Astroparticle Physics 77 (2016) 1–20

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

The sensitivity of past and near-future lunar radio experiments to ultra-high-energy cosmic rays and neutrinos

J.D. Bray [a,b,c,*]

[a] School of Chemistry and Physics, University of Adelaide, SA 5005, Australia
[b] CSIRO Astronomy and Space Science, Marsfield, NSW 2122, Australia
[c] JBCA, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Article history:
Received 22 September 2015
Revised 23 December 2015
Accepted 11 January 2016
Available online 20 January 2016

Keywords:
Ultra-high-energy neutrinos
Ultra-high-energy cosmic rays
Radio detection
Moon

ABSTRACT

Various experiments have been conducted to search for the radio emission from ultra-high-energy (UHE) particles interacting in the lunar regolith. Although they have not yielded any detections, they have been successful in establishing upper limits on the flux of these particles. I present a review of these experiments in which I re-evaluate their sensitivity to radio pulses, accounting for effects which were neglected in the original reports, and compare them with prospective near-future experiments. In several cases, I find that past experiments were substantially less sensitive than previously believed. I apply existing analytic models to determine the resulting limits on the fluxes of UHE neutrinos and cosmic rays (CRs). In the latter case, I amend the model to accurately reflect the fraction of the primary particle energy which manifests in the resulting particle cascade, resulting in a substantial improvement in the estimated sensitivity to CRs. Although these models are in need of further refinement, in particular to incorporate the effects of small-scale lunar surface roughness, their application here indicates that a proposed experiment with the LOFAR telescope would test predictions of the neutrino flux from exotic-physics models, and an experiment with a phased-array feed on a large single-dish telescope such as the Parkes radio telescope would allow the first detection of CRs with this technique, with an expected rate of one detection per 140 h.

1. Introduction

Observations of ultra-high-energy (UHE; $> 10^{18}$ eV) cosmic rays (CRs), and attempts to detect their expected counterpart neutrinos, are hampered by their extremely low flux. The detection of a significant number of UHE particles requires the use of extremely large detectors, or the remote monitoring of a large volume of a naturally occurring detection medium. One approach, suggested by Dagkesamanskii and Zheleznykh [1], is to make use of the lunar regolith as the detection medium by observing the Moon with ground-based radio telescopes, searching for the Askaryan radio pulse produced when the interaction of a UHE particle initiates a particle cascade [2]. The high time resolution required to detect this coherent nanosecond-scale pulse puts these efforts in a quite different regime to conventional radio astronomy.

Since the first application of this lunar radio technique with the Parkes radio telescope [3], many similar experiments have been conducted, none of which has positively detected a UHE particle. Consequently, these experiments have placed limits on the fluxes of UHECRs and neutrinos. To determine these limits, each experiment has developed an independent calculation of its sensitivity to radio pulses and, in most cases, an independent model for calculating the resulting aperture for the detection of UHE particles. This situation calls for further work in two areas, both of which are addressed here: the recalculation of the radio sensitivity of past experiments in a common framework, incorporating all known experimental effects, and the calculation of the resulting apertures for both UHECRs and neutrinos using a common analytic model.

An additional benefit of this work is to provide a comprehensive description of the relevant experimental considerations, with past experiments as case studies, to support future work in this field. To that end, I also present here a similar analysis of the radio sensitivity and particle aperture for several possible future lunar radio experiments. The most sensitive telescope available for the application of this technique for the foreseeable future will be the Square Kilometre Array (SKA), prospects for which have

* Corresponding author at: JBCA, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK.
E-mail address: justin.bray@manchester.ac.uk

http://dx.doi.org/10.1016/j.astropartphys.2016.01.002

been discussed elsewhere [4], but phase 1 of this instrument is not scheduled for completion until 2023; in this work, I instead evaluate three proposed experiments that could be carried out in the near future (<5 yr) with existing radio telescopes. Most other experiments that could be conducted with existing radio telescopes will resemble one of these.

This work is organised as follows. In Section 2 I address the calculation of the sensitivity of radio telescopes to coherent pulses, obtaining a similar result to Eq. (2) of Gorham et al. [5], but incorporating a wider range of experimental effects. This provides the theoretical basis for the re-evaluation in Section 3 of past lunar radio experiments, in which I calculate a common set of parameters to represent their sensitivity to a lunar-origin radio pulse. Alongside these, I calculate the same parameters for proposed near-future experiments.

In Section 4 I discuss the calculation of the sensitivity of lunar radio experiments to UHE particles. For each of the experiments evaluated in Section 3, I calculate the sensitivity to neutrinos based on the analytic model of Gayley et al. [6], and the sensitivity to UHECRs based on the analytic model of Jeong et al. [7]. Finally, in Section 5, I briefly discuss the implications for future work in this field.

2. Sensitivity to coherent radio pulses

The sensitivity of a radio telescope is characterised by the system equivalent flux density (SEFD), conventionally measured in janskys (1 Jy $= 10^{-26}$ W m^{-2} Hz^{-1}), which is given by

$$\langle F \rangle = 2\,\frac{k\,T_{\rm sys}}{A_{\rm eff}} \tag{1}$$

where k is Boltzmann's constant, $T_{\rm sys}$ the system temperature and $A_{\rm eff}$ the effective aperture (i.e., the total collecting area of the telescope multiplied by the aperture efficiency). In the context of a lunar radio experiment, the system temperature is typically dominated by thermal radiation from the Moon—or, at lower frequencies, by Galactic background emission—with a smaller contribution from internal noise in the radio receiver. However, the strength of a coherent pulse, such as the Askaryan pulse from a particle cascade, is expressed in terms of a spectral electric field strength, in, e.g., V/m/Hz. To describe the sensitivity of a radio telescope to a coherent pulse, we must relate this quantity to the parameters in Eq. (1).

The factor of 2 in Eq. (1) occurs because the flux contains contributions from two polarisations, whether these are considered as orthogonal linear polarisations or as opposite circular polarisations (left and right circular polarisations; LCP and RCP). The bolometric flux density in a single polarisation is given by the time-averaged Poynting vector

$$\langle S \rangle = \frac{E_{\rm rms}^2}{Z_0} \tag{2}$$

where $E_{\rm rms}$ is the root mean square (RMS) electric field strength in that polarisation, and Z_0 is the impedance of free space. If the received radiation has a flat spectrum over a bandwidth $\Delta\nu$, the total spectral flux density is found by averaging the combined bolometric flux density in both polarisations over the band, giving us

$$\langle F \rangle = 2\,\frac{\langle S \rangle}{\Delta\nu} \tag{3}$$

$$= 2\,\frac{E_{\rm rms}^2}{Z_0\,\Delta\nu}\ \text{from Eq. (2)} \tag{4}$$

which is the SEFD again. Combining Eqs. (1) and (4) shows that

$$E_{\rm rms} = \left(\frac{k\,T_{\rm sys}\,Z_0\,\Delta\nu}{A_{\rm eff}}\right)^{1/2}. \tag{5}$$

It is also useful to define

$$\mathcal{E}_{\rm rms} = \frac{E_{\rm rms}}{\Delta\nu} \tag{6}$$

$$= \left(\frac{k\,T_{\rm sys}\,Z_0}{A_{\rm eff}\,\Delta\nu}\right)^{1/2}\ \text{from Eq. (5)}, \tag{7}$$

the equivalent RMS spectral electric field for this bandwidth, although for incoherent noise it should be borne in mind that, unlike the flux density, the spectral electric field varies with the bandwidth. This is in contrast to the behaviour of coherent pulses, for which the spectral electric field is bandwidth-independent, and the flux density scales with the bandwidth.

The sensitivity of an experiment to detect a coherent radio pulse can be expressed as $\mathcal{E}_{\rm min}$, a threshold spectral electric field strength above which a pulse would be detected. This is typically measured with respect to $\mathcal{E}_{\rm rms}$, in terms of a significance threshold n_σ. Note that the addition of thermal noise will increase or decrease the amplitude of a pulse, so that $\mathcal{E}_{\rm min}$ is actually the level at which the detection probability is 50% rather than an absolute threshold, but this distinction becomes less important when n_σ is large. $\mathcal{E}_{\rm min}$ further depends on the position of the pulse origin within the telescope beam, as

$$\mathcal{E}_{\rm min}(\theta) = f_C\,\frac{n_\sigma}{\alpha}\sqrt{\frac{\eta}{\mathcal{B}(\theta)}}\,\mathcal{E}_{\rm rms} \tag{8}$$

where $\mathcal{B}(\theta)$ is the beam power at an angle θ from its axis, normalised to $\mathcal{B}(0) = 1$ and assumed here to be radially symmetric (e.g., an Airy disk). This same equation is used to calculate $\mathcal{E}_{\rm max}$ as described in Section 3. The factor η is the ratio between the total pulse power and the power in the chosen polarisation channel, typically found as

$$\eta = \begin{cases} 2 & \text{for circular polarisation} \\ 1/\cos^2\phi & \text{for linear polarisation} \end{cases} \tag{9}$$

with ϕ the angle between the receiver and a linearly polarised pulse such as that expected from the Askaryan effect. The term α is the proportion of the original pulse amplitude recovered after inefficiencies in pulse reconstruction, as described in Section 2.1. The remaining factor, f_C, accounts for the improvement in sensitivity from combining C independent channels with a threshold of n_σ in each, as described in Section 2.2.

The behaviour of coherent pulses as described above is quite different to that of conventional radio astronomy signals. As a consequence of Eq. (7), sensitivity to coherent pulses scales as $\sqrt{A_{\rm eff}\Delta\nu}$ in electric field and hence as $A_{\rm eff}\Delta\nu$ in power, whereas sensitivity to incoherent signals scales as $A_{\rm eff}\sqrt{\Delta\nu}$ in power. Fundamentally, this is because the signal of a coherent pulse combines coherently both across the collecting area of the telescope and across its frequency range, while most radio astronomy signals combine coherently across the collecting area and incoherently across frequency. Because of this difference it is not entirely appropriate to represent a detection threshold in terms of an equivalent flux density, as the flux density of a coherent pulse depends on its bandwidth, which defeats the purpose of using a spectral (rather than bolometric) measure such as flux density in the first place. However, this quantity is occasionally reported in the literature, so I calculate it in several cases for comparative purposes; ensuring, to the best of my ability, that both values are calculated for the same bandwidth, so that the comparison is valid. For a polarised pulse at the detection threshold, with spectral electric field $\mathcal{E}_{\rm min}$ and total electric field $E_{\rm min} = \mathcal{E}_{\rm min}\Delta\nu$, the equivalent flux can be found similarly to Eq. (4)—omitting the factor of 2, as the pulse appears in only a single polarisation—as

$$F_{\rm min} = \frac{\mathcal{E}_{\rm min}^2\,\Delta\nu}{Z_0}. \tag{10}$$