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UHE particle astrophysics with the SKA

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The Lunar Cherenkov technique is a method to detect ultra-high energy (UHE) cosmic rays and neutrinos. It involves observing the Moon with ground-based radio-telescopes to identify pulses of coherent Cherenkov radiation from such particles interacting near the lunar surface. Initially devised to solve the mystery of the origin of the highest-energy cosmic rays, fluxes of UHE neutrinos are predicted from AGN, topological defects, and UHE cosmic ray interactions. Successful detection - or otherwise - would provide great insight into these exotic phenomena, with the possibility of new physics at energies inaccessible to terrestrial particle accelerators. This contribution describes the current state of observations, and why the characteristics of the SKA will make it the most powerful instrument for performing UHE particle astronomy.

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1. Introduction

The highest energy particles observed in nature are the ultra-high energy (UHE) cosmic rays (CR), with energies measured up to 2×10^{20} eV. Their origin is not fully understood, although very recent results from the Pierre Auger Observatory [1] show a statistical correlation with the matter distribution in the Universe as represented by nearby active galactic nuclei. Even at energies above 10^{19} eV, the observed UHE CR arrival directions will not point back directly to their sources because of magnetic deflection and scattering over extragalactic distances. Furthermore, during their propagation UHE CR suffer photo-production interactions on the cosmic microwave background radiation (CMBR) typically within a few tens of Mpc of their source, a process referred to as the 'GZK effect' after Greisen, and Zatsepin & Kuzmin, who first suggested it. In these interactions pions are produced, and subsequent decay yields 'GZK neutrinos' which should indeed point back to the UHE CR sources. The spectrum of these neutrinos may even retain some information about the UHE CR spectrum on acceleration [2].

As well as UHE CR acceleration scenarios, top-down scenarios involving topological defects (TD) have also been suggested, and in these cases UHE neutrinos also trace UHE CR origin. Thus observation of UHE neutrinos may well solve the mystery of UHE CR origin, as well as exploring a new window on the Universe and on new physics.

The lunar Cherenkov technique (first proposed by Dagkesamanskii and Zheleznykh [3] and attempted at Parkes [4]) utilises ground-based radio telescopes observing the Moon to search for the characteristic nanosecond-duration pulses of coherent Cherenkov radiation escaping the surface from UHE particle interactions in the lunar regolith (the sandy layer of ejecta covering the Moon's surface to a depth of ~ 10 m, with a visible volume of approximately 2×10^6 km^3). Here we discuss the prospects of using the lunar Cherenkov technique with the SKA to search for UHE neutrinos and allow high-statistics correlation studies of UHE CR arrival directions with potential source distributions, and compare the SKA to both previous and future instruments. Also, we propose methods for determining the nature and arrival direction of detected particles, enabling the SKA to perform true UHE particle astronomy.

2. Observations with the SKA

The lunar Cherenkov technique involves searching for the characteristic pulses (or 'ticks') of coherent Cherenkov radiation coming from the Moon. The duration of these pulses can be less than a nanosecond, and since the pulses are rare, once-off transients, a search for candidate events must be performed in real time. This requires the coherent addition of the output of many antennas over a broad bandwidth, and real-time RFI discrimination. Two methods have been developed to discriminate against terrestrial RFI — using the characteristic dispersion of the ionosphere over a broad frequency range to ensure the signal is of extraterrestrial origin [4], and using an array of antennas to pinpoint the arrival direction as coming from the Moon [5]. Being a large, broad-bandwidth array, the SKA will be able to use both techniques simultaneously, and combined with the location in a low-RFI environment, we expect sensitivity to be limited only by thermal statistics.

The dispersion in the ionosphere destroys the coherency of the signal, smearing the pulse over a larger time interval and reducing its peak strength, and therefore experimental sensitivity unless

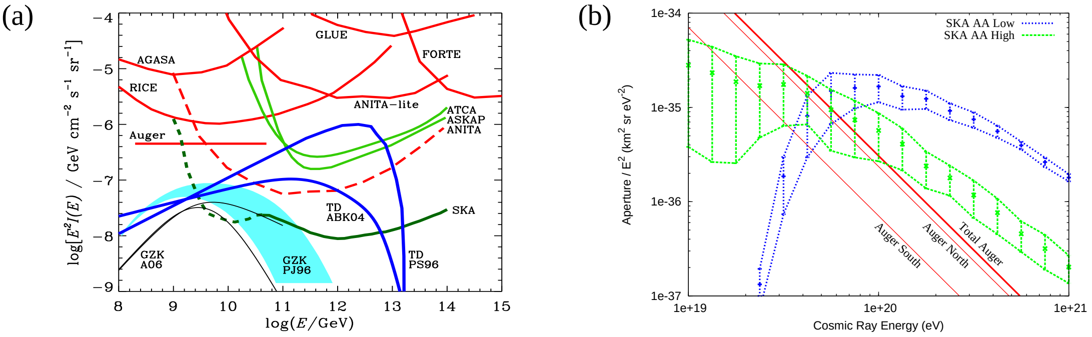

Figure 1: (a) Existing limits on the isotropic UHE neutrino intensity (adjusted for all flavours) from several experiments, expected limit from ANITA, and sensitivity for a calendar year's worth of observation time (i.e. taking account of % on-time) of ATCA, ASKAP and the SKA (solid–Aperture Arrays, dashed–Dishes). IceCube will be sensitive mostly below 10^{16} eV. Predicted fluxes for a range of TD models (PS96–Protheroe & Stanev 1996, ABK04–Aloisio, Berezinsky & Kachelreiss 2004), and 'GZK neutrinos' (PJ96–Protheroe & Johnson 1996, A06–Allard 2006) are shown. Due to lack of space, references to limits, sensitivities and models will be given elsewhere (in preparartion). (b) Comparison of the % run-time-weighted effective aperture to cosmic rays of the SKA aperture arrays (AA-high and AA-low) with the potential Pierre Auger sensitivity. The range of estimates represent the limits of current modelling of lunar surface roughness.

real-time coherent dedispersion is performed prior to triggering. This requires accurate knowledge of the Earth's ionosphere. Fortuitously, the thermal emission near the limb of the Moon contains a few percent linearly polarised fraction, with the polarisation aligning perpendicular to the limb. By measuring the Faraday rotation of the polarisation vector in the Earth's magnetic field (for which accurate models exist), the dispersion measure can be determined, allowing us to use our source also as our calibrator.

We expect the majority of events to appear to come from near the lunar limb, which should be entirely covered in summed-array beams to maximise the event rate. Assuming a limit of 250 such beams, this corresponds to a maximum baseline of 3.3 km $\times(1\ \text{GHz}/f_{\max})$, and probably less since the portion of the Moon near the limb should also be observed. A compact configuration is therefore desirable, and data from longer baselines will have to be buffered and written upon triggering if the full sensitivity is to be recovered.

A major advantage of the SKA is its broad frequency range. The peak frequency of the observed emission is strongly dependent upon the geometry of the interaction, ranging from less than 100 MHz to above 3 GHz. Events with a low-frequency peak are much more common, but the available power is less, and consequently experiments observing at low frequencies have a high energy threshold, while observations at high frequencies (e.g. with SKA dishes) — which have a low threshold — can detect only comparatively rare interactions. The combined sensitivity of the SKA high-frequency and low-frequency aperture arrays (AA-high and AA-low) and the dishes will, for the first time, allow the best of both worlds.

3. Sensitivity to UHE Cosmic Rays and Neutrinos

We have updated our earlier calculations (SKA Virtual Telescope 'proposal') of the sensitivity of the SKA to UHE neutrinos based on current probable design parameters. Of particular importance is the likely use of multiple technologies to cover the key frequency range of ~ 0.1-3 GHz, and a worse sensitivity, particularly at the lowest frequencies. Within these constraints however, we have used optimum observations frequencies at each energy, resulting in a greatest aperture to $< 1.5 \times 10^{19}$ eV neutrinos from the > 0.7 GHz dishes, and from the AAs at higher energies.

In Fig. 1(a), we compare our simulated SKA limits on a flux of UHE neutrinos, calculated from a calendar year's worth of observation time, to that of other experiments (both current and future) and expectations of the UHE neutrino flux. While the range of UHE neutrino productions models is large, the SKA will be sensitive to the almost-guaranteed GZK flux, which arises from interactions of observed UHE CR with the CMBR, and will readily be able to detect or eliminate any flux from models predicting a super-GZK neutrino flux. The SKA's sensitivity complements that of experiments such as the Pierre Auger project, while occupying a similar energy regime to ANITA (a balloon experiment to detect the radio emission from UHE neutrinos in the Antarctic ice sheet) but with greater declination coverage, whereas the ANITA sensitivity is restricted to declinations $-10^\circ < \delta < 15^\circ$. Only the SKA dishes will be sensitive to GZK neutrino fluxes consistent with the more pessimistic models, and since we do not expect the SKA to be devoted to UHE particle astronomy, this flux may prove to be unobservable for practical reasons. We emphasise however the huge parameter space of UHE particle astrophysics for exploration above 5×10^{10} GeV using the AAs, and that should be able to be done simultaneously with standard radio astronomy observations.

The effective aperture of the SKA to UHE CR is compared to that of the current 3000 km^2 Pierre Auger experiment (Auger South), and a potentially expanded future observatory (Auger North), in Fig. 1(b). Adjusting for an assumed SKA AA horizon of 30° and consequently reduced observation time compared to Auger, the SKA's UHE CR sensitivity will greater above approximately $\sim 5 \times 10^{19}$ eV, which is coincidentally the approximate energy above which the correlation with AGN found by the Auger collaboration has the strongest significance [1].

4. UHE Particle Astronomy

We require methods to determine the energy, type, and arrival direction of the primary particles generating any observed Cherenkov signals. Both the signal polarisation and its apparent origin on the lunar surface allow a crude reconstruction of the origin of the primary particle, as illustrated in Fig. 2, which is limited by both the large-scale surface roughness of the Moon, and the angular breadth of the emission of Cherenkov radiation. The first limitation might be overcome by combining extremely accurate positional determination of the signal origin from large stations at long baselines with accurate maps of the lunar surface, as will be provided by the next generation of lunar orbiters such as SELENE. Overcoming the second limitation will probably require reconstructing the signal spectrum to determine the interaction geometry, given the known dependencies on viewing angle. Such a reconstruction also will allow differentiation between cosmic rays and neutrinos, since neutrino signals will tend to show evidence of some absorption in the regolith, while signals from comic rays, which always interact at the surface, will not.

It is unlikely that the energy of primary UHE neutrinos will be determined on an event-by-event basis, though this should be readily achievable in the case of cosmic rays. In the low-frequency limit, the field strength is directly proportional to the energy deposited in the regolith,

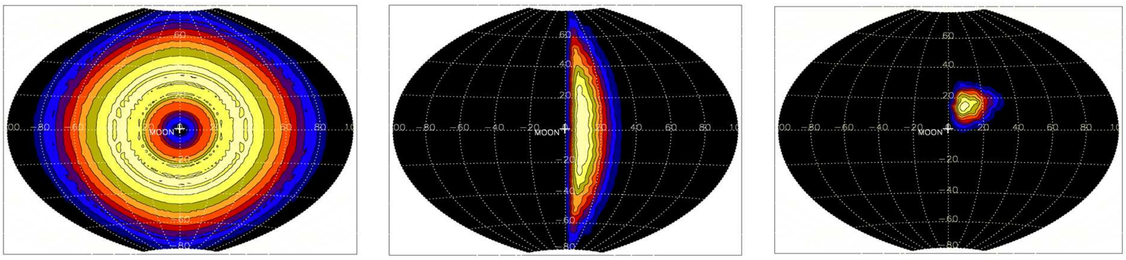

Figure 2: Simple maximum likelihood reconstruction of the arrival direction of a primary particle, assuming (left) no information, (centre) the position of signal origin to within 5”, (right) the position on the Moon and signal polarisation within ±5° accuracy, for an observation frequency of approximately 200 MHz. This assumes no knoweldge of the signal spectrum or the lunar surface.

which for cosmic rays is always the entire energy of the primary particle. For neutrinos, this is only the case for $\nu_e/\overline{\nu_e}$ charged-current interactions, representing roughly two ninths of all expected UHE neutrino interactions, while for the remainder, the fraction of energy given to cascading is highly variable.

5. Conclusions

The Square Kilometre Array will be a powerful instrument for performing UHE particle astronomy. Its sensitivity will enable it to detect both the known flux of UHE CR, and the expected flux of GZK neutrinos, while probing the highest-energy particle sky for as-yet unknown phenomena to an unprecedented degree. The frequency range and configuration of the SKA should also allow a determination of the origin and nature of any detected UHE particles. The methods required to utilise the Lunar Cherenkov technique with a giant radio array are highly non-standard however, and continued development in close partnership with both the particle-astrophysics and radio-astronomy communities will be required if the SKA is to meet its potential.

References

[1] The Pierre Auger Collaboration *et al.*, *(*Correlation of the Highest Energy Cosmic Rays with Nearby Extragalactic Objects), *Science* **318** (2007) 938 [`astro-ph/0711.2256`].

[2] R. J. Prothroe, *Effect of energy losses and interactions during diffusive shock acceleration: applications to SNR, AGN and UHE cosmic rays, Astropart. Phys.* **21** (2004) 415 [`astro-ph/0401523`]

[3] R. D. Dagkesamanskii, I. M. Zheleznykh, *A radio astronomy method of detecting neutrinos and other superhigh-energy elementary particles, Sov. Phys. JETP Let.* **50** (1989) 233

[4] T. H. Hankins, R. D. Ekers, J. D. O’Sullivan, *A search for lunar radio Čerenkov emission from high-energy neutrinos, MNRAS* **283** (1996) 1027.

[5] P. W. Gorham *et al.*, *Experimental Limit on the Cosmic Diffuse Ultrahigh Energy Neutrino Flux Phys. Rev. Lett.*, **93** (2004) 041101 [`astro-ph/0310232`].