Lunar Space Missions for Ultrahigh-energy Cosmic Rays and Neutrinos Observation

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Abstract. Two stages of exploring the lunar surface as a target for the interaction of ultrahigh-energy cosmic rays and neutrinos are discussed. The first step is connected with the Lunar Orbital Radio Detector (LORD) experiment in the space mission Luna-Glob, scheduled for the near future. The current status of the LORD instrument development is represented. The aperture of the lunar orbital radio detector exceeds all existing ground-based detector arrays. Successful completion of the LORD experiment will permit to consider the second step of the program namely multi-satellite lunar systems to increase the statistics and the accuracy of the experiment.

Keywords: GZK cut-off, ultrahigh-energy particles, radio detector, regolith, Vavilov- Cherenkov radiation, multi-satellite lunar systems
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1. INTRODUCTION

Studies into the nature of sources and spectra of cosmic particles having the highest possible energies in the Universe are among the interesting issues of modern physics and astrophysics [1-7]. New experimental data of such particles are important for solving fundamental problems of astrophysics and particle physics related to acceleration mechanisms of cosmic rays and neutrinos, as well as to the nature of dark matter. The capabilities of current and future experimental installations to detect ultrahigh-energy cosmic rays (UHECRs) are restricted by the aperture of the current detectors. Despite the progress in the development of detectors there is an ambiguity in the interpretation of experimental data for energies above $E_{CR} \approx 10^{20}$ eV. This is due to insufficiently large apertures of giant ground-based detectors. One of the purposes of latter-day neutrino astronomy is the detection of ultrahigh-energy neutrinos (UHENs). New neutrino telescopes have volumes exceeding 1 km^3 and allow for the detection of neutrinos with energies of up to $E_\nu \approx 10^{19}$ eV and more. However, if the neutrino flux turns out to be lower than that predicted by the most pessimistic models, the proposed detectors will be insufficient for its detection. To detect cosmic rays and neutrinos with energies $E \approx 10^{20}$ eV, a new generation of detectors based on novel principles and using modern experimental technologies is required. In recent years, a method based on registration of coherent Vavilov-Cherenkov radio emission from cascades in radio-transparent media generated by ultrahigh-energy particles was experimentally tested and has become wide-spread. As a current state-of-the art in Moon orbital space technology, we consider the prospects of detecting UHECRs and UHENs by LORD [8-11]. The current status of the LORD instrument development is represented. The detection potential of space experiments which utilize the surface layer of the Moon as a target for particle interaction was estimated in the papers [8-11]. Multi-satellite lunar systems as a development of space technology are proposed.

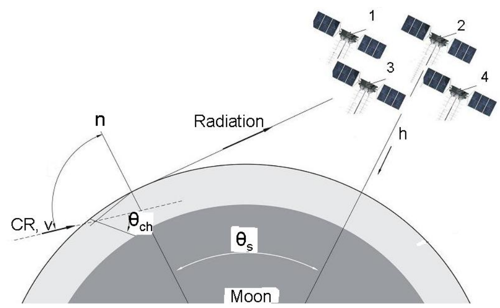

FIGURE 1. Sketch of a four-satellite system orbiting the Moon.

2. RADIO DETECTION AND DESIGN OF THE LORD INSTRUMENT

In recent years, it became apparent that a very promising method for detecting both UHECR and UHEN is the method originally proposed and justified in the Lebedev Physical Institute. In this method the Askarian effect of coherent radio-wave Vavilov-Cherenkov radiation (radio-method for short) is used [12]. The idea to use the Moon as a target for neutrinos (and cosmic rays) detection by the radio method using receivers on the lunar surface was originally proposed also by G. Askaryan [13]. Currently the radio method of registering UHEN using ice as target was successfully employed in the experi-

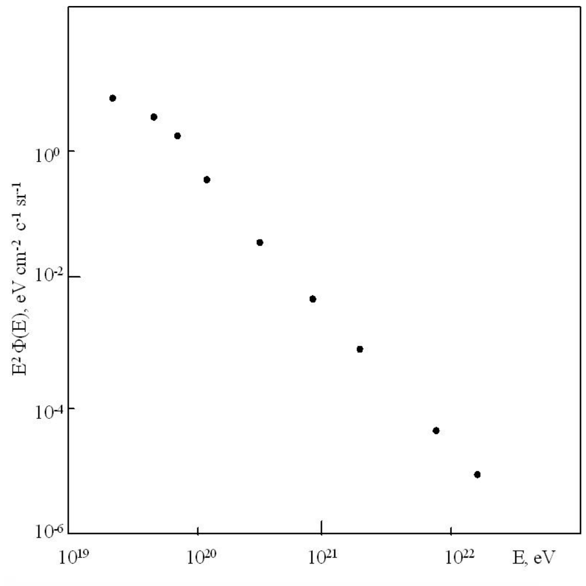

FIGURE 2. CR spectrum extrapolated from AUGER data [20].

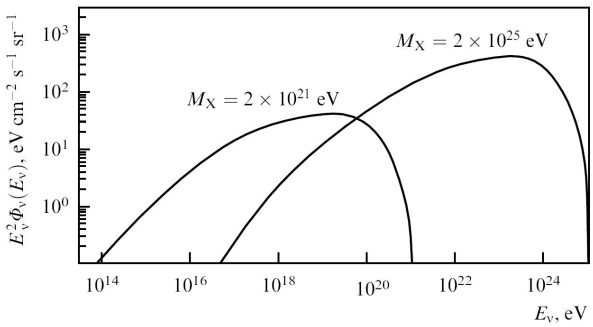

FIGURE 3. Neutrino spectra due to the decay of X-particle [21] of a mass $2{\cdot}10^{21}$ eV and $2{\cdot}10^{25}$ eV.

ments GLUE [14], FORTE [15], RICE [16], NuMoon [17] and ANITA [18]. In ANITA, the most recent of the experiments, 36 horn antennas were used in the high-altitude balloon flight around the Antarctic continent. At an altitude of about 40 km a total volume of about $\sim 9 \cdot 10^5$ km^3 of the ice target can be browsed. By now two flights of balloons were realized with a total duty time of 66 days [18,19]. The analysis of these experiments does not reveal certain candidates for UHEN events. Currently, the LORD apparatus is under construction. It consists of a very sensitive two-channel large-band (200-800 MHz) radio receiver with data acquisition system, calibration system, microcontroller and power supply. The antenna system consists of two log-periodic spirals with two circular polarizations and an average gain of 7.5 dB. The low noise amplifier (LNA) for the antenna signals has a gain of about 30-40 dB and a noise factor of 1.1 dB (about 30 K). Depending on observations the frequency band may be optimized for a high signal-to-noise ratio with the aim to increase the statistics of event registration. To match the dynamics of the analog part to the digital block, the attenuators and supplementary amplifiers are envisaged. For the trigger system a FPGA architecture is used. Signals with noise during 1024 ns before and after them are routed to a 16-bit microcontroller and are stored in a 16 MB memory, the microcontroller being linked with the data acquisition system and the spacecraft memory.

3. MULTI-SATELLITE LUNAR SYSTEM SIMULATION

It is considered to use the LORD experimental technology to create a lunar orbital multi-satellite systems (LOMS). In the framework of these studies, the detection of cosmic rays (CRs) and of neutrinos by LOMS was simulated. The sketch of a four-satellite system is given in Fig.1,which illustrates the scheme of the radio emission registration from UHECRs and UHENs by a radio detectors installed at four orbital spacecrafts. 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 with semiangle θ_{ch} . The radio wave crosses the lunar surface, and then is refracted and propagates in space in the direction to the group of the satellites orbiting at the medium altitude h. The angle between the normal, to the lunar surface and the radius, connecting the center of the moon and the exit point of the radio emission from the cascade, is designated as θ_s . Based on the CR spectrum extrapolated from the AUGER data [20] (see Fig. 2), we have simulated certain parameters of the registration process (for a satellite altitude of 1000 km and a detection threshold for the electric field fixed at 0.2 μV/mMHz). The signal coincidence was considered in 2, 3 or 4 radio detecting modules separated latitudinally by 2 angular degrees.

The expected number of events attained in one, two, three, and four modules is 28, 24, 20, and 19 per year, respectively (for a CR-energy detection threshold of about 10^{20} eV). For a module separation of 12 angular degrees, we found 23, 3, 0, and 0 events in one, two, three, and four modules, respectively. This implies that the significant spatial separation (exceeding 15 angular degrees) makes the registration of the same CR impossible in two or more separated modules because the registration in each module occurs independently. In this case, events coming from different areas of the lunar surface are registered in different modules, with the statistics increas-

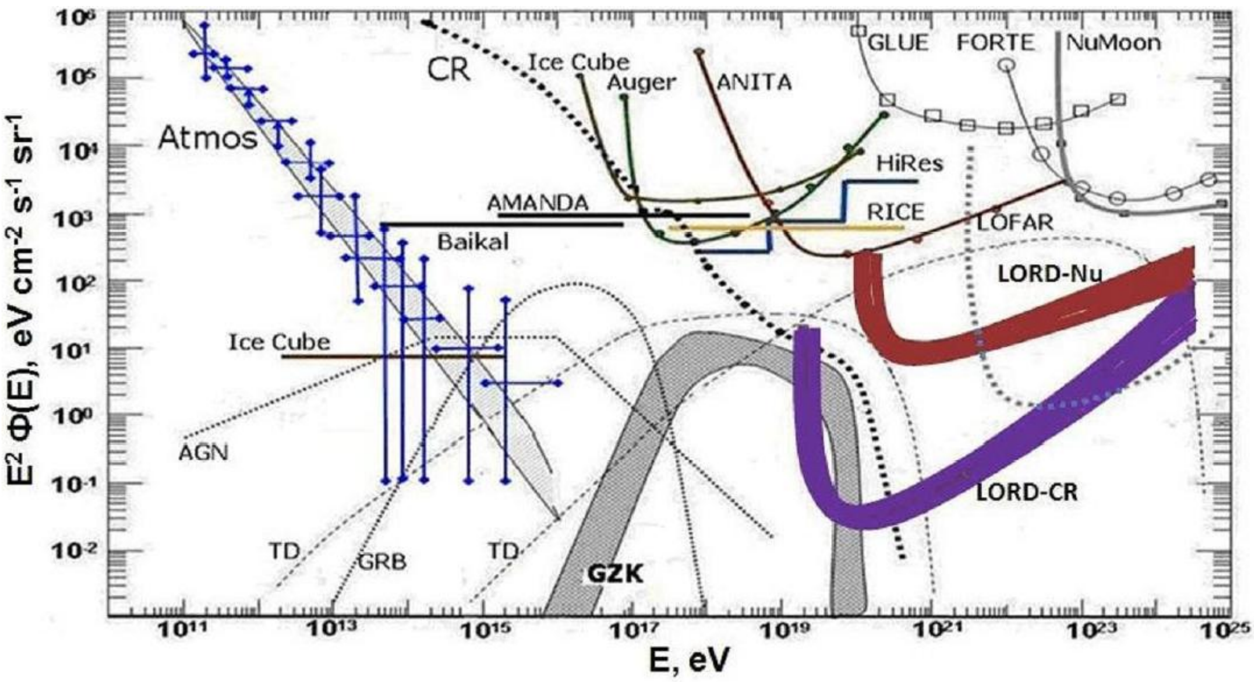

FIGURE 4. Experimental bounds for ultrahigh energy cosmic ray and neutrino fluxes.

ing proportionally to the number of separated modules. We now analyze, as an example, results of the neutrino-detection simulation in the top-down scenarios. We assume the mass for a decaying X-particle [21] to be $2{\cdot}10^{25}$ eV (see Fig. 3)and the separation of modules to be 10 angular degrees. In this case, for one, two, three, and four modules, we arrive at 40, 34, 27 and 22 events, respectively (for 10 degrees separation). Thus, in the case of a radio-detector array for neutrino detection (NA), it is possible to realize a radio-detector array that presents better possibilities for reconstructing events, as compared with one detector. Thus, the simulation results have shown that it is possible to construct an array for simultaneous registration of both CRs with a small admixture of neutrinos (cosmic ray array(CRA)) and neutrinos with a small admixture of CRs (neutrino array(NA)). Events that are registerred in more than one module are considered neutrinos, if they are registered in only one module, they are considered CRs. The aperture of a CRA (4 satellites) exceeds the LORD aperture by a factor of four. At the same time, the NA aperture can be about two times smaller than the LORD aperture, because the area seen from 4 satellites is approximately two times less for 10 degrees separation. However, it is not difficult to discriminate CRs and neutrinos with LOMS, wheras it is not easy with a one-module LORD detector. The maximum aperture for the lunar CRA (24 satellites) can exceed the LORD aperture by a factor of twenty-four. On the surface of the Earth, this huge aperture for CR registration is unattainable. To conceive the performances of the LORD experiment let us refer to Fig. 4, which exemplifies the results obtained for different experiments and projects associated with ultrahigh-energy cosmic-ray and neutrino detection. The LORD sensitivities are given for a time factor, equal of 1 year. The TD (topological defect) model [21] used in the simulation corresponds to the second curve (TD) with higher neutrino flux in Fig. 4. The references to all experiments exemplified in Fig. 4 are given in [22]. The hatched regions correspond to uncertainties in the simulation models used. As is seen in Fig. 4 in the energy range above $\sim 10^{21}$ eV, the performances of the LORD experiment are the best.

4. CONCLUSIONS

The LORD apparatus (antenna system, amplifiers, and data acquisition system) has been developed and now is under construction. Currently, all electronic components are investigated with the goal to develop the array performance in order to improve the determination accuracy for physical parameters studied in the LORD experiment. The simulation results for the circumlunar CR array (CRA) show the possibility to increase the CR-registration aperture proportionally to the number of satellites, with neutrino events being a small background. The same array of LORD detectors can be used simultaneously as CRA and as NA with a small background of CR events. For the CRA, the apperture will be increased 24-fold with respect to that of a single LORD detector while the capabilities for cascade energy reconstruction will be similar in both cases. In the case of the NA, the capabilities of a multi-satellite system for cascade energy reconstruction exceed significantly those of the single LORD detector.

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