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Editorial

Problems of Ultra-High Energy Cosmic Rays

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Cosmic rays are energetic particles coming to the Earth from space. They bombard the atmosphere producing cascades of particles that spread over a large area when they reach the ground. Cosmic ray energies vary in the wide band from about 10^8 eV up to few 10^{20} eV. It is established that most particles with energies of ~ (10^8-10^9) eV come from the Sun, cosmic rays with higher energies, up to ~ 10^{17}-10^{18} eV are produced in the Galaxy. In these energy bands, particles are called solar cosmic rays and galactic cosmic rays, respectively.

Particles with the highest energies, from approximately $4 \cdot 10^{19}$ to few 10^{20} eV, are called Ultra-High Energy Cosmic Rays (UHECRs). It is likely that they are originated outside the Milky Way. The common argument is that magnetic fields in the Galaxy cannot confine particles at ultra-high energies. Indeed, no significant excess of UHECRs has been observed toward the galactic disk. Still, the hypothesis about extragalactic origin of UHECRs is not confirmed experimentally.

The flux of cosmic rays at the Earth decreases rapidly with energy and it becomes very low at ultra-high energies: At the energy $E \approx 10^{20}$ eV the flux equals about 1 particle per year per 100 km^2. Because of this, the only way to detect UHECRs is through their interactions with the Earth's atmosphere. UHECRs produce huge cascades with billions particles which are distributed over areas of ~10-1000 square kilometers. Therefore, giant arrays are operated to detect UHECRs. These are Pierre Auger array having a detection area of 3,000 km^2, located in Argentina and Telescope array sampling events over almost 780 km^2 in Uta, USA. At arrays particle energies and arrival directions are measured, mass composition and parameters of hadronic interactions at the highest energies can be derived as well.

Until now the main problem of UHECRs is where they come from. Many ideas were suggested on this subject. They can be divided into two groups. First, particles, possibly, are accelerated to high energies in various astrophysics objects (active galactic nuclei, powerful radio galaxies, gamma-bursts, etc.). Second, it was expected that UHECRs were produced in top-down scenarios through topological defects or heavy dark matter decays not far from the Earth. In addition, some exotic models were suggested (e.g., micro black holes can exist in the Earth's atmosphere and produce UHECRs).

Information about UHECR origin can be retrieved from particle energy spectrum. In space, particles lose energy in interactions with cosmic microwave background. UHECRs coming from distances of more than ~100 Mpc, the spectrum is suppressed above $E \approx 4 \cdot 10^{19}$ eV (GZK-effect predicted by Greisen, Zatsepin and Kuzmin). UHECR collected from nearer distances have no GZK-suppression. Thus, the measured spectrum has specific shape depending on distances that UHECRs propagate. At present both giant arrays give similar result on UHECR energy spectrum: It has suppression. However, there may be another reason for suppression along with GZK-effect. Physical conditions in possible UHECR sources limit the particle maximum energy to the value of about 10^{21} eV (interpretation of UHECR data confirms this limit). As the sources that produce UHECRs are still unknown, the acceleration energy limit cannot be ruled out. So it is not clear what the reason for the spectrum suppression, GZK-effect or the energy limit in possible sources may be.

Besides this, different models predict some features in particle arrival directions. What are these predictions? In the first group of models, large or small scale anisotropy in UHECR arrival directions is expected, along with the possibility in principle of UHECR source direct identification. No anisotropy is expected in other models. At present the data collected at both arrays show no clear evidence of anisotropy. Point sources are not yet discovered as well.

Another key to understand UHECR origin and propagation is the particle mass composition. It is inferred through variables related to the atmospheric cascade (external air shower) development, namely via the depth where the shower reaches its maximum, X_{max}. Proton induced showers have on average deeper X_{max} with larger fluctuations, with respect to iron primaries. At the Auger observatory, X_{max} analysis disfavors pure proton composition of UHECRs: There is a trend towards a heavier composition at the highest energies, though the statistics is limited. This mass composition confirms models in which UHECR sources are active galactic nuclei located at ~ 50 Mpc with UHECR energy limit of 10^{21} eV. Oppositely, in UHECR top-down scenarios photons are expected as primaries. The X_{max}

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analysis shows no primary photons in UHECRs and thus excludes top-down mechanism.

Neutrinos can be detected using giant arrays as well. Due to the very low interaction cross-section, they traverse a large amount of air without interactions and produce showers deeply in the atmosphere. These cascades discern from showers starting early in the atmosphere and due to this neutrino-initiated showers are selected. Neutrinos are also detected by searching for very inclined showers (near the horizon). Now, upper limits on diffuse neutrino fluxes are obtained constraining astrophysical models.

Lack of information about hadronic interactions at ultra-high energies impede correct interpretation of cascade development. However air showers themselves are instrument of obtaining information about interactions at the highest energies. The Auger observatory has measured the proton-air cross section at the energy $E \approx 3 \cdot 10^{18}$ eV that corresponds to the equivalent center-of mass energy $s^{1/2} = 57$ TeV (that is far beyond operating accelerators including LHC):
$\sigma_{\text{p-Air}} \approx 506$ mb. This value corresponds to the proton-proton cross section $\sigma_{\text{p-p, inel}} \approx 133$ mb at $s^{1/2} = 57$ TeV and shows smooth growth of the cross section as the energy increases.

Yet there is no understanding of UHECR origin though top-down scenarios are excluded. Point UHECR sources seem to be appropriate but they are not yet discovered. Now UHECRs are a probe both of energetic processes in the Universe and in hadronic interactions at the highest energies. Recent experimental data and some theoretical results one can find in [1-3].

References

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