NuMoon: Status of Ultra-High Energy Cosmic Ray detection with LOFAR and improved limits with the WSRT.

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Abstract: LOFAR (Low Frequency Array) is a new distributed digital radio telescope built in the Netherlands and surrounding countries. It can be used to detect radio emission induced by cosmic rays as well as other transient signals, due to its design of stations of simple antennas. We will present LOFAR and how the NuMoon project plans to use the telescope to detect ultra-high-energy cosmic rays ($> 10^{21}$eV). The flux at these energies is very low, therefore, the Moon is chosen as target because of its large surface area of 10^7 km^2. When a cosmic ray hits the Moon surface it will produce a cascade of secondary particles with an excess of electrons. This causes radio emission, which is known as the Askaryan effect. Until recently, an unsolved problem was the possibility of formation-zone suppression of near-surface cascades, as produced by cosmic rays, which could prevent this radiation from being visible from Earth. We will show an analytic calculation that solves this problem. With this result we are able to set a limit on the flux of cosmic rays at the highest energies with data from the Westerbork Synthesis Radio Telescope and provide the expected sensitivity for LOFAR and the Square Kilometre Array.

Keywords: Observations and simulations at energies $> 10^{18}$ eV; New experiments and instrumentation.

1 Introduction

Cosmic rays have been measured up to energies of a few times 10^{20} eV [1]. An open question is still what objects can accelerate particles to these extremely high energies. The next question is: up to what energies can these objects accelerate particles. It is also possible that very heavy unknown particles decay into Ultra-High Energy Cosmic Rays (UHECR). These particles are predicted by various extensions to the standard model either to explain dark matter, or to add more symmetry to the standard model, i.e. super symmetry. Also, above $5 \cdot 10^{19}$ eV, the Greisen-Zatsepin-Kuzmin (GZK) effect [2] is expected to reduce the flux due to cosmic rays interacting with cosmic microwave background photons. Limits on particle fluxes at energies above 10^{20} eV constrain the standard model extensions and will give more information about the GZK cut-off and the sources of UHECR.

Because the flux at energies above $3 \cdot 10^{19}$ is less then 1 per square kilometer per century and the latest indication is that it drops off faster than $dN/dE = E^{-4.0}$ [3] a large collecting area is needed to answer these questions. In order to observe particles with an energy ten times higher, a collecting area even larger than the Pierre Auger Observatory is needed. In the first section we explain that the Moon, with a surface area of 10^7 km^2, combined with a powerful radio telescope is a suitable detector as first proposed by [4]. In that section we also solve an outstanding problem, the possibility of suppression of radiation in the formation zone, close to the Lunar surface. We continue in the next section with a limit on the UHECR flux as set by the Westerbork Synthesis Radio Telescope (WSRT) within the NuMoon project. To improve the sensitivity a larger telescope is needed: LOFAR [5]. In the fourth section it is explained how we plan to use this revolutionary telescope in our search for UHECR.

2 Detection principle for UHE Cosmic Rays

2.1 The Askaryan effect

When an UHE cosmic ray or neutrino impinges on the Moon, it creates a shower of secondary particles in the Moon. In this shower a charge excess builds up, because electrons from the Lunar regolith are kicked out by photons and electrons in the shower. This charge excess acts like a current and this current creates a radio pulse of a few nanoseconds. This is known as the Askaryan effect [6]. The frequencies at which this radiation is coherent depend on the dimensions of the shower. The lateral distribution is of the order of 15 cm, which gives coherent radiation at 3 GHz, but only close to the Cherenkov angle. The longitudinal distribution is a few metres, which gives coherent radiation around 150 MHz, but spread out over a much wider angle. This wider spread is essential for cosmic ray detection, because cosmic ray induced showers are always directed inwards, which means it is highly unlikely that the Cherenkov angle is directed towards Earth. The radiation at lower frequency is less strong which leads to a higher energy threshold, but this is compensated for by the larger acceptance regarding the incoming angle.

2.2 The absence of formation zone suppression

Until recently, an unsolved issue in the detection of cosmic rays with the Lunar Askaryan technique was the possibility of suppression in the formation zone. Because cosmic rays create showers at the surface, there may not be enough material to create coherent waves before the Lunar surface is reached, and also internal reflection could diminish the signal. Detailed modeling [7] shows that there is no formation zone effect, because we can view the radiation as coming mainly from the endpoints of the shower (or each electron in the shower) instead of Cherenkov radiation from the electron tracks.

To calculate the Askaryan effect the problem is usually split in two separate calculations. The first part calculates the radiation from the shower to the Lunar surface, the second part calculates the transmission through the surface and the radiation to Earth. In both calculations a far field approach is used. This is fine if the shower is induced far below the surface, as is the case for neutrinos. However, if the shower is induced at the surface, the first far field approximation cannot be used. As cosmic rays interact at the surface another approach has to be taken.

To do this we consider two half-spaces divided by the plane $x = 0$. For $x > 0$ the refraction index is n' (=1 for vacuum). For $x < 0$ the refraction index is n (=1.8 for the Moon). In the lower half-space a particle with charge Q and velocity β moves from $z = -L/2$ to $z = L/2$ at $x = -a, y = 0$ passing through $z = 0$ at $t = 0$. We start out with the vector potential and write it as an integral over waves in the frequency domain:

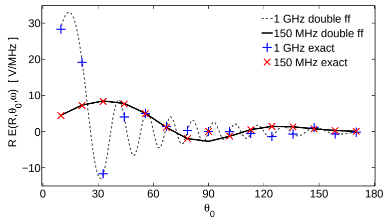

Figure 1: [color online] Electric field strength as a function of angle at 150 MHz and 1 GHz at a distance of 1400 km for a shower length of 3 m and a charge $Q = 10^{12}$e, calculated according to the double far-field analytic and the exact numerical methods.

$$\mathbf{A}(\mathbf{r},t) = \int \frac{d^3k\, d\omega}{4\pi^2} \mathbf{A}(\mathbf{k},\omega) e^{i\mathbf{k}\cdot\mathbf{r}-i\omega t} \; . \qquad (1)$$

Here $\mathbf{A}$ is the vector potential, k is the wave vector, ω is the wave frequency, r denotes the spatial coordinates and t denotes time. Each incoming wave $e^{i\mathbf{k}\cdot\mathbf{r}-i\omega t}$ generates a transmitted wave $t_{A_z||} e^{i\mathbf{k}'\cdot\mathbf{r}-i\omega t}$ for $x > 0$ where $t_{A_z||}$ is the transmission coefficient for the vector potential that can be obtained from the transmission coefficient of the electric potential and k' is the refracted wave vector. The transmitted radiation ($x > 0$) can now be expressed as

$$A'_z(\mathbf{r},t) = \int \frac{d^3k\, d\omega}{4\pi^2} t_{A_z||} A_z(\mathbf{k},\omega) e^{i\mathbf{k}'\cdot\mathbf{r}-i\omega t} \; , \qquad (2)$$

The full calculation is performed in detail in [7] and is compared with the double far field approach. In this calculation is the implicit assumption that the observer is far from the surface and the outgoing waves can be treated as plane waves. Still a complete integral is calculated, partly numerically, over all waves leading from the source to the surface, that contribute to the field at the observer. Fig. 1 shows that the result is the same for both methods for a shower deep under the Lunar surface, thus the double-far-field approach is correct. Fig. 2 shows that the emission does not depend on the shower depth, if observed from sufficiently far away. Therefore there is no suppression effect in the formation zone. This means that Lunar cosmic ray showers can in principle be observed by radio telescopes on Earth.

3 UHECR flux limit with the WSRT

The NuMoon project is part of the LOFAR Cosmic Ray Key Science Project and aims to detect Cosmic Rays and Neutrinos at the highest energies using the Lunar Askaryan technique. So far, measurements were taken with the Westerbork Synthesis Radio Telescope (WSRT) for the NuMoon project to search for UHE neutrinos[8]. In 46.7 hours no pulse was detected above 240 kJy with a 87.5 % probability. Because of the absence of a formation zone suppression (Section 2), this also sets a limit on the cosmic ray flux as shown in Fig 3 according to the theory in [9]. The

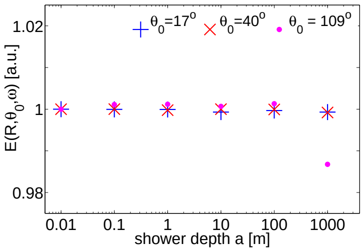

Figure 2: Electric field strength as a function of depth, normalized by the strength at $a = 10^{-2}$ m, for 3 different angles at 150 MHz at a distance of 1400 km for a shower length of 3 m. [a.u.] stands for arbitrary units.

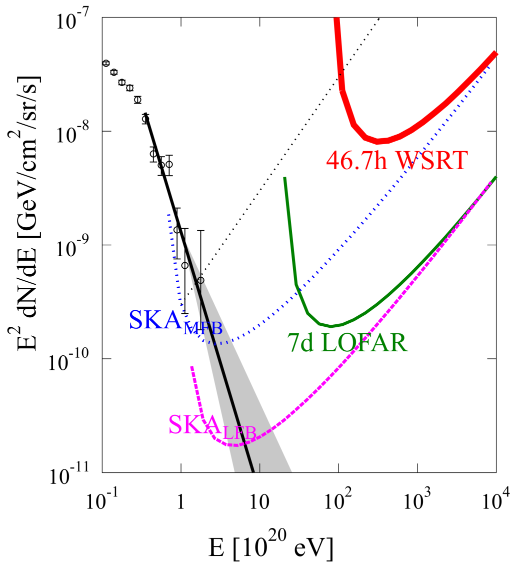

Figure 3: The currently established cosmic-ray flux limit from WSRT observations [8] (thick upper line) is compared to the flux determined by the Pierre Auger Observatory [11] (data points with error bars) and a simple polynomial expansion (grey band). Also the prospective flux sensitivities are indicated that can be obtained with LOFAR [5] and SKA [13] observations.

limits set by the WSRT are at a much higher energy threshold than the highest energy measured by the Pierre Auger observatory [3], but are the best limits above 10^{22} eV. To increase the sensitivity new observations are planned with LOFAR, currently the most sensitive radio telescope at frequencies between 100-200 MHz.

4 LOFAR

LOFAR (Low Frequency Array) [5] is a new digital radio telescope that consists of several thousand simple dual polarization antennas. There are two types of antennas: the Low Band Antennas (LBA), operating from 10-90 MHz, and the High Band Antennas (HBA), operating from 110-190, 170-230 or 210-250 MHz. The HBA are grouped in tiles of 16 antennas. The antennas are grouped in stations. There are three types of stations, named Core Station, Remote Station, both placed in The Netherlands, and International Stations, currently in Germany, France, Sweden and the United Kingdom. Stations in more countries may follow. Each station has 96 LBA antennas, but the number and configuration of the HBA tiles is different. The Core Stations have two groups of 24 tiles, the Remote Stations have one group of 48 tiles and the International Stations have one group of 96 tiles. LOFAR furthermore consists of a central processing facility, with a BlueGene/P supercomputer and two computer clusters to combine and analyze the data from the different stations.

In traditional radio telescopes the signal is enhanced by using a dish. A larger dish gives a higher sensitivity, but also takes more effort to move around. To increase the resolution and the sensitivity, multiple dishes can be used together. The signal is then corrected for the time difference between the different dishes, according to the viewing direction. LOFAR takes this multiple dish approach one step further, by not using multiple dishes, but fields of many simple antennas. By correcting the time delays for the signal within one field, the field can act as a dish. This has three benefits: it is cheap to make a large telescope, the telescope can point in a different direction very fast because the antennas do not have to move, and the telescope can point in multiple directions at once. In addition, LOFAR is a digital telescope which means that with enough computing resources the telescope can run multiple observations at the same time.

4.1 Operation modes

LOFAR has three main operation modes: aperture synthesis imaging, beam forming, and analyzing/obtaining data from the antenna ring buffers. The first mode is making images of the sky with high spatial resolution. The second mode is used to look at one or more patches of the sky with high time resolution. The last is the most basic level of data. It can be used to search for radio emission from air-showers [10]. In this mode the data from each dipole is searched for pulses caused by cosmic-ray induced air showers. When pulses in enough dipoles are found with the correct time delay it is a hint for an air shower detection and the buffers from the dipoles are read out for further analysis. These buffers, the Transient Buffer Boards (TBBs), are specifically designed for this observation mode.

4.2 Transient detection

There are a lot of transient phenomena at radio frequencies from our galaxy and beyond. Examples are pulsars, the Jupiter/Io system, lightning on Earth and other planets and cosmic rays. To look for these transient phenomena with LOFAR the beam-forming mode is used. In beam-forming mode the data from each station is added either in voltage domain (coherently) or in power domain (incoherently). Coherent addition has the benefit of a higher signal to noise ratio, while the incoherent mode probes a larger part of the sky. We use this last method to probe a large part of the sky (10 sq. deg. instantaneous coverage) for single pulses of a few milliseconds from pulsars and other objects, parallel to other observations. When such a pulse is found, the buffers from each antenna are read out and analyzed further. With this TBB data it is possible to reconstruct a telescope pointing to determine the origin of the pulse more precisely and also to check if it is not of terrestrial origin. As a test we have detected a giant pulse from the Crab pulsar and reconstructed the position of the Crab pulsar from the TBB data.

4.3 NuMoon @ LOFAR

With LOFAR a similar detection as used to detect Fast Radio Transients can be used to look for pulses created by UHE Cosmic Rays. Instead of using a less sensitive beam that covers a large part of the sky, we use multiple coherent beams to cover the Moon surface. The size of such a beam depends on the distance between the different stations. Because it is not feasible to make hundreds of beams, we limit ourselves by using only the 24 Core Stations within a radius of 2 km. In this case 50 beams are required to cover the complete Moon surface. Each beam has 48 MHz of bandwidth that can be chosen freely in chunks of 195 kHz bandwidth between 110 and 190 MHz. In this way narrow band radio frequency interference (RFI) can be excluded. Simulations have shown that it is best to choose the lowest possible frequencies, excluding the channels containing RFI. In order to look for pulses, the data first has to be corrected for dispersion in the atmosphere. Then the data is transfered to time domain. For this an inverse polyphase filter has been developed, because the station conversion to frequency domain also uses a polyphase filter (an advanced fast Fourier transformation with better separation in the frequency domain). In time domain the samples are 5 ns but because of the limited bandwidth the intrinsic resolution is 10 ns. To check for cosmic ray induced pulses the data is summed over a sliding window of 15 samples. When a sufficiently high peak is found for a certain beam a trigger message is send. A central program handles the trigger messages from all beams. If many beams are triggered at the same time, the signal is probably interference and is discarded. However, if a pulse is found in only a few adjacent beams, another message is sent to obtain 1 millisecond of data from all the antennas from all the stations, not only the Core Stations on which the trigger was based, at full bandwidth. In this way a more sensitive beam can be formed towards the Moon, because the bandwidth and the number of stations is larger. This data can then be analyzed to check if this pulse is indeed of Lunar origin and if it resembles a cosmic ray signal. More details and the application to detect neutrinos can be found in [12].

5 Status and outlook

As shown in section 2, ultra-high energy cosmic rays and neutrinos can be found by detection of Lunar Askaryan radiation by pointing a radio telescope at the Moon. With data from the WSRT a new limit has been set. The next telescope we will use for this is LOFAR. In the next months we will investigate if the suggested trigger, based on simulations of the whole system under the assumption that the noise is Guassian, works as expected on real data and if the anti-coincidence trigger between the beams is efficient enough to suppress interference. This should lead to a definition of the real trigger algorithm for LOFAR.

The expected sensitivity that can be reached in a one week measurement using the LOFAR telescope is shown in Fig. 3 as well as the expected sensitivity for a one day measurement with the future SKA telescope [13]. At lower frequencies (100-300 MHz band, SKA-l in Fig. 3) the SKA is sensitive to a smaller flux, while at intermediate frequencies (300-500 MHz band, SKA-m in Fig. 3) the SKA is sensitive to cosmic-rays of lower energy. The increased sensitivity will make this method sensitive to cosmic ray energies of the order of 10^{20} eV where, due to the large collecting area, competitive measurements are possible.

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), and an advanced grant (Falcke) of the European Research Council.

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