Ultra-High-Energy Cosmic Ray and Neutrino Physics using the Moon

Olaf Scholten
KVI, University of Groningen, Groningen, The Netherlands
E-mail: Scholten@kvi.nl

Abstract. The intriguing mystery of ultra-high energy (UHE) cosmic particles is the nature of their sources. In this presentation we indicate how these UHE particles, in order to uncover their sources, can be detected using radio observations of the Moon. When high-energy cosmic rays impinge on a dielectric, such as the lunar regolith, radio waves are produced through the Askaryan effect. At wavelengths comparable to the length of the shower produced by an UHE cosmic ray or neutrino, radio signals are an extremely efficient way to detect these particles. First results of observations obtained with the Westerbork Synthesis Radio Telescope will be reported, already showing improved flux limits for neutrinos with energies in excess of $3\times10^{22}$ eV. The status of the planning of similar observations with LOFAR will be presented.

1. Ultra-high-energy cosmic rays
The flux of cosmic rays [1] falls off by about 32 orders of magnitude with energy increasing by about 11 orders of magnitude from $1\text{ GeV}$ to $10^{20}$ eV. The intriguing aspect is that at energies above $10^{16}$ eV the spectrum falls off almost like a straight line when plotted on a double logarithmic scale, indicating that the flux is a power law as function of energy $E$, falling off like $E^{-2.7}$. From this observation, indicating that the spectrum is non-thermal, it can immediately concluded that there are sources producing cosmic rays, even at the highest energies of $10^{20}$ eV. The highest energies are really large, the kinetic energy of a single proton at $10^{20}$ eV exceeds the kinetic energy of a tennis ball in a very good service. This energy is of such a magnitude that, even on astronomical scale, it is not possible to find objects where such energies can be reached.

The usual mechanisms for accelerating UHE cosmic-rays involves the Fermi acceleration process which can occur only in the presence of magnetic fields which obey the Hillas criterium [2]; they have to be sufficiently strong over large enough distances to bend the particles in semi-circular orbits. At the highest energies there are no known objects that have strong enough magnetic fields over sufficient distances to obey this criterium and one has to explore other possible sources, see Ref. [3] for a discussion. The challenge is thus to locate the astrophysical sites where these particles originate from. At the Pierre Auger Observatory it has been observed that the arrival directions of cosmic rays at the highest energies show a strong correlation with the distribution of mass in the universe [4] which is what one would expect. A difficulty to measure these particles is presented by the extremely low flux of well below a single particle per km$^2$ per century. The detection method discussed here is shown to be very efficient to detect these small fluxes.

Protons at energies exceeding $6\times10^{19}$ eV may create pions when interacting with the cosmic
microwave-background radiation through the so-called GZK process [5]. This suppresses the flux of UHE protons, evidence of which is seen in recent data [6], while creating neutrinos. It is also very likely that neutrinos are generated at the production sites of the energetic cosmic rays. This, compounded with the fact that neutrinos are moving on straight lines (unlike charged cosmic rays which are deflected by intergalactic magnetic fields) may make neutrinos much more effective as a signal directing towards the astrophysical sources, which could be extremely powerful cosmic accelerators or, more exotically, decaying super-massive dark-matter particles or topological defects. Recent limits on the photon flux at high energies [7] have made the latter scenario less likely. Since neutrinos interact only weakly and since their flux at the highest energies is extremely low we need exceedingly large and efficient detector systems to measure them. In the following section it will be shown that the Moon, with an area of $2 \times 10^7$ km$^2$, can be used as a highly efficient detector [8] for ultra-high energy neutrinos.

2. Principle of particle detection using the Moon
In the interaction of an UHE neutrino with the material in the lunar regolith, the top layer of the Moon consisting of dust and small rocks, about 20% of the energy of the neutrino is converted into a cascade of particles, called the hadronic shower, while the remaining energy is carried by a single lepton which will not significantly contribute to the process considered here. In the hadronic shower there are large numbers of energetic hadrons, leptons, and photons all moving through the regolith with the light velocity $c$. Due to processes like Compton scattering and positron collisions off electrons bound in the atoms of the regolith a net excess of electrons is formed in the shower. This excess is typically of the order of 20% of the number of particles in the shower, $N \gg 10^6$. This large charge cloud is moving with almost the light velocity through a medium where the propagation velocity of electromagnetic waves is considerably less (index of refraction $n = 1.8$) and therefore Cherenkov radiation is emitted.

At wavelengths that are larger than the typical dimension of the charge cloud (10 cm) the emitted Cherenkov radiation is coherent, a process known as the Askaryan effect [9]. The intensity of this radiation reaches a maximum at a frequency of about 3 GHz where the wave length is of the same order of magnitude as size of the charge cloud. At this frequency the emitted radiation is strongly concentrated at the Cherenkov angle since the distance over which the shower extends, about 3 m, is much larger than the wave length. At lower frequencies the angular spread of the emitted radiation increases. At frequencies of 100-200 MHz the wavelength is comparable to the longitudinal extent of the shower which gives rise to a large angular spread of the emitted radiation. The increase of the angular spread is important for two reasons, one is that for many more directions of the incoming cosmic ray the signal will be detectable at Earth. A second, even more important reason is that for a shower parallel to the lunar surface the Cherenkov emission angle is the same as the angle of total internal reflection at the surface. As a result only the cosmic rays impinging at the rim of the moon, directed towards the Earth, emit a detectable signal at high frequencies while at the lower frequencies the total lunar surface may emit detectable signals [8]. A major advantage for the detection of neutrinos on the Moon is the rather long attenuation length of $\lambda_r = (9/\nu[\text{GHz}])$ m for radio waves which makes a very large detection volume. As a result the detection efficiency increases with about the third power of the wave length.

The idea of measuring cosmic rays through their impacts on the Moon was first proposed in Ref. [10] while the first experiments were carried out with the Parkes telescope [11], later followed by others [12, 13]. These observations are all performed at relatively high frequencies (2 GHz) where the emission is strongest. It should be noted that the radio-emission process for cosmic rays in the Earth atmosphere is governed by another mechanism. The magnetic field of the Earth induced electric current in the shower plasma and radio waves are emitted due to the changing magnitude of this electric current [14] while the Askaryan effect plays only a secondary
role. Similar to the case of radiation from the Moon, the frequency spectrum can be understood by considering the important length scales in the problem [15].

3. WSRT Observations

The emission of 3 m radio waves from impacts of high energy neutrinos on the Moon is exploited in our observations with the Westerbork Synthesis Radio Telescope (WSRT) and has resulted in the most stringent flux limit at the highest energies [16]. The WSRT consists of an array of 14 parabolic antennas of 25 m diameter. Only 11 of the 12 equally spaced WSRT dishes are used for this experiment. In the observations we have employed the Low Frequency Front Ends (LFFEs) which cover the frequency range 115–180 MHz with full polarization sensitivity, sampled as 8 subbands of 20 MHz each by the Pulsar Machine II (PuMa II) backend [17]. We have used 4 frequency bands centered at frequencies of 123, 137, 151 and 165 MHz for each of two different beams aimed at different sides of the Moon. This creates the possibility of an anti-coincidence trigger since a lunar Cherenkov pulse should only be visible in only one of the two beams. The total bandwidth per beam is 65 MHz. The time series data is recorded for each subband with a sampling frequency of 40 MHz. The data is processed in blocks of 0.1 s, where each block is divided in 200 traces of 20,000 time samples.

In a first processing stage the data is searched for large pulses after applying the following two corrections. First the narrow band Radio Frequency Interference (RFI) is filtered from the data. All frequency channels exceeding a smooth background by 50% or more are marked as RFI lines and set equal to zero. Second, the dispersion due to the ionosphere of the Earth is eliminated. The vertical total electron content (TEC) values of the ionosphere is corrected for the elevation of the Moon to obtain the slanted-TEC (STEC) value. Because of variations of the ionosphere on short timescales, in the analysis we account for an inaccuracy in the determined STEC value which will result in an increased time width of the pulses.

From the de-dispersed and RFI-mitigated spectrum a 5-time-sample-summed relative-power spectrum is constructed,

$$P_5 = \frac{\sum_{5 \text{ samples}} P_x}{\left\langle \sum_{5 \text{ samples}} P_x \right\rangle} + \frac{\sum_{5 \text{ samples}} P_y}{\left\langle \sum_{5 \text{ samples}} P_y \right\rangle},$$

where the averaging is done over one time trace (20,000 time samples), and $x$ and $y$ denote the two polarizations. The summation over 5 time samples corrects for a possible error in the STEC value. A trigger is generated when in all four frequency bands in the same beam a value $P_5 > 5$ is found. The first and last 250 time samples are excluded since the RFI noise is not properly eliminated from these parts of the spectrum. The value $S$ is defined as the sum over the maximum $P_5$ values in the 4 frequency bands, $S = \sum_{4 \text{ bands}} P_5$.

In the subsequent off-line analysis the data is ‘cleaned’ by eliminating a timer signal that repeats with a frequency of $102.4 \, s^{-1}$, pulses that are very wide, and pulses that appear in both beams in the same time trace. The largest remaining pulse in the data has a value of $S = 76$. On the basis of simulations we can show that this observation translates into being able to exclude pulses coming from the moon with a strength exceeding $S > 120$ (corresponding to $120 \sigma^2 \times 5 = 240 \, k\text{jy}$) over a period of 40 h observation [16]. The lack of pulses of a certain power converts into a limit on the flux of neutrinos where attenuation of the signal in the Moon, transmission at the lunar surface, and angle with respect to the direction of the neutrino have to be taken into account [8]. The resulting 90% confidence limit flux limit shown in Fig. 1 assuming that the neutrino cross sections given in Ref. [18]. The limit is still well above the Waxman–Bahcall limit [19] but borders on the predictions of a top-down model [20] for exotic
particles of mass $M_X = 10^{24}$ eV. The previous limits in the UHE region have been set by ANITA [21] and FORTE [22].

The determined limits are subject to systematic errors on the acceptance simulation which are due to uncertainties in the density (10% in threshold energy), the attenuation length (40% in flux), and the stopping power of the regolith, (20% in flux). The error in the moon coverage of the two beams is estimated at 20%. Adding these errors in quadrature gives a systematic error on the flux of 50% as indicated in Fig. 1.

4. Future
LOFAR (Low Frequency Array) is a new concept radio telescope that is presently being rolled-out in The Netherlands and other European countries and is also used for the detection of cosmic rays [23, 24]. LOFAR couples a large number (thousands) of simple wire dipole antennas. Via software control the relative phasing of the antennas can be tuned such that the array is (virtually) pointed towards a certain direction in the sky. The fact that this pointing is done in software without any physical movement of antennas makes the system very flexible and gives the possibility to simultaneously perform observations with multiple beams.

Part of our ongoing activity in this field concerns the optimization of the neutrino observations with LOFAR [25]. For the observation of neutrino impacts on the moon the multi-beam option, combined with the large collecting area, is very important. The large area improves the signal-to-
noise ratio thus increasing the detection sensitivity at lower energies while the multi-beam option allows for the formation of sufficiently many beams to cover the complete lunar surface. The position resolution on the moon, offered by the large baselines, further improves the sensitivity to genuine pulses generated by neutrino impacts. In Fig. 2 the sensitivity is indicated that can be reached with a week of observation using only the stations in the core (blue curve) while the sensitivity attained by using all LOFAR stations, including the international ones, is such that in one month accumulated time should result in a large number of observed events for a neutrino flux at the level of the Waxman-Bahcall limit.

The large detection efficiency of LOFAR opens the possibility to observe neutrino absorption lines. UHE neutrinos will be absorbed on the low-energy cosmic neutrino background (CνB) through the excitation of the Z boson resonance. This annihilation process is expected to lead to sizable absorption dips in the UHE neutrino spectra [26]. The positions of these absorption lines depend on the red-shift of the source emitting the UHE neutrinos, $z_s$. An exciting alternative is that the neutrino mass is not constant but varies with red-shift, mass varying neutrinos (MaVaN) [27], proposed as a model for dark energy. Such a neutrino mass variation introduces a structure of the absorption lines which is distinctly different to that obtained for red-shift independent $\nu$-masses.

The magnitude of a radio pulse created by the impact of neutrinos of a given energy on the Moon depends on the viewing angle and the distance below the lunar surface of the shower. The pulse-height is thus not a direct measure of the neutrino energy but the measured pulse-height spectrum does reflect the energy distribution of the neutrinos as has been investigated in Ref. [28]. The predicted pulse-height spectra for different scenarios for the neutrino mass and various red-shifts for the neutrino sources is shown in Fig. 3, indicating that with a sensitive detection system one should be able to distinguish sources at $z_s=50$ from more nearby ones.

![Figure 2](image-url)

**Figure 2.** The predicted sensitivities for two different LOFAR configurations (see text) are compared with the results obtained from the NuMoon observations with WSRT [16].
Figure 3. The expected count rate [28] for a realistic experiment for the different neutrino absorption dips for sources at various red-shifts $z_s=5$ (drawn line), $z_s=20$ (dotted line), and $z_s=50$ (dashed line). The thick, blue, curves give the absorption spectra for the case where the neutrino mass is independent of red-shift, while the thin, red, curves gives the predictions in the MaVaN model.

Acknowledgments
This work was performed as part of the research programs of the Stichting voor Fundamenteel Onderzoek der Materie (FOM), with financial support from the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO). I wish to thank all members of the NuMoon collaboration. Without their contributions it would not have been able to perform the observations summarized in this work.

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