LUNASKA searches for ultra-high-energy particle interactions in the Moon

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Abstract: The Moon offers the largest potential volume for the detection of ultra-high-energy particles through the Askaryan radio emission resulting from their interactions. Through experiments with the Parkes and the ATCA radio telescopes, the LUNASKA project has been exploiting the lunar radio technique to search for the highest-energy neutrinos and cosmic rays. In this contribution, over two hundred hours of observations with these telescopes, both individually and in combination, are described. We present an overview of these experiments, and the methods used to search the data for the characteristic nanosecond pulses expected from cosmic particles interacting in the outer lunar layers. The techniques developed by the LUNASKA project to reject anthropogenic radio pulses are discussed, which establishes the capability of such experiments to accurately exclude false signals, potentially allowing the unambiguous identification of cosmic particles. Using these techniques, we present the resulting sensitivity to the ultra-high-energy neutrino and cosmic-ray fluxes.

Keywords: ultra-high-energy neutrinos, cosmic rays, lunar radio detection, Askaryan effect.

1 Introduction

The lunar radio technique, as proposed by Dagkesamanskii and Zheleznykh [1], is a method to detect the highest-energy cosmic rays and neutrinos. By monitoring the Moon with Earth-based radio telescopes, the entire visible lunar surface can be utilised as a detection volume. The detection principle relies on the Askaryan effect [2], by which the rapid rise and fall of excess negative charges entrained by a particle cascade from the interaction medium produces a coherent pulse at wavelengths comparable to the shower dimensions [3] — in the lunar regolith, this corresponds to a peak pulse amplitude at GHz frequencies, and thus a characteristic time-duration of a nanosecond. Both the first attempt at lunar pulse detection with the Parkes radio telescope in 1995 by Hankins *et al.* [4], and subsequent efforts such as those at Goldstone [5], have focused on detecting and placing limits on the ultra-high-energy (UHE) neutrino flux. These experiments have mostly observed in the range 1.0–2.5 GHz, and typically had effective neutrino-detection energy thresholds above 10^{21} eV, making them sensitive only to relatively optimistic predictions of the neutrino flux. Observations at lower frequencies ($\sim$ 100 Mhz) promise a much higher effective volume, due to the greater width of the emission cone and the reduced attenuation in the interaction medium [6]. However, such experiments also have a higher detection threshold, of the order of $3 \cdot 10^{22}$ eV and above. Given the down-turn in the cosmic-ray spectrum observed by the Pierre Auger collaboration [7], a flux of neutrinos at energies significantly above the GZK threshold is currently disfavoured, though by no means ruled out. Current efforts at lunar pulse detection therefore have three main motivations: probing the remaining parameter space for a post-GZK flux of UHE neutrinos; developing the technique for future generations of instruments, in particular the Square Kilometre Array; and searching for UHE cosmic rays. This contribution focuses on the latter two points.

The Square Kilometre Array (SKA) is a giant radio-telescope array to be constructed in Australia and Southern Africa from 2016 onwards [8]. Estimates indicate that utilising the lunar radio technique with the SKA would allow the flux of cosmogenic neutrinos from UHE cosmic-ray interactions to be probed [9], which must exist regardless of the origin of the UHE cosmic rays themselves. Given the current state of non-detection of any UHE neutrino flux, a possibly-more interesting conclusion is that the SKA could detect the known cosmic-ray flux above $4 \cdot 10^{19}$ eV at rates 10–40 times that of the current Pierre Auger observatory [9]. Both possibilities strongly motivate the development of lunar pulse-detection techniques — this has been the goal of the LUNASKA (Lunar UHE Neutrino Astrophysics with the SKA) collaboration.

In this report, the latest series of LUNASKA observations with the Parkes and the ATCA radio-telescopes are reported. The final experimental detection thresholds from 173.5 hr of observations taken with the Parkes radio telescope in 2010 have been calculated and are reported here, together with the resulting experimental effective apertures to both UHE neutrinos and cosmic rays. Additionally, the latest series of observations using both Parkes and the ATCA in coincidence are described. The techniques used in both sets of observations to reduce RFI, and their applicability to future experiments, are also discussed.

2 Observations at Parkes

The Parkes radio-telescope is a 64 m parabolic dish antenna located in New South Wales, Australia. For all observations described here, a multi-beam receiver was used, which provides 13 independent beams with an approximate 1.2–1.5 GHz bandwidth, each with linearly-polarised receivers.

The receivers are fixed in a hexagonal pattern relative to the primary beam, though the entire system can be pointed and rotated freely. Coincidentally, this receiver system allows three beams to be simultaneously placed near the lunar limb, from which most high-frequency Askaryan emission is expected to originate [5]. The digital signal processing board used at Parkes to search for lunar pulses (the 'Bedlam backend' [10]) is able to accept eight input channels and digitise them with 8-bit precision at a rate of 2.048 GHz. The eight inputs were connected to both polarisation channels of four of the thirteen beams. This allowed the maximum number of three 'on-Moon' beams to be used for detection purposes, and a fourth beam used as a veto beam for RFI rejection.

The timing of the observations was chosen to maximise sensitivity to Centaurus A, the closest radio galaxy to the Milky Way and a candidate UHE particle acceleration site, as per the prescription of James and Protheroe [11]. The observations were made when the Moon was as close as possible to Centaurus A (between 30° and 45° separation), the central beam pointed at that part of the lunar limb closest to the source, and the receiver continuously rotated such that one polarisation of the receiver was kept aligned perpendicular to the limb to match the expected polarisation of lunar signals. This produced the top-most 'limb' beam in Fig. 1. Since the lunar thermal emission dominates the intrinsic receiver noise, pointing the beam marginally off-limb (by $\sim 0.06°$) was found to maximise the expected signal-to-noise ratio. One of the remaining two detection beams (the other 'limb' beam) was then located at a similar limb offset to maximise sensitivity to an all-sky flux. A third detection beam could then be placed at a 'half-limb' position, and an RFI-rejection beam in an off-Moon position, as shown in Fig. 1 — although in some runs, the half-limb beam was shifted to an off-Moon beam for additional RFI rejection.

Each observation channel was digitally de-dispersed, interpolated, and searched for significant pulses, as described in detail in Ref. [12]. The trigger thresholds on the three detection beams were continuously adjusted to produce a combined trigger rate of order 1 Hz with equal contributions from all six trigger bands, corresponding approximately to $\gtrsim 6\sigma$ random thermal noise fluctuations. The veto beam — which prevented triggering from 20 ns before to 100 ns after an RFI event — had a threshold set in the tens of kHz range, for a negligible loss of efficiency ($\sim 0.2\%$). Since the veto beam did not see the lunar thermal emission, it was more sensitive to RFI than the three trigger beams, and hence provided an extremely good method to discriminate against unwanted events which would otherwise dominate the trigger rate. Upon triggering, usually 4 μs of data was recorded about the trigger time from all four beams for later analysis, which included interpolation of the data and analysis of the signal-envelope. In total, 173.5 hr of observations (during 2010) were recorded in this mode.

The sensitivities of lunar radio experiments typically do not reach limit of thermal noise fluctuations, due both to difficulties in triggering in real-time, and the ability to reject RFI. A detailed analysis of the triggered field amplitudes is given by Bray *et al.* [12] — the results are summarised in Fig. 2, which compares histograms of the pulses at different stages of data reduction to the theoretical expectations from random noise. A marginal excess of events with peak amplitude corresponding to $\sim 8\sigma$ noise fluctuations was observed ('cut 3' vs 'envelope' in Fig. 2). While this excess is not statistically significant, it is

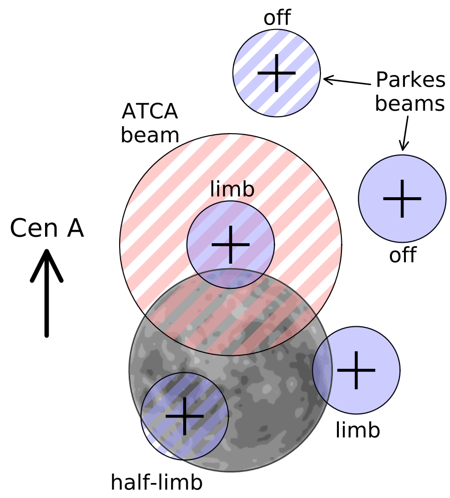

Figure 1: Typical pointing configuration of the Parkes beams (blue) with respect to the Moon during the 2010 Parkes-only observations and also of the ATCA beams (red) during combined observations in 2011. In the 2010 observations, the top-most 'off' beam was not usually used, while during 2011, the bottom-most 'half-limb' beam was not used. Crosses show the direction of the polarisation channels in the receivers; the overall orientation is relative to the offset from Centaurus A.

sufficiently interesting to warrant an investigation of its origin. Possible candidates include local RFI marginally increasing the background noise, and thereby pushing a fraction of e.g. 7σ events into the 8σ category; non-local RFI, such as that from satellites between Parkes and the Moon, from which RFI might enter one beam only and so evade the anti-coincidence filter; and true lunar-origin signals from a steeply-falling particle spectrum. In order to discriminate between these possibilities, a second telescope with a significant geographical offset from Parkes was required.

The instantaneous sensitivity of lunar radio experiments is usually expressed in terms of the free-space bandwidth-averaged spectral field strength (V/m/MHz) of a signal which, if incident in the centre of the telescope beam, would be detected with 50% probability. This allows both an easier comparison between experiments with different antenna responses, and an easier use of simulation output, which is usually expressed as a function of frequency in units of V/m/MHz. For the Parkes experiment, this characteristic threshold is calculated for a signal originating from the closest point on the lunar limb, since the beam-centre was off-Moon. Is is found to be $5.3 \cdot 10^{-9}$ V/m/MHz for the radial linear polarisation. For comparison, the threshold for the experiment at Goldstone (GLUE) was $9.14 \cdot 10^{-9}$ V/m/MHz [16] — the gain from Parkes comes from using a broader bandwidth, a linear (as opposed to circular) polarisation, and from observing at lower frequencies, where the lunar thermal noise contribution is lower.

In order to accurately convert the field-strength threshold into an effective aperture to UHE particles, a detailed simulation is required. Using the simulation package of James & Protheroe [9] to calculate the instantaneous effective apertures to UHE neutrinos produces the result shown in Fig.

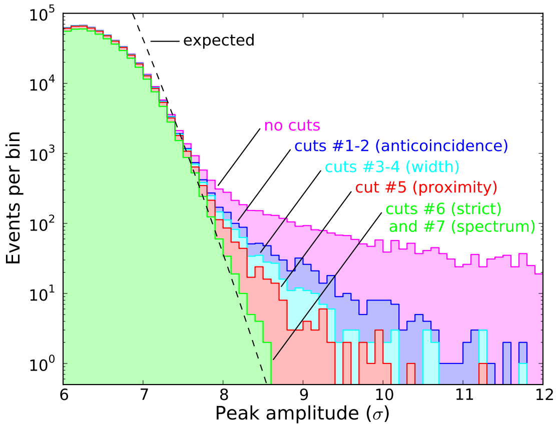

Figure 2: Histograms of peak voltage amplitude (relative to the noise, with RMS fluctuations of 1σ) in events recorded during the Parkes-only experiment, showing the raw triggered amplitudes ('no cuts'), the cumulative effects of different RFI-rejection criteria (cuts #1–#7), and the expected amplitude distribution after all stages of signal processing, assuming a purely thermal noise spectrum. The slight excess near 8σ is shown by the difference between the green 'cuts #6 and #7' curve, and the dotted black line expectation. See Ref. [12] and [10] for a full description of the signal processing and RFI rejection methods.

3 (thick line). Observe that the instantaneous sensitivity is the most sensitive to any $E < 10^{21}$ eV neutrino flux of any lunar experiment to date.

3 Simultaneous observations with the ATCA

In order to eliminate the possibility of local RFI or low-flying satellites passing the RFI-rejection criteria at Parkes, the Australian Telescope Compact Array (ACTA), located approximately 300 km north of Parkes, was used in coincidence. The ATCA consists of six 22 m antennas, with an extremely large available bandwidth of 1.1-3.1 GHz over two linearly polarised channels. For the 2011 observations reported here, five antennas were used in a compact configuration, which were simultaneously pointed in the direction of the Parkes limb beam closest to Centaurus A (see Fig. 1). Coherently combining these antennas produces a sensitivity comparable to that of the larger (and narrower-band) Parkes telescope. However, the required number of beams to cover the portion of the limb to which even a single Parkes beam is sensitive could not be formed in real-time. The data at the ATCA was therefore buffered, and 200 μs segments recorded upon receiving a trigger generated at Parkes. The relative timing of the two telescopes was calibrated to within 50 ns [17]. Using this configuration, 15 hr of data was recorded in 2011. While the analysis for this experiment is not yet finished, the timing and sensitivity calibration have been completed, indicating that the goal of the observations — to provide a long-distance RFI rejection observation without limiting the sensitivity of the primary Parkes trigger — has already been achieved.

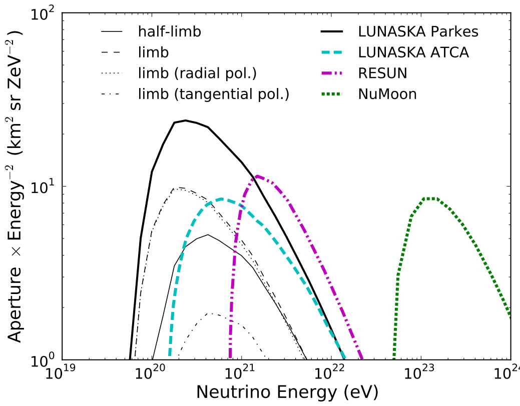

Figure 3: Neutrino apertures for the LUNASKA experiment with the Parkes radio telescope, for the individual beams (thin black lines) shown in Fig. 1, and the total combined aperture (thick solid line). The effects of the RFI exclusion procedure are fully accounted for. These are compared to other recent lunar neutrino experiments: the original LUNASKA experiment with the ATCA [14] the RESUN search with the EVLA [15]; and the NuMoon observations with the WSRT [6]. Note that the methods used to calculate the apertures differ significantly between experiments.

4 Cosmic ray aperture

The UHE cosmic ray flux is a much easier target for the lunar radio technique than any UHE neutrino flux. Cosmic rays always interact immediately upon hitting the surface of the Moon, so that their radio radiation suffers little to no absorption, and 100% of their energy is always converted to hadronic cascades, which, being shorter, have a much broader emission cone. The radiated field strength will be proportional to the primary particle energy, and almost independent of the composition. While the expected angular resolution to each event may be no better than 10° [18], this is comparable to the observed scale at which anisotropy is seen by the Pierre Auger experiment [19], and the angular size of potential sources such as the radio-lobes of Centaurus A, and local galaxy clusters such as Virgo. And, unlike UHE neutrinos, UHE cosmic rays have been observed, allowing concrete estimates of expected event rates to be made.

The known cosmic-ray flux has traditionally been viewed as a secondary objective for lunar radio experiments, for two very different reasons. Firstly, the radiation resulting from the Askaryan effect is commonly thought to be coherent Cherenkov radiation, whereas it has recently been shown that Askaryan emission is almost completely due to coherent bremsstrahlung — macroscopically, the radiation resulting from the rapid rise and fall of the excess charge [3]. This becomes important because Cherenkov radiation vanishes when the source charge is moving close to the edge of the dielectric medium (the 'formation-zone effect'), as is the case with cosmic-ray cascades near the lunar surface, whereas bremsstrahlung does not. Thus only in the last two years has it been shown that Askaryan radiation from cosmic ray interactions in the Moon could be observed at all. The second reason is that lunar experiments were assumed not to reach the GZK threshold, so that ground-based cosmic-ray experiments such as Pierre Auger would

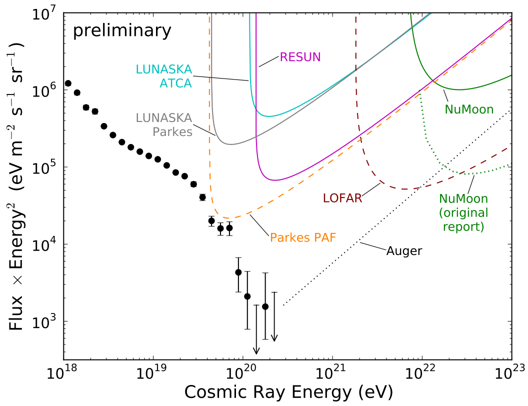

Figure 4: Sensitivity of prior (RESUN [15]; LUNASKA ATCA [20]; LUNASKA Parkes (these proceedings); NuMoon [6]) and future (LOFAR [21]; Parkes phased-array feed (PAF), with an assumed threshold of $4.8 \cdot 10^{-9}$ V/m/MHz, full lunar coverage, and one week's observations) lunar searches compared to the UHE CR flux measured by Pierre Auger [7] (black points) and the UHE flux levels corresponding to no events being observed about $3 \cdot 10^{20}$ eV.

dominate all useful observations. James & Protheroe [9] however have estimated that at energies above $4 \cdot 10^{19}$ eV, where the Pierre Auger experiment observes the greatest anisotropy, the SKA could observe of order 15–40[1] times as many events as the Pierre Auger (South) observatory. While such a measurement would be technically challenging, the prospects for studying the UHE cosmic-ray flux are sufficiently promising that efforts to develop the technique should continue regardless of any potential detection of UHE neutrinos.

The recent interest in the cosmic ray flux as a science goal for lunar observations means that many older experiments, which have published limits on the UHE neutrino flux, have no corresponding calculation of their sensitivity to cosmic rays. The analytic methods of Gayley *et al.* [22] however, adapted to cosmic-ray calculations as per Jeong *et al.* [23], provides a relatively simple method to evaluate the sensitivity of both previous, current, and future lunar experiments to the known cosmic-ray flux. The only required modification to the methods of these authors is to replace the 20% fraction of particle energy going into hadronic cascades (applicable to neutrino events) by 100% (applicable to cosmic rays). The result of these calculations is compared to measurements of the UHE cosmic-ray flux as measured by the Pierre Auger collaboration in Fig. 4. In particular, note that observations with the Parkes radio telescope with a proposed phased array feed come very close to being able to detect the flux. Such a measurement would be extremely important, since it would allow the theoretical sensitivity to be compared to real data — and provide the proof of principle which would likely be required before any significant time on the SKA could be procured.

5 Conclusions

The LUNASKA series of lunar observations searching for a UHE particle flux interacting with the Moon continues to provide improvements in sensitivity to these particles. It has been shown that the use of multiple beams on a single antenna can provided very good RFI rejection, although a coincidence over a long baseline would likely be required to provide unequivocal proof of a detection. Such an observation — using the ATCA and Parkes, two very different telescopes separated by 300 km — has been successfully performed, and the required accuracy to identify nanosecond pulses seen on both instruments achieved. Calculations of the sensitivity of these experiments indicate that they are the most sensitive lunar observations to date — and in particular, that not only is the known cosmic-ray flux a viable target for lunar observations, but that it might be observable in the near future.

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1. The uncertainty stems both from the UHE flux, and the effects of large-scale surface roughness.