Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 62 (2018) 2708–2728

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Prospects of probing the radio emission of lunar UHECRν events

A. Aminaei [a,*], L. Chen [b], H. Pourshaghaghi [c,d], S. Buitink [e], M. Klein-Wolt [c]
L.V.E. Koopmans [f], H. Falcke [c,g]

[a] Department of Physics, University of Oxford, OX1 3RH, UK
[b] National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China
[c] Department of Astrophysics/IMAPP, Radboud University, Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
[d] Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands
[e] Astrophysical Institute, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
[f] Kapteyn Astronomical Institute, University of Groningen, PO Box 800, NL-9700 AV Groningen, The Netherlands
[g] ASTRON, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands

Received 7 April 2017; received in revised form 19 July 2018; accepted 31 July 2018
Available online 13 August 2018

Abstract

Radio detection of Ultra High Energetic Cosmic Rays and Neutrinos (UHECRν) which hit the Moon has been investigated in recent years. In preparation for near-future lunar science missions, we discuss technical requirements for radio experiments onboard lunar orbiters or on a lunar lander. We also develop an analysis of UHECRν aperture by including UHECν events occurring in the sub-layers of lunar regolith. It is verified that even using a single antenna onboard lunar orbiters or a few meters above the Moon's surface, dozens of lunar UHECRν events are detectable for one-year of observation at energy levels of 10^{18}–10^{23} eV. Furthermore, it is shown that an antenna 3 m above the Moon's surface could detect lower energy lunar UHECR events at the level of 10^{15}–10^{18} eV which might not be detectable from lunar orbiters or ground-based observations.

Keywords: UHECRν; Cosmic rays; Cosmic neutrinos; Lunar lander; Lunar orbiter; Space radio experiment

1. Introduction

Radio emission from the cascades of energetic particles has been studied intensively in recent years. Particle accelerators such as Stanford Linear Accelerator Center (SLAC) produces radio emission from particle cascades (Saltzberg et al., 2001; Belov et al., 2015). Along with lab experiments, radio experiments for studying the cosmic energetic particles in air showers and on the lunar surface are being developed. These experiments help to investigate the fundamental questions about the UHECRν such as their origin and the acceleration mechanism. The Moon has been long known as a detector for UHECRν events. The unique properties of Moon regolith such as very low conductivity and low attenuation makes it an ideal environment for detection of coherent radiation based on the Askaryan effect (Askaryan, 1965). We refer to this radio emission, also known as Cherenkov-like radiation, as Askaryan radiation through the paper (as stated in James et al. (2011) and ter Veen et al. (2010)). Askaryan radiation is spread over a broad spectrum covering microwave frequencies (GHz band corresponds to cm wavelengths) in dielectric solids, but it may also reach a peak at lower frequencies within tens of MHz (Scholten, 2007). Most of radio UHECRν experiments at MHz regime operate, however, at frequencies higher than 100 MHz where dispersion in the Earth's ionosphere, and the Galactic background

* Corresponding author.
E-mail address: amin.aminaei@physics.ox.ac.uk (A. Aminaei).

https://doi.org/10.1016/j.asr.2018.07.036
0273-1177/

noise, become low. Also the dimension of antennas becomes reasonably smaller at higher frequencies. In our analysis frequencies of 1.5 GHz and 150 MHz represent the GHz and MHz frequency regimes. From theoretical estimates (Zas et al., 1992) and the SLAC experiments (Saltzberg et al., 2001) can be understood that the dominant mechanism for producing lunar UHECRv radiation is charge excess. This is mainly due to the absence of strong magnetic fields, such as the Earth's magnetic field, which is a key element in radio emission of air showers. The impact of energetic charged particles with lunar regolith generates electromagnetic pulses which develop and propagate as a cascade of electric currents through the layers of lunar regolith and lunar exosphere. Antennas onboard lunar orbiters, a lunar lander or a ground-based array can detect these events by measuring corresponding electric fields (also known as the lunar Askaryan technique (Dagkesamanskii and Zheleznykh, 1989)). In this paper we generalize the analytical methods in the literature for calculating the UHECRv apertures of ground based arrays so it can be used also for lunar orbiter experiments as well as for antennas on the Moon's surface. For the latter we modified the method and included the events occurring in the sub-layers of lunar regolith. The results are used to estimate the number of events that can be detected for various radio experiments for a one-year observation.

- Radio Experiments of Lunar UHECRv Emission
- Analysis of Lunar UHECRv Events
- Categorization of Lunar UHECRv Events
- Technical Requirements of Future Lunar Radio Experiments
- Summary and Conclusion

2. Radio experiments of lunar UHECRv emission

Radio detection of lunar UHECRv emission is limited by antenna sensitivity which depends on the effective collecting area of antennas. Thus large ground-based antenna arrays provide the highest sensitivity, however, the measured electric field of lunar UHECRv emission is weak because of the distance. Another limiting factor is the physical area of the Moon which is illuminated by antennas. As shown in Fig. 1, the physical area depends on the beamwidth of the antenna and its distance from the lunar surface. The larger the area the higher chance of detection of lunar UHECRv events. A probability function then relates the physical area to the actual aperture for detection of UHECRv events. The probability function depends on the electromagnetic properties of UHECRv. It also depends on system parameters that we will shortly present. There are various experiments capable of detection of Lunar UHECRv events (Bray, 2016). We compare the expected outcome of the LOw Frequency ARray (LOFAR) (Hörandel et al., 2009) and the Square Kilometer Array (SKA) (Bray et al., 2014) telescopes with observations from a lunar orbiter or the lunar surface (e.g. antenna onboard a lunar lander).

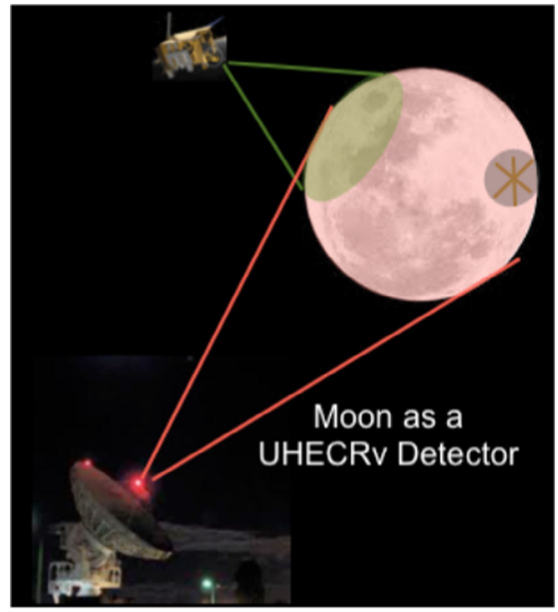

Fig. 1. Observations of lunar UHECRv events using ground-based, lunar orbiter and Moon's surface radio experiments. Dimensions are not to scale.

2.1. Lunar UHECRv experiments

Orbital Low Frequency ARray (OLFAR) (Bentum et al., 2009) and Lunar Orbiter Radio Detector (LORD) (Gusev et al., 2006; Raybov et al., 2016) are examples of planned Lunar Orbiter Observations of UHECRv events. We analyze the UHECRv detections from different altitudes and compare the expected results with results of simulations of UHECv events from a tripole antenna at 100 MHz onboard lunar orbiter satellites (Stål, 2007).

For observations of UHECRv events on the lunar surface, the analysis is done for an individual antenna onboard a lunar lander. It is based on the preliminary analysis (Aminaei et al., 2013) of the Lunar Radio eXplorer (LRX) experiment. LRX is a dedicated radio experiment initially designed for the proposed European lunar lander mission. LRX includes a tripole antenna and a sensitive digital receiver in the frequency range of 5 kHz to 100 MHz. The experiment was designed to observe radio emissions on the lunar surface including UHECRv radiation. Technical requirements and science cases of LRX are described in Klein-Wolt et al. (2012) and Zarka et al. (2012).

An individual antenna is used for both the lunar orbiter and the lunar surface experiments in this study. The analysis can be extended for multiple lunar orbiter antennas or for an array of antennas on the Moon's surface.

For all observations, UHECRv events can be detected if the maximum electric field of Askaryan radiation is equal to or greater than the minimum electric field detectable