Extreme Energy Particle Astronomy

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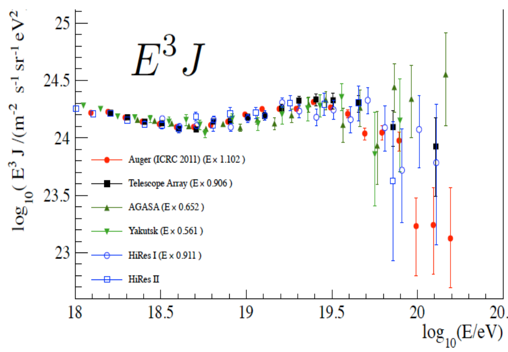
Particles have been measured with individual energies greater than 10^{20} eV! This must immediately seize the scientific imagination! Are these charged particles? What accelerators are responsible? How do the particles interact with the sea of CMB photons and the magnetic fields that they must traverse? The mystery of extreme energy cosmic rays (EECR: E ≥ 50 EeV) is one of the most compelling and, perhaps, least appreciated in astrophysics. A space-based observatory using current technology can both solve this mystery and enable EECR astronomy. Now is the time to add one to the NASA Astrophysics Roadmap.

Detailed EECR measurements are exceptionally challenging. The flux is minuscule, ~1 per km^2 per century. To exploit the potential of EECR astronomy, exposures of ~10^6 km^2 sr yr are needed, and the largest current ground instruments, the 3000 km^2 Pierre Auger Observatory (Auger) and 762 km^2 Telescope Array (TA), would require many decades. Only moving the observatory to space allows this leap.

The majority of EECR come from extragalactic acceleration engines. Greisen, Zatsepin, and Kuzmin (GZK, 1966) showed that hadrons above ~50 EeV undergo pion photoproduction interactions with the CMB, strongly suppressing the spectra from sources more distant than ~100 Mpc and producing associated ultra-high-energy (UHE) neutrinos traveling in the direction of the original particle. Composite nuclei dissociate and give a similar limit. Because this was not clearly confirmed until recently, EECR direct production by exotic processes, such as the decay of topological defects in the fabric of the universe, was actively modeled. However, the GZK-like feature observed by the High Resolution Fly's Eye (HiRes), Auger, and now TA shows that cosmic accelerators can explain most EECR.



Measured energetic particle spectrum multiplied by E^3; GZK feature ~ 5 10^{19} eV.

Luminous matter is inhomogeneously distributed within the GZK sphere. Predicted extragalactic magnetic fields deflect charged EECR from sources in the GZK sphere by only ~1° and the isotropic flux from distant sources is suppressed. Thus, with a large enough observatory, true extreme energy particle astronomy is possible, including identification and characterization of individual sources. These might be e.g. AGN, GRB explosions, or the birth of compact objects. Observation of UHE neutrinos from the GZK process or directly from the accelerators also has tremendous potential because they are not attenuated or deflected in transport and can probe sources far beyond the GZK horizon.

EECR and UHE neutrinos must be measured from space using the atmosphere as a huge "imaging calorimeter" to accurately determine particle energy, arrival direction, and interaction characteristics. UHE charged particle and neutrino interactions in the atmosphere produce cascades of huge numbers of charged particles traveling in a compact disk at $\beta \approx 1$ and dissipating the energy of the primary particle by ionization. Measuring the time and spatial development of the cascade by imaging the UV-fluorescence light produced enables a true calorimetric measurement. A space observatory, viewing ~10^5 – 10^7 km^2 with ~km^2 resolution, could exceed exposures of current ground instruments by at least an order of magnitude, even considering duty cycle, and measure particle energies and arrival directions with great accuracy. Instruments can be built with current optical, focal plane, electronic, and vehicle technologies. Such space telescopes do not need fine pointing and could be on the ISS or free flyers. The light collectors need ~3 m optical apertures and full FOV >45°, but can be orders of magnitude above the diffraction limit. The number of pixels, sensitivity, and trigger selectivity needed are typical of particle collider systems. Focal planes can use existing multi-anode vacuum photomultipliers and performance may be enhanced with new UV solid-state photomultipliers now in development. The telescope could be monocular, using measurements at ~3 μs intervals, very slow by accelerator standards, to resolve tilt out of the image plane. A later stereo implementation with two telescopes viewing the same volume of atmosphere could provide superior resolution of energy and arrival direction. A single observatory would be well suited to both charged particle and neutrino measurements and so provide a true multimessenger view of their sources.