The Directional Dependence of the Lunar Cherenkov Technique for UHE Neutrino Detection

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Abstract

The LUNASKA (Lunar UHE Neutrino Astrophysics with the Square Kilometre Array) project is a theoretical and experimental project developing the lunar Cherenkov technique for the next generation of giant radio-telescope arrays. This contribution presents our simulation results on the directional dependence of the technique for UHE neutrino detection. In particular, these indicate that both the instantaneous sensitivities and time-integrated limits from lunar Cherenkov experiments such as those at Parkes, Goldstone, Kalyazin and ATCA are highly anisotropic. We study the regions of the sky which have not been probed by either these or other experiments, and present the expected sky coverage of future experiments with the SKA. Our results show how the sensitivity of Lunar Cherenkov observations to potential astrophysical sources of UHE particles may be maximised by choosing appropriate observations dates and antenna-beam pointing positions.

Key words: UHE neutrino detection, coherent radio emission, lunar Cherenkov technique, UHE neutrino flux limits

1. Introduction

Observations of ultra-high energy neutrinos (UHE $\nu$) have been proposed to resolve the mystery of the origins of the UHE cosmic rays (CR), either by using the flux (or limits thereon) to discriminate between production models, or by using observed UHE $\nu$ arrival directions to point back to their source. Recent results from the Pierre Auger observatory \cite{1} show that the UHE CR flux itself is not isotropic, indicating that at the highest energies some directional information is preserved. Thus observations of either UHE $\nu$ or a large increase in UHE CR statistics could be used to resolve the mystery. For an experiment aiming to observe either of these particles therefore, the dependence of experimental sensitivity on UHE particle arrival direction becomes important.

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The Lunar Cherenkov technique — proposed by Dagkesamanskii and Zheleznykh \cite{2} — is a method to observe both UHE CR and $\nu$. By observing the Moon with Earth-based radio-telescopes, the pulses of microwave-radio radiation produced via the Askaryan effect \cite{3} from these particles interacting in the Lunar regolith may be detected. The first attempt utilised the Parkes radio telescope \cite{4}, and subsequent experiments \cite{5,6,7} have placed limits on an isotropic flux of UHE neutrinos, though these are not currently competitive with experiments such as ANITA \cite{8} and RICE \cite{9} except for those of \cite{7} at the very highest energies. However, with the advent of the next generation of giant radio arrays such as LOFAR \cite{10} and the Square kilometre Array (SKA), the sensitivity of the technique will increase greatly, and observations with the SKA are expected to probe the ‘cosmogenic’ neutrino flux from UHE CR interactions, and could detect a very high rate of the UHE CR themselves \cite{11}.
In this contribution we examine the directional-dependence of the sensitivity of the Lunar Cherenkov technique to UHE $\nu$, and analyse the ability of current experiments (such as ours with ATCA \cite{12}) to make targeted observations. We calculate a limit on UHE $\nu$ from the Parkes experiment and GLUE as a function of particle arrival direction, which combined with approximate dependencies for experiments such as RICE and ANITA, allows us to identify regions of the primary energy–arrival direction parameter space which have been relatively unprobed by all current observations. Finally, we examine the likely sky coverage of future experiments with the ATCA, ASKAP, and the SKA. Though current simulation methods are appropriate with the ATCA, we expect our results to be broadly applicable to the detection of UHE CR to which some sensitivity is expected, for which the comparable experiment is Auger.

2. Instantaneous Sensitivity of the Lunar Cherenkov Technique

The most common measure of the sensitivity of Lunar Cherenkov experiments is the effective aperture $A_{\text{eff}}$ (km$^2$-sr) as a function of primary particle energy. Whether explicitly or otherwise, this function is effectively the integral of the (particle arrival-direction dependent) detection probability $p$ multiplied by the effective experimental collecting area $a(\hat{\Omega})$ over the whole sky, as expressed below:

$$A_{\text{eff}}(E_\nu) = \int_{\text{sky}} d\Omega \, p(E_\nu, \hat{\Omega}) \, a(\hat{\Omega}) \quad (1)$$

where we use $\hat{\Omega}$ to express a position on the sky in some appropriate coordinate system. In the case of Lunar Cherenkov experiments and accompanying simulations, the ‘collecting area’ $a(\hat{\Omega})$ is best defined as the Lunar cross-section $\pi R_m^2$ (a constant in the approximation of Lunar sphericity), and $\hat{\Omega}$ defined relative to the centre of the Moon to eliminate time-dependencies from the Moon’s motion. We define the effective area $a_{\text{eff}}(\hat{\Omega})$ as follows:

$$a_{\text{eff}}(\hat{\Omega}, E_\nu) = \pi R_m^2 \, p(E_\nu, \hat{\Omega}) \quad (2)$$

This provides a useful measure of the sensitivity to a directionally-dependent flux. In Fig. 1 we plot the calculated effective area of our 2007 observations with ATCA (see our contribution \cite{12}) in both centre-pointing and limb-pointing modes, using the simulation we developed in \cite{11}.

Treating the combined antenna-Moon system as our detector, the plots in Fig. 1 give the effective ‘beam-pattern’. Though large compared with the $\sim 0.5^\circ$ beam width of antenna itself, nonetheless the coverage is small when compared to the entire $4\pi$ sr of sky. At any one instant, the experiment will be sensitive to particles arriving only from a small range of directions.

A useful measure of the importance of directional-dependence in experimental sensitivity is what we define as the ‘directionality’ $D$, the ratio of the peak effective area $a_{\text{max}}$ over the mean value $\bar{a}$, which can be related to the effective aperture as follows:

$$D = a_{\text{max}}/\bar{a} = 4\pi a_{\text{max}}/A_{\text{eff}} \quad (3)$$

For our experiment, we find values for $D$ at $10^{22}$ eV of 10 and 13 in centre-pointing and limb-pointing modes respectively. That $D$ is higher in limb-pointing mode should come as no surprise, since this mode sacrifices sensitivity to the majority of events in return for increased sensitivity to a minority. Also, as primary particle energy increases above the experimental threshold, events with a greater range of non-optimal interactions geometries become detectable, decreasing $D$. Simulations of low-frequency experiments indicate a reduced $D$, since here the Cherenkov cone (and therefore the acceptance) is broader at lower frequencies.

The directionality gives the possible gain in sensitivity to a point-like UHE particle source over that to an isotropic flux (or alternatively over a blind observation). The high values for $D$ for high-frequency experiments suggest potential gains of an order of magnitude, and thus the importance of this type of analysis and of optimising observation times and beam-pointing positions.

3. Current Limits on an UHE $\nu$ Flux

Since the instantaneous aperture of previous Lunar Cherenkov experiments covers a small fraction of the sky, and observations have tended to be sporadic, the limits set by these experiments are expected to be highly anisotropic. Sufficiently accurate observation times could only be obtained for GLUE from \cite{5}, and the Parkes experiment (our recent observations with ATCA are discussed in another contribution \cite{12}). Integrating the calculated instantaneous sensitivity (with the appropriate ori-
The effective area $a_{\text{eff}}$ (defined in text) of our (inferior 2007) experiment with ATCA to $10^{22}$ eV neutrinos in both (a): centre-pointing mode, and (b): limb-pointing mode, with the beam pointing 0.5$^\circ$ to the right of the Moon.

The greater contribution comes from the Goldstone experiment, where the effect of pointing at the Northern limb of the Moon is obvious. The peak sensitivity however lies in the declination range accessible to ANITA/ANITA-lite, which has set the strongest limits at this energy. Other experiments with significant limits to $10^{22}$ eV neutrinos are RICE and the Kalyazin experiment. Since RICE is mostly sensitive to Southern latitudes, it will not compete with Lunar Cherenkov contributions in these regions. To UHE neutrinos arriving from the declination of Sgr A* (−29$^\circ$), RICE has a maximum exposure of approximately 340 km$^2$-days, and 260 km$^2$-days to Cen A at −43$^\circ$ [9]. For Kalyazin, the exposure is expected to be similar to that for GLUE given the similarity of the experiments, though probably more spread over the lunar cycle.

Evidently from Fig. 2, significant regions of the sky have been relatively unprobed by UHE neutrino detection experiments, particularly in the Northern hemisphere. Our recent observations with ATCA [12] have begun targeting the region outside ANITA’s in the South, around Sgr A* and Cen A. A significant contribution can be made by lunar Cherenkov experiments via a careful choice of observation times and beam pointing positions in cases where the isotropic sensitivity may not be competitive.

4. Future Experimental Exposure

Future lunar Cherenkov experiments planned with ATCA, ASKAP, LOFAR, and the SKA should constitute dedicated observing runs over the entire lunar month. However, observations will still be limited by the constraints of the Moon’s orbit, which is inclined at $\sim 5^\circ$ to the ecliptic with nodal precession period 18.6 years. Therefore the potential exposure to putative UHE particle sources will be a function of angular distance from plane of the Lunar orbit.

In Fig. 3 we plot our calculated exposures for a calendar year’s worth of observing for a fully optimised ATCA (not our current experiment), ASKAP, and various SKA frequency ranges as a function of this angular distance, and for comparative purposes include the position of ‘interesting’ astronomical objects, though we do not intend this to be a complete list of potential sources (see [13]).

It is particularly of interest that only for very low frequency experiments such as our modelled 70 – 200 MHz component of the SKA does the exposure become uniform, and then only at energies at
10^{21} \text{ eV} and above. Below this energy, all foreseeable lunar Cherenkov experiments will have excess sensitivity within $\sim 30^\circ$ of the lunar orbit, or half the sky. There will thus exist an unprobed gap in the primary energy–arrival direction parameter space near the ecliptic poles below 10^{21} \text{ eV}, which will require alternative detection methods to fill.

5. Conclusions

We have calculated the effective ‘beam-pattern’ of the antenna-Moon system for a range of lunar Cherenkov experiments, finding both the instantaneous sensitivity to, and past limits on, UHE neutrinos to be highly anisotropic. Our results show how the sensitivity of Lunar Cherenkov observations to potential astrophysical sources of UHE particles may be maximised by choosing appropriate observations dates and antenna-beam pointing positions. The likely coverage of future experiments will be broad, but will leave large regions near the ecliptic poles unprobed to $E < 10^{21} \text{ eV}$ neutrinos.

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