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The Prospects of Radio Detection of UHECRv on the Moon's Surface

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Abstract: Detection of Ultra High Energetic Cosmic Rays and Neutrinos (UHECRv) using the Moon surface has been a hot topic of astrophysics in the recents years. In light of presently considered lunar missions, we present the opportunities for detection of UHECRv radio emissions using a single antenna on the Moon surface. The novel design is including a tripole antenna and a digital receiver to operate at low frequencies up to 100 MHz. This range is known as the optimized window for detection of UHECRv coherent radio emissions. Besides it covers the frequencies (below 10 MHz) which are not accessible from the Earth and is much less affected by terrestrial RFI. We therefore propose the experiment as an excellent complement for ground-based observations of UHECRv.

Keywords: UHE Cosmic Rays, Neutrinos, Radio Detection, Moon Surface, Lunar Radio Explorer (LRX).

1 Introduction

Lunar Radio eXplorer (LRX), is an experiment initially planned for the European Lunar Lander mission but can be adapted for other Lunar lander missions. LRX uses a tripole antenna with 2.5 m length (tip to tip) and a sensitive digital receiver in a broad spectral range of 5 kHz-100MHz. The tripole antenna consisits of 3 orthogonal dipoles. Technical requirements and science cases of LRX are described in details in [1, 2].The experiment aims to observe radio emissions on the Lunar surface. One of the scientific aspects for LRX is to detect radio pulses caused by UHECRv. It has been well known that Moon surface can act as a detector for UHECRv [3]. The phenomenon, Askaryan Effect, occurs when the UHECRv interacts with a dielectric medium such as Moon regolith which results in propagation of coherent radio pulses known as Cherenkov radiation. The radio spectrum extends up to microwave frequencies (cm wavelengths) in dielectric solids but it also reaches a peak at lower frequencies [4], which is within the frequency range of LRX. The intensity of radio emission depends on the energy of cosmic ray particles. The detectable signal is identified with the distance to the observer (i.e Antenna), the sensitivity of the receiver and electromagnetic properties of the Lunar regolith. The radio emissions contain important information about the energy and the composition of UHECR. In addition, the LRX is capable of localising the radio emissions [5] which could hint towards the possible source of UHECRv which is not answered yet by certain. In this paper we briefly introduce the analytical methods used for detection of UHE Neutrinos and CRs using LRX characteristcs and Lunar regolith parameters. The results are discussed and compared with those predicted for LOw Frequency ARray (LOFAR) [4, 6] and Lunar Orbiter Radio Detector (LORD) [7] as examples of ground based and lunar orbiter observations. In addition we introduce the radio emissions in the lunar environment and discuss the methods to localize the UHECRv events and to distinguish between the Cosmic Rays and the Neutrino events.

2 UHECRv Detection

2.1 UHE Neutrinos Detection

An analytical method was presented in [8] to calculate the aperture for UHE neutrinos colliding with Moon. The aperture consists of the physical area in the antenna FoV (the black area in the Fig.1) times a complex function P(E) which represents the probability of neutrino interaction with Moon surface to produce Cherenkov radiation in the area:

$$A(E) = A_0\, P(E) \tag{1}$$

$$where \quad A_0 = \pi R_{ap}^2 \times 4\pi \; and \tag{2}$$

The function P(E) is defined by properties of Cherenkov radiation in the Lunar environment. We used the method by applying the LRX system parameters and modified it by adding the effect of radio emissions inside the lunar regolith using the formula presented in [9] and by taking into account the attenuation of the lunar regolith. This is for neutrino events which occur inside the regolith. The total aperture for UHE neutrino then becomes a virtual cone which covers both the events on the surface and those occurs inside the lunar regolith (Fig.1).The LRX antenna is assumed to be 3 m above the Moon surface which is an estimate for the height of the lunar lander. As the Moon is opaque to the UHE neutrinos, both downward and upward neutrinos can produce the Cherenkov radiation. Also surface roughness plays a role by scatterring the radiation [8] . However, analysis shows that at LRX frequencies the major contribution is from downward neutrinos. Typical numbers for refractive index of lunar regolith (n_r=1.73) and sublayers (n_r=2.5) [9] have been used in the aperture calculation. Considering the height of antenna and the radius of the Moon, the maximum line of sight is about 3 km which identifies the largest area of UHECRv detection. The actual physical area of UHECRv detection depends on the sensitivity of the receiver and the intensity of the Cherenkov radio emission: [8]

$$\varepsilon_{min} = N_{\sigma}\left(\frac{2\,k_b\,T_{sys}\,Z_{Moon}}{A_e\,\Delta v\,n_r}\right)^{1/2} \quad V/m \tag{3}$$

Here ε_{min} is the minimum detectable electric field by the radio receiver. It is identified by the system noise temperature T_{sys}, the antenna collecting area A_e and the receiver bandwidth Δv so the more the number of antennas and the broader the bandwidth the better the sensitivity. K_b is the Boltzmann's constant and Z_{Moon} is the impedance of the lunar regolith. n_r is refractive index of the lunar regolith and N_σ is the minimum standard deviation to reject the statistical noise (here it is set to 5). For current LRX design (f= 50 MHz, Δv=100 MHz) the sensitivity is 1.5 Microvolt / (m MHz).

To detetc the events, the intensity of the received signal should be greater than the ε_{min}. The intensity of the radio emission of UHECRv at the antenna place depends on the energy of the particles, the distance of the impact and the frequency of observation: [9] .

$$\varepsilon_0(d,\ f,\ E) \propto \frac{V}{m\,MHz}\left[\frac{d}{m}\right]^{-1}\left[\frac{E_s}{EeV}\right]F(f) \tag{4}$$
$$where\ E_s = 0.2E\ \ for\ v\ and\ E_s = E\ for\ CR$$

The factor 0.2 represents the percentage of the neutrino energy which is converted to the energy of hadronic shower. The frequency dependence function F(f) is different for the regolith and its sublayers[9]. Here we only present the simulation results for the observing frequency of 50 MHz which gives the maximum bandwidth. However LRX can be set up at different frequency subbands. This is particularly important at low frequencies below 10 MHz which is not accesible from the Earth due to the ionospheric blockage. This range is a bit off the peak of the shower spectrum but gives the bigger aperture and less attenuation therefore higher chances for UHECRv detection. It is also important that LRX can be set up at higher frequencies where strong RFI (e.g. FM band) interupts the terrestrial observation, while LRX in principle could benefit the relatively quiet lunar environment. Both cases are being investigated by our team and will be presented in the future work.

With calculating the aperture and applying it into the standard models of neutrinos flux densities, one can estimate the detection rates for a certain period:

$$N_v = T\sum_{E_1}^{E_2}\Phi_v(E)\,A(E)\,\Delta E \tag{5}$$

3 models for the various neutrino process are presented (Fig.2). Possibly the most interesting one is the GZK neutrinos which corresponds to the Greisen-Zatsepin-Kuzmin (GZK) limit of about 5×10^{19} eV. As the UHECR interaction with cosmic microwave background (CMB) generates neutrinos through the secondary pion decay process (GZK effect), the detection of neutrinos at GZK limit [10], can justify the observations of cosmic rays with energies above the GZK limit . For the neutrinos with energies well beyond

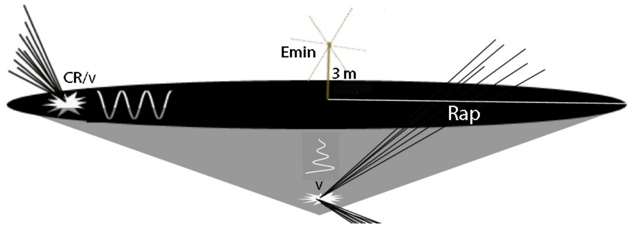

Figure 1: A sketch of UHECRv detection using LRX experiment on the Moon surface.

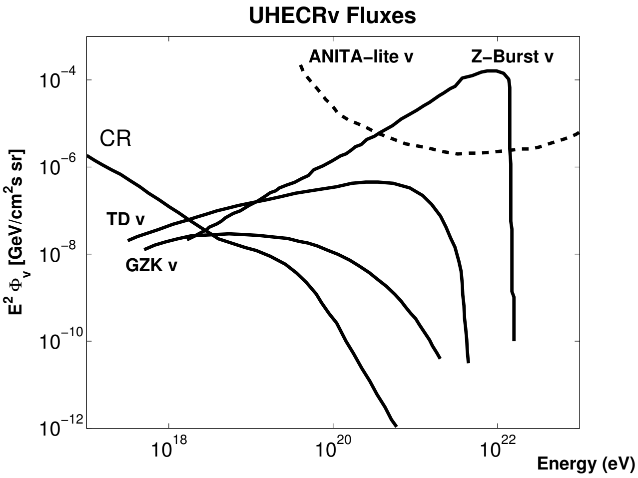

Figure 2: Predicted fluxes for Cosmic Rays (CR) [13] and neutrinos in GZK [10], Topological Defects (TD), Z-Burst processes [14] and ANITA-lite v flux limit [15]

the GZK limit the Topological Defects (TD) [e.g. [11] and Z-Burst processes [e.g. [12]] are suggested. For calculation of the occurrence of Z-Burst neutrinos we limit the model with Anita observations [15] up to 1.6×10^{-6} GeV cm^{-2} sr^{-1} s^{-1} the same way that has been applied in [6] .

2.2 UHECR Detection

The method in [8] has been developed in [16] for detection of UHE Cosmic Rays which collides with Moon. The main difference is that CR, containing energetic primary particles, can not penetrate through the lunar regolith therefore only surface impacts are taken into account.(downward CR, upper left in Fig.1). For surface events, the radio emission is propagated in the lunar exosphere so attenuation is neglected. Again the event rate is estimated using the known CR flux density model [13] and the calculated apertures (Fig.3).

Finally, the LRX fluxes plotted in Fig.4 are calculated using the same method used in [6]:

$$E\Phi_v(E) \leq \frac{S_{up}}{A(E)\,T} \tag{6}$$

Here S_{up} is the Poisson factor set to 2.3 for a limit of 90 % Confidence Level(CL).

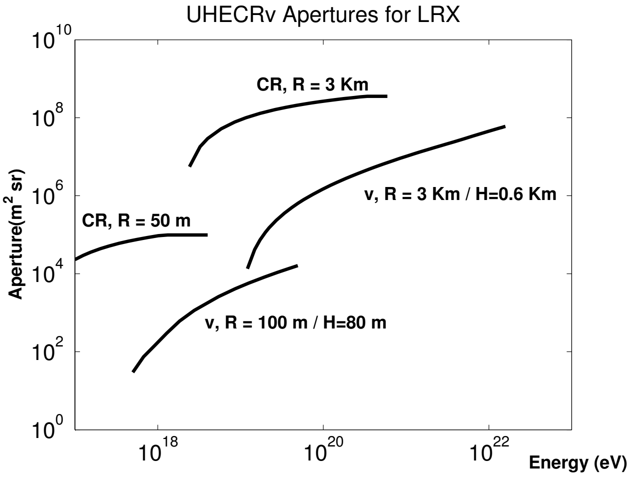

Figure 3: The calculated 1 apertures of LRX experiment for UHECRv detection on the Moon surface.

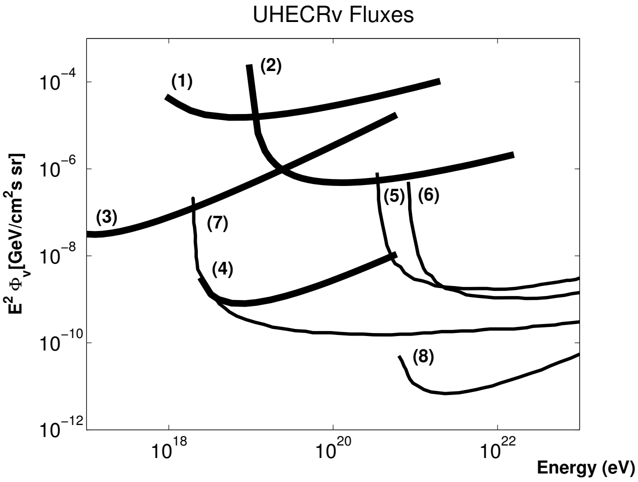

Figure 4: The calculated 6 E ^{2}-weighted flux of UHECRv for 1 year observation of : (1) LRX v, R=100 m/H=80 m; (2) LRX v, R=3 Km/H=0.6 Km; (3) LRX CR, R=50m ; (4) LRX CR, 3 Km. Results are compared to flux of (5) neutrinos(v) with a tripole antenna at 100 km and frequency of 100 MHz [6]. Also fluxes for (6) 30 day observation of LOFAR v [4] ; (7) 1 year observation of LORD v at 1000 km and 500 MHz [7] and (8) 30 day observation of LOFAR CR [4].

3 Results

The predicted LRX aperture 1 for UHECRv detection is plotted in (Fig.3). Here we seperate the events to the nearby and distant events. For CR, the nearby events occur within the distance of 50 m from the antenna. For neutrinos the events occur either within 100 m from the antenna on the surface or 80 m inside the lunar regolith. These typical numbers represent closeby antenna areas and are chosen to show the possibility of detection of less energetic events for one year observation time. On the other hand, the aperture for distant range up to 3 km is defined. This range is the maximum antenna line of sight at the height of 3 m on the Moon surface. The aperture at 3 km range, corresponds to the more energetic events. For the neutrinos events this area will be added to the area inside the regolith up to the depth of 600 m where the radio emission of the possible impacts is attenuated but still detectable with LRX antenna . These two type of events overall have a broad energy range of 10^{17} eV to 10^{22} eV which mostly covers the energy range of CR and neutrino flux models.

Using 6 and calculated apertures, the flux densities of LRX for different regimes are illustrated along with the predicted results of other experiments in Fig.4. It can be seen that even though the sensitivity of LRX (for one year observation) can not compete with large array radio telescopes such as LOFAR (the LOFAR flux is for 30 days observation) but LRX can detect the events with lower energy which is out of reach for LOFAR observation. Particularly LRX CR curves have a reasonable sensitivity to detect lunar surface CR emission as suggested by [17]. The predicted results for other experiments, a tripole at 100 Km [6] and LORD at 1000 Km [7] , are only for neutrinos so should be compared with LRX v (curves 1,2 in Fig.4). With LORD set up at the same LRX sentivity, frequency of 500 MHz and much larger detectable area of the Moon surface, the chance of detecting GZK neutrino is 50 times more but LRX would detect more CR events. (see 1). For the detection of different type of neutrinos, LRX behaves similar to the tripole antenna at 100 MHz and 100 Km altitude but at a lower detection rate which is likely due to the much smaller detectable area. Again the LRX advantage will be in detection of lunar surface CR emissions at the low energy regime. The aperture calculation and the event rates have been examined with the method presented in [7] and comparable results have been achieved. Table 1 show the predicted event rate for detection of UHECRv events using LRX, tripole at 100 Km and LORD experiment.

Experiment/Time	Radio Emission	Events
LRX/1Yr	UHECR Low Energy	135
LRX/1Yr	UHECR High Energy	122
LRX/1Yr	UHE-GZKv	0.02
LRX/1Yr	UHE-TDv	6
LRX/1Yr	UHE-ZBurstv	29
Tripole 100 Km/1Yr	UHE-GZKv	0.05
Tripole 100 Km/1Yr	UHE-TDv	220
Tripole 100 Km/1Yr	UHE-ZBurstv	3300
LORD 500 MHz/1Yr	UHECv	1
LORD 500 MHz/1Yr	UHECR	20

Table 1: The event rate of Lunar UHECRv Radio Detection for Various Experiments

4 Radio emissions in the lunar environment

Table 2 shows various radio emissions in the lunar environment which could be picked up by LRX antenna. Auroral Kilometric Radiation (AKR) and Radio Frequency Interference (RFI) are two major terrestrial noises which cover the LRX frequency spectrum. The radiation from the Sun and large planets, if visible from the landing site, will affect the spectrum too. These radiations are strong and can be considered as point sources from the sky, therefore,

Radio Emission	Characteristics	Detection
Terrestrial noise (AKR,RFI)	On the Earth visibility	Removal by post data processing
Sky Radio Sources (Sun, Planets)	Strong Point Sources	Digital Beamforming
Galactic background noise	Global emission	Removal by post data processing
Lunar Dust and Charged Particles	Nearby Antenna Surface Emissions	Antenna Dust Camera and Langmuir Probe
Impacts of Micro Meteorites	Nearby Antenna Surface Emissions	Antenna, Dust Camera and Langmuir Probe
UHECR	Lunar Surface (Horizontal Angles)	DOA methods/ post data processing
UHECv	Lunar Surface and Regolith	DOA methods/ post data processing

Table 2: Major radio emissions in the lunar environment

should be distinguishable from the UHECRv short pulses which come from the lunar surface. The global galactic noise background can be also subtracted from the spectrum by post data processing (e.g. data averaging). The most likely radio emission to be confused with UHECRv radio emission are the pulses due to the dust discharge and impact of micrometeorites on the Antenna and its nearby surface. Although their peak occurs in the KHz regime, they could have frequency overlap with UHECRv pulses. Depending on the distance of the impact from the antenna, the pulse intensity varies but they could be at the same level of those for UHECRv radiation. However, the pulses from UHECRv are likely to come from far distances (Farfield antenna pattern) and at horizontal angles while radiation from micrometeorite and dust particles are only detectable in the nearby antenna (Nearfield antenna pattern). For the European Lunar Lander mission, a dust camera and Langmuir probes were proposed to be mounted on the lander which can detect these events and separate them from the UHECRv events. The UHECR at the lower energy levels (nearby events) could be seperated from UHECRv events at higher energy levels (distant events) by DOA finding of the received signal. DOA technique ([5]) using LRX tripole antenna calculates the direction of the detected pulses using 3 orthogonal components of the received signal. These components identify a vector which shows the direction of the signal. By determining the angle of the vector with the horizon one can estimate whether the signal is coming from the nearby or distant area. There are also minor neutrino events which occur inside the regolitgh but the majority of detected neutrino events would be the surface events and could have the same direction as cosmic ray events have. Therefore most of the cosmic ray events and neutrino events are pretty much similar from the antenna point of view. This means that the received signal can be from the either event. The overlap between the energy level of the UHECR and UHECv radio emissions makes the distinction even more difficult. Due to the differences in the impact depth of two categories, it is likely that generated cascade showers behave differently in each case and have different characteristics (e.g. polarization, propagation paths). This is being investigated by our team using the simulation of the wave propagation in the lunar environment.

5 Conclusion

Considering future lunar missions, we present the possibility of UHECRv detections using only a single tripole antenna on the Moon surface. For one year observation, a significant number (257 CR and 35 Neutrinos) of events is expected. The detectable events by LRX mostly occur at lower energy levels which the generated pulses are too weak to be detected from the ground based radio arrays such as LOFAR. In addition LRX observations include frequencies below 10 MHz which is not accessible from the Earth and it is less affected by terrestrial noises (AKR and RFI).

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