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Prospects for ultrahigh-energy particle observation based on the lunar orbital LORD space experiment

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Abstract

The problem of searching for highest-energy cosmic rays and neutrinos in the Universe is reviewed. Possibilities for using the radio method for detecting particles of energies above the GZK cut-off are analyzed. The method is based on the registration of coherent radio emission produced by cascades of most energetic particles in radio-transparent lunar regolith. The Luna-Resurs Orbiter space mission to be launched in the near future (2020) involves the Lunar Orbital Radio Detector (LORD). The design of the LORD space instrument and its scientific potentialities for registration of low-intense cosmic ray particle fluxes of energies above the GZK cut-off up to 10^{24} eV are discussed. The designed LORD module (including the antenna, amplification, and data-acquisition systems) now is under construction. Exposure and capabilities of the LORD space experiment for detection of ultrahigh-energy cosmic rays and neutrinos have been compared with those for well-known current and proposed experiments. The LORD space experiment will make it possible to obtain important information on the highest-energy particles in the Universe, to verify modern models for the origin and the propagation of ultrahigh-energy cosmic rays and neutrinos.

Keywords: Ultrahigh-energy particles; Cosmic rays; Neutrino; Charge excess radio emission; Cascades; Lunar regolith

1. Introduction

For many years, the nature of cosmic rays (CRs) has remained one of the main open issues of astrophysics and particle physics, while the uncertainty of their origin increases with their energy (Watson, 2014). The question of what are the highest particle energies in the Universe and what are their sources is one of the great mysteries of modern science. Information about ultrahigh-energy particles is important for solving fundamental problems of astrophysics and elementary particle physics that touch upon such issues as CR sources, mechanisms of CR acceleration, and may be the origin of dark matter particles (Ryabov et al., 2008).

On the whole, several dozen ultrahigh-energy cosmic rays (UHECRs) shower events have been registered in the Haverah Park, SUGAR, AGASA, Fly's Eye, HiRes, Telescope Array and Auger experiments at energies $E > 6 \times 10^{19}$ eV. In several of these, the reconstructed energy exceeded 10^{20} eV, which corresponds to an energy in the center of mass system $\sqrt{s} = \sqrt{2m_N E_{CR}} \geqslant 500$ TeV, where m_N is the nucleon mass. Interest in the particles that produced showers of such grandeur in the atmosphere is not restricted to the desire to reveal the sources at which they were produced, or the processes in which they were accelerated to such high energies. Their origin may be directly related to manifestations of new physics at an

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energy scale essentially exceeding the energies of modern accelerators. We know neither the nature of these particles nor the sources and processes in which they were accelerated to such high energies.

From the traditional standpoint of physics, neither hadrons and nuclei, nor photons, nor leptons (with the exception of neutrinos) could reach Earth with energies $E_{CR} \geqslant 6 \times 10^{19}$ eV. This is not only related to the problem of generating particles of such high energies in an astrophysical source. The main complication consists in the particle retaining such energy in traveling through distances of a cosmological scale from the source where it was produced to Earth. The propagation of protons of ultrahigh energies is restricted by pion photoproduction processes in the microwave background. This is the well-known Greisen–Zatsepin–Kuzmin (GZK) effect, which results in a cutoff of the primary CR spectrum (Greisen, 1966; Zatsepin and Kuzmin, 1966). Protons of energies above the resonance production threshold lose energy in each reaction $p + \gamma_{MBG} \rightarrow \Delta^* \rightarrow p + \pi$. The proton interaction length L_{int} in this reaction is a value of about tens of Mpc. As for nuclei, they experience photodisintegration on the cosmic microwave background and infrared radiation, loosing on average from 3 to 4 nucleons per 1 Mpc for $E > 2 \times 10^{19} - 2 \times 10^{20}$ eV.

There exist no known sources within the limits of our galaxy that are capable of generating particles with energies above the GZK-cutoff of the CR spectrum. Most known sources, such as GRBs or AGNs, in which the acceleration of protons up to energies $E_{GZK} \geqslant 6 \times 10^{19}$ eV is theoretically possible, are at distances $D \geqslant 100$ Mpc from Earth. If events with energies $E_{CR} \geqslant 10^{20}$ eV are registered by detectors on Earth, then the primary proton energy inside a source at such a distance should be at least 2 orders of magnitude greater than the registered energy. However, the possibility of the existence of powerful sources of ultrahigh-energy cosmic ray at shorter distances from the Earth is not excluded (Taylor et al., 2011).

The universe is also opaque to photons of energies above 10 TeV. This limitation should be due to reactions of electron–positron pair production in the interaction of a primary cosmic photon with infrared, microwave and radio background photons $\gamma + \gamma_{BG} \rightarrow e^+ + e^-$. Evidently, the electron cannot serve as the particle causing the observed showers with energies above the GZK-cutoff of the CR spectrum either, since its energy losses during its propagation through the universe are great. At present, the only particle known to be capable of covering cosmological distances with virtually no absorption is the neutrino. The interaction lengths of neutrinos with TeV energies amount to 2.5×10^{11} g cm^{-2}; photons with the same energy cover distances of only about several hundred g cm^{-2}.

The observation of an extraterrestrial neutrino flux in the 0.1 PeV to 1 PeV range with the IceCube detector at the South Pole has signaled the beginning of the era of high-energy neutrino astronomy (Aartsen et al., 2013a, 2014a). The long awaited discovery of high-energy cosmic neutrinos has arrived. Since neutrinos are stable and can travel cosmological distances practically without undergoing absorption even with energies $E_\nu \gg E_{GZK} \sim 6 \times 10^{19}$ eV, neutrino fluxes from different astrophysical sources can be regarded as a sensitive instrument in studying the universe right up to its observable boundaries and to explore the origins of UHECR.

Possible astrophysical sources where protons and nuclei can be accelerated up to energies of $\sim 10^{20}$ eV include GRB and AGN (Becker, 2008). In such space ‘accelerators’, pp and pγ – interactions must produce charged pions decaying into UHENs with energies up to $E_\nu \sim 10^{19}$ eV. Neutrino fluxes could also be generated in decays or annihilations of relic superheavy particles produced in the early Universe and surviving up to now (Bhattacharjee and Sigl, 2000). Maximum neutrino energies in such scenarios depend on the mass of decaying heavy particles and can reach $E_\nu \sim 10^{24}$ eV (Kalashev et al., 2002; Barbot et al., 2003). The interaction of UHECRs with cosmic microwave background photons is the ‘guaranteed’ source of UHENs. Decays of pions produced in photoproduction reactions generate the so-called cosmogenic (or GZK) neutrino flux. The energy spectrum of the cosmogenic flux has a maximum at energies $E_\nu \sim 10^{19}$ eV. However, the value of this flux is indefinite due to the unknown form of the initial proton spectrum in sources, the proton source distribution over redshifts, and their evolution (Engel et al., 2001; Ahlers et al., 2010). UHECR nuclei also interact with the cosmic microwave and infrared backgrounds, undergoing photodisintegration. The disassociated nucleons then interact with the cosmic microwave and infrared backgrounds to produce cosmogenic neutrinos. The cosmogenic neutrino fluxes generated by the propagation of ultrahigh-energy nuclei over cosmological distances also calculated (Anchordoqui et al., 2007; Kotera et al., 2010). The possibility of measuring the cosmogenic neutrino flux is usually considered as the starting point in optimizing apertures of the planned neutrino detectors (Ryabov, 2006).

The central problem with both the ultrahigh-energy cosmic rays and neutrinos (UHECR and UHEN) event detection is related to the rarity of these events. The flux of CR particles at energies $E \sim 10^{20}$ eV is extremely low: it is less than one particle per km^2 per century. Therefore, for detection of such particles, detectors with huge areas (for CR) and volumes (for neutrino) are required. The ability of present-day and future experiments to register ultrahigh-energy particles is determined by the aperture of the detector in use Ryabov (2009).

Despite the progress in the development of UHECR detectors there is an ambiguity in the interpretation of experimental data in which the restored energy of the primary particle exceeds 10^{20} eV. Currently, for studying these particles, gigantic ground-based detectors with areas of a several thousand km^2 – Pier Auger Observatory (Abraham et al., 2010) and Telescope Array (Abu-Zayyad

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