LORD Space Experiment for Investigation of Ultrahigh Energy Cosmic-ray Particles

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Abstract. The problem of detecting cosmic rays and neutrinos of energies above the GZK cut-off is reviewed. Nowadays, it becomes clear that registration of nature’s most energetic particles requires approaches based on new principles. First of all, we imply the detection of the coherent Cherenkov radio emission in cascades of ultrahigh-energy particles in radio-transparent natural dense media, i.e., ice shields of Antarctica, mineral salt, and lunar regolith. The Luna-Glob space mission planned for launching in the near future involves the Lunar Orbital Radio Detector (LORD) whose aperture for cosmic rays and neutrinos of energies $E \geq 10^{20}$ eV exceeds all existing ground-based arrays. The feasibility of LORD to detect radio signals from showers initiated by ultrahigh-energy particles interacting with the lunar regolith is examined. The design of the LORD space instrument and its scientific potentialities for registration of low-intense cosmic-ray particle fluxes above the GZK cut-off up to $10^{25}$ eV is discussed.

1. Introduction

Investigating the nature of the most energetic cosmic particles ($E \geq 10^{20}$ eV) in the Universe is one of the “hottest” problems of modern science. The study of ultrahigh-energy cosmic rays and neutrinos opens a unique possibility to explore particle physics within the extremely high energy scale [1]. The ability of present-day and future experiments to detect ultrahigh-energy cosmic rays (UHECRs) is limited by the aperture of detectors in use. It could be quite possible that apertures of the Auger, Telescope Array, and even JEM-EUSO detectors would be insufficiently large to reliably detect UNECRs of energies $E_{\text{CR}} \geq 10^{20}$ eV (if they exist in the Universe).

The basic goal of the present-day neutrino astronomy is the detection of ultrahigh-energy neutrinos (UHENs) [2]. These neutrinos can be produced in remote astrophysical sources as a result of both super-heavy particle decays and the propagation of UHECRs in the interstellar medium. At present, several neutrino telescopes are under construction in Mediterranean Sea (ANTARES, NESTOR, NEMO, KM3NeT) and Ice Cube in the Antarctica. The effective volumes of water or ice exceed 1 km$^3$. New-generation neutrino telescopes allow the detection of neutrinos of energies up to $E_{\nu} \approx 10^{19}$ eV. However, if the neutrino flux turns out to be lower than the flux predicted by most advanced models, the volumes of water and ice ($\sim 1$ km$^3$), are insufficient to detect these neutrinos.

In order to detect cosmic rays and neutrinos of energies $E \geq 10^{20}$ eV, new methods based on novel principles are required. We here discuss the modern status of the Lunar Orbital Radio-wave Detector (LORD) experiment for exploration of the most ultrahigh-energy particles in the Universe. In the
LORD experiment, the Moon is used as a target for UHE particle interactions, and a system of lunar-satellite radio antennas will detect coherent Cherenkov radio emission produced by cascades initiated by ultrahigh-energy particles in the lunar regolith. Luna-Glob space mission planned for launch in the nearest future involves the LORD experiment. As a current state-of-art in Moon orbital technology, we consider the prospects for the detection of UHECRs and UHENs, which use the LORD.

2. Radio method for observation of ultrahigh-energy cosmic rays and neutrinos

In recent years, a method proposed by G. Askarian as early as in the beginning of 1960s [3], and based on the detection of coherent Cherenkov radio emission arising from cascades generated by ultrahigh-energy particles has become widespread. The most important advantage of this method is the possibility to exploit huge target volumes transparent to radio emission. The currently used radio method to detect UHEN in ice targets (blocks in Greenland and Antarctica) was approved in the FORTE, RICE, and ANITA experiments. It should be emphasized that experiments employing ground-based ice targets can detect only cascades initiated by ultrahigh-energy neutrinos. Cosmic rays do not reach the ice target and interact already in the upper layers of the Earth atmosphere.

The idea to employ the Moon as a target for detecting UHECRs and UHENs by the radio method was first proposed by G. Askarian [4]. In essence, production of cascades and generation of radio emission occur in the near-surface layer of the lunar soil, viz. in the radio-transparent regolith that consists of small stones ejected as a result of meteorite impacts with the Moon. Usually, the depth of the regolith attains 10 to 30 m. Radio emission is generated in a wide frequency band by a cascade initiated by an ultrahigh-energy particle within the solid angle close to the Cherenkov angle. A part of the radio emission after refraction at the “regolith-vacuum” interface escapes the lunar soil and can be registered by a radio telescope. As the Moon has no atmosphere, both UHECR and UHEN interactions with the lunar soil can be detected. In [5], R. Dagsamasanskii and I. Zhelenzykh have proposed using ground-based radio telescopes for this purpose. The radio method for UHECR and UHEN detection using such telescopes was utilized (or proposed to exploit) in the Parkes, GLUE, NuMoon/WSRT, and LUNASKA experiments.

In [6–7], we for the first time have proposed to detect radio emission from UHECRs and UHENs on the base of a circum lunar satellite in the framework of the LORD experiment. The basic features of this experiment have been presented elsewhere [8–12].

3. Conceptual design of the LORD instrument

Figure 1 illustrates the scheme of the radio emission registration from UHECRs and UHENs by a radio detector installed at an orbital spacecraft. An incident particle interacts with the lunar regolith and gives rise to a cascade whose excess negative charge generates the Cherenkov radio emission propagating within a cone of the semitange \( \Delta \theta_C \). The radio wave crosses the lunar surface, and then being refracted according to the laws of geometric optics, propagates in space for a large distance \( R_s \). By reaching the antenna A aboard the spacecraft at the altitude \( h \), the radio emission can be registered by the detector.

![Figure 1. Schematic diagram for registration of cosmic rays and neutrinos by the radio antenna A aboard a spacecraft.](image-url)
Currently, the LORD apparatus is under construction. It consists of a very sensitive two-channel broad-band (200 – 800 MHz) radio receiver equipped with a data acquisition system, a calibration system, a microcontroller and a power-supply unit. The antenna system of 7.5-dB gain consists of two log-periodic spirals for two opposite circular polarizations (figure 2). The low-noise amplifier has the gain of about 30 – 40 dB and the noise factor of 1.1 dB.

Depending on observations, the frequency band can be optimized for a high signal-to-noise ratio with the goal to increase the statistics of events. To conjugate the analog and digital blocks, attenuators and supplementary amplifiers are envisaged. Finally, signals detected by the antennas arrive at analog-to-digital converters (ADCs, 2 Gsps, 10 bit).

Signals arriving at the ADCs from the analog electronics are digitized and transformed by 1:4 demultiplexers. For the trigger system, the FPGA architecture is used. The trigger for an UHECR or an UHEN interaction is formed as a coincidence of signals exceeding threshold values for any antenna within the time gate of about 10 ns. In figure 3, a typical simulated variant of the trigger event is presented. The data from the FPGA memory are recorded by the onboard computer for subsequent processing, packing, and transmission to the Earth.

Figure 2. Schematic view of the LORD antenna system.

Figure 3. Trigger simulation for an UHECR or UHEN signal: the coincidence of signals exceeding a threshold value for any antenna within the time gate of about 10 ns.

4. Monte Carlo simulation of the LORD aperture for registration of cosmic rays and neutrinos

Capabilities of existing and planned experiments on the detection of UHECRs and UHENs are determined by the energy dependence of the aperture of the experiment, which is associated with target’s characteristics. The registration apertures for cosmic rays and neutrinos of energies of $10^{18} - 10^{19}$ eV were calculated by the Monte Carlo method. The simulation procedure was presented in detail in [8, 10]. The calculation of the aperture was carried out with the allowance for the geometric size and basic characteristics of the Moon regolith and the orbital radio detector rotating about them. The following simulation algorithm was used. First, the number of particles hitting the target was calculated in accordance with the energy spectrum $E^k$, where $k$ is the exponent of cosmic-ray or neutrino energy spectra. Then, spherical angles for points of particle’s incidence and arrival angles were simulated, as well as, energy and interaction depth for neutrino interaction. Finally, threshold conditions were imposed, and the aperture was calculated by integrating over spherical angles. The results of the LORD aperture calculation under these conditions are presented in figure 4 for UHECRs and UHENs.

Figure 5 exemplifies the results obtained for different experiments and projects associated with ultrahigh-energy cosmic-ray and neutrino detection. The hatched regions in Figures 4 and 5 correspond to uncertainties in the simulation model used. As is seen in figure 5 in the energy range above $10^{20} - 10^{22}$ eV, the performances of the LORD experiment are the best.
5. Conclusion
The LORD experiment will make it possible to obtain important information on the highest-energy particles in the Universe, to verify modern models of the origin and the propagation of UHECRs and UHENs. The LORD apparatus (antenna system, amplifiers, and data acquisition system) now is designed and under construction. The Monte Carlo method was applied to calculate the LORD apertures aboard a circum lunar spacecraft. The calculations were carried out for the energy range of $10^{18} - 10^{25}$ eV with account for physical properties of the Moon such as its density, lunar regolith radiation length, radio-wave absorption length, refraction index, and radius. Modeling has separately been performed for UHECRs and UHENs because of a significant difference in the pN- and νN-interaction cross sections. We may conclude that the LORD experiment surpasses in its apertures and capabilities the majority of well-known current and proposed experiments dealing with the detection of both UHECRs and UHENs.

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