technologies are achieved. With a coordinated effort, the next generation of observatories can explore more of the ~5 million trans-GZK events the Earth's atmosphere receives per year.

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