Detection of Ultra High Energy Cosmic Rays with LOFAR

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***Abstract*— The low flux of Ultra High Energy (>10^{21} eV) Cosmic Rays (UHECRs) makes their detection very difficult. We explore the feasibility of using the Moon as a detector for these high energy particles. Our strategy is to cover the whole visible lunar surface with digital beams of an array of omni-directional antennas of LOFAR (LOw Frequency ARay) and to look for short pulses of Cherenkov radiation emitted by a shower induced in the lunar crust when a cosmic rays strike it. The instantaneous power of the pulses is so strong that they can be detected on earth with a sensitive telescope. We investigate the sensitivity of LOFAR to detect these incoming radio signals from the Moon. If the cosmic ray spectrum continues beyond the GZK limit with unchanged energy dependence, observation of super GZK particles with LOFAR will indeed be possible.**

***Index Terms*— Cosmic rays, GZK cutoff, Cherenkov radiation, Radio interferometry.**

I. INTRODUCTION

AFTER the discovery of Cosmic Microwave Background (CMB) it was predicted by Greisen, Zatsepin and Kuzmin [1, 2] that cosmic ray spectrum would end at an energy just below 10^{20} eV because the high-energy nuclei would interact with the CMB photons and, even if cosmic ray particles were accelerated to high energies, they would not be able to survive the propagation from their sources to us. This poses a constraint that these sources cannot be far away. However, energetic protons, by interacting with the CMB photons loose energy and produce pions with energies the same order of magnitude..Subsequential decays of pions gives rise Ultra High-Energy Neutrinos (UHENs) which may traverse long distances in the universe almost un-deflected and un-attenuated. Therefore, observation of UHENs makes it possible to point back to their source of generation.

Although no satisfactory particle acceleration theory has been developed yet, the assumption is that these Ultra High Cosmic Rays (UHECRs) are of extragalactic origin. The gyroradius of a 10^{20} eV proton exceeds the dimension of the whole galaxy. Therefore, they have to be accelerated in much bigger and more powerful astrophysical systems. Specifically, there are four systems that might be able to accelerate protons above 10^{20} eV, high magnetic field neutron stars, Active Galactic Nuclei (AGNs), lobes of giant radio galaxies, and gigaparsec shocks in the extragalactic medium [3, 4, 5].

The realization of the difficulties in extending the galactic cosmic-ray acceleration to the observed high energies led to the development of exotic particle-physics models of ‘top-down’ production of cosmic rays at the highest energies. There are generally two classes of top-down models – one related to topological defects (like magnetic monopoles, cosmic strings) and another related to cold dark matter which is related with decay of quasi-stable massive X particles produced in the early universe [6, 7].

The Pierre Auger Observatory in Argentina recently observed an anisotropy in the arrival direction of UHECRs and confirmed their extra galactic origin. They observed a correlation of UHECR sources with the spatial distribution of AGNs [8].

The cosmic-ray flux spectrum follows a power law $\frac{dN}{dE} \propto E^{-\gamma}$ where the spectral index γ is above 3.0 in the energy range above 10^{19} eV, therefore, the cosmic ray spectrum is so steep that even with rather large air shower arrays on Earth, it is difficult to observe events above 10^{20} eV because of their very low flux (a few per km^2 per millennium). Therefore, detectors with large collecting area and high duty cycles are needed.

In 1989, Dagkesamanskii and Zhelenznykh [9], proposed to detect showers initiated by Ultra High Energy Cosmic Rays (UHECRs) and neutrinos (UHENs) by measuring coherent Cherenkov radiation emitted just below the surface of the Moon when a high energy cosmic rays strike it. Based on the concept of looking for pulses coming from the Moon, experiments have been performed at Goldstone (GLUE) and are running at the Australian Telescope Compact Array (ACTA–LUNASKA) [10, 11]. An observarion program

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running at the Westerbork Synthesis Radio Telescope (WSRT–NuMOON) is also looking for radio pulses from the Moon at a lower frequency than used in the GLUE experiment. This results in a lower intensity of the emitted radiation which is compensated by an increase in the angular spread resulting in an overall increase of the detection probability [12, 13]. LOFAR will also observe at similar low frequencies, but because of a larger collecting area than the WSRT, it has a better sensitivity [12, 14, 15]. LOFAR is a path finder of the Square Kilometer Array (SKA), hence SKA will have an even better sensitivity [13].

II. THEORY

The intensity of radio emission from hadronic shower in the lunar regolith with energy E_S, in units of Jansky's (1 Jy = 10^{-26} W m^{-2} Hz^{-1}), in a bandwidth $\Delta\nu$ at central frequency $\nu_0\,(=2.5\,GHz)$ can be parameterized as [12]

$$F(\theta,\nu,E_S)=3.86\times10^{6}\,e^{-Z^2}\left(\frac{\sin\theta}{\sin\theta_C}\right)^2\left(\frac{E_S}{10^{20}\,eV}\right)^2\times\left(\frac{d_{moon}}{d}\right)^2\left(\frac{\nu}{\nu_0(1+(\nu/\nu_0)^{1.44})}\right)^2\left(\frac{\Delta\nu}{100\,MHz}\right)Jy,$$

with $Z=(\cos\theta-1/n)\left(\frac{n}{\sqrt{n^2-1}}\right)\left(\frac{180}{\pi\Delta_C}\right)$. The Cherenkov angle is related to the index of refraction of medium, $\cos\theta_C=1/n$, where the bulk of the radiation is concentrated. θ is the emission angle relative to the shower direction. The spreading of the Cherenkov cone of the radiation from the cascade is given by

$$\Delta_C=4.32^{\circ}\left(\frac{1}{\nu[GHz]}\right)\left(\frac{L(10^{20}\,eV)}{L(E_S)}\right).$$

The refractive index and the lunar regolith density are $n=1.8$ and $\rho=1.7\,g/cm^3$ respectively. The lunar radius is ≈ 1760 km, while d is the average distance between moon and observer at earth. The thickness of the near surface regolith, from which radio signals can emerge, is of the order of 500m. The radio wave absorption length in lunar regolith is $\lambda_r=(9/\nu[GHz])$ m [16]. At lower frequency the emission is much closer to isotropic [12] than at higher frequencies. An additional advantage of observing at lower frequency is that surface irregularity will make less of a difference.

III. EXPERIMENTAL SETUP

LOFAR is an interferometric array of dipoles which can be synthesized as a dish of a telescope. The plan is to have 18 antenna fields (or stations) densely populated in an area with a diameter of 2 km. In addition to the core stations, 18 remote stations are planned further away from the central core within 100 km diameter [15, 17]. Each station will have 96 dual polarized Low Band Antenna (LBAs), optimized for 30 to 80 MHz, and 48 High Band Antennas (HBAs) tiles for 120-240 MHz [15, 17]. LBAs are dual polarized inverted–V antennas [Fig 1.a] and HBA tiles consist of 16 bowtie–shaped fat dipoles [Fig. 1 b].

Figure 1.a: LOFAR – Low Band Antennas (LBAs)

Figure 1.b: LOFAR –High Band Antenna (HBA) tile.

The LBAs and HBAs tiles share the same receiver. HBAs at each station are grouped into two sub-fields, each with 24 tiles. Only 48 LBAs from a station can be used simultaneously however, another observer can use the HBAs at the same time. In addition to this, a number of international stations across

Europe (E-LOFAR) are planned in Germany, UK, France, Sweden and Ukraine. Each international station will have 96 LBAs and 96 HBA tiles. Interferometric baselines within Netherlands are up to 100 km however, E-LOFAR baselines are up to 1000 km.

The electric signals from the antennas will be transported to a series of electronic boards where appropriate phase delays will be applied so that station beams on the sky can be formed in a predetermined direction. Each of the stations has 4 Gb/s connection to the central processor which is an IBM Blue/ Gene. It has 25 Tflops capability combined with an input I/O system, which can correlate 32000 frequency channels of 1 KHz each. At the central processor these station beams are tied together to enhance the signal to noise ratio and weights, necessary for the beam-former, are provided by the central processor. In parallel with the filtering and beam-forming at stations and tied array beam forming at the central processor, the digitized raw data is written into a ring buffer at station level. These ring buffer modules have their own triggering capability and can hold raw data from 8 dual polarized antennas for 1 sec each which can then be accessed later, for offline processing. However, the buffering time of 1 sec has posed a serious time constraint. We are currently planning to increase the memory of these buffers so that we will have buffer time of more than 1 sec. Another technical difficulty is related to being able to do online calibration of the dispersion of the ionosphere. Because we are looking for pulses coming from outside of earth's ionosphere, which is a dispersive media, the pulse (or signal) will be dispersed. Therefore, we need to de-disperse the data online before checking for a signal to trigger the buffer boards at station level.

IV. Experimental Method

As proposed by Scholten et al. [12], 100 – 200 MHz is optimal for detecting of Ultra High Energy Cosmic Rays (UHECRs) hitting the surface of the Moon. Coherent addition of electric signals from all stations (or antenna fields) will reduce sky noise as well as system noise. The strategy is that all antennas of LOFAR will be configured in tied array mode, and beams will be formed into the direction of the Moon for the frequency range of 100 -200 MHz using the HBAs. The field of view should cover a sizable part of the whole lunar surface. The Moon has a field of view of half a degree. A number of tied array beams are required to cover the whole lunar surface and will constantly track the Moon. The buffer boards at the stations will trigger if in any tied array beam a pulse is seen with power larger than a predefined threshold. A real event can be discriminated from a false event by performing an online anti-coincidence check on number of units. However, offline processing would be done on buffered data of individual antennas to find the nature and precise direction of the pulse.

Triggering will be performed on tied array beams using 18 core stations only since the remote stations are further away from the central processor which makes it difficult to transport the data within the buffering time limit of 1 sec. After a trigger is detected the raw time series data of the last few milliseconds will be read from the buffer boards at core and remote stations, as well as from E-LOFAR stations. Therefore, remote stations and international stations will be included in the offline data analysis to locate the cosmic-ray impact direction .

V. Results and Discussion

We calculated the sensitivity of LOFAR for detection of UHECRs. The total collecting area of a telescope fixes the detectable lower energy threshold of a particle, while the observing time determines the expected count rate. In Figure 2.a sensitivity limits are plotted for coherent beams formed from core stations as well as beams combining core stations, remote stations and international stations. To estimate the efficiency to observe UHECRs the latest Pierre Auger data is also plotted. The fitted spectral index is 4.4 for energies in excess of above 4×10^{19} eV [18].

The sensitivity limit is calculated for 1 month, 3 months and 1 year of accumulated observing time. A linear fit with spectral index is 4.4 is plotted, showing that we would not be able to observe any event within 1 month. However it there is a powerful local sources, such as for example Centaurus A [8], the steepness of the at high energy may be reduced. For this reason also another fit with spectral index 3.2 is plotted which meets the expected sensitivity. It is clear from the fit for spectral index 4.4, that 1 year observing time will be needed if spectrum follows power law $E^{-4.4}$.

For triggering only core stations will be used, This moves the energy threshold above 10^{21} eV [See Figure 2.a]. However, after triggering data from all stations will be available and beams can be formed offline which enhances the available collecting area and therefore lowers the detection threshold.

The flux limits of neutrinos are compared in Fig. 2b to the predictions of several models and with those of other experiments. Calculations are done for an observing time of 90 days. With LOFAR a neutrino flux limit will be reached, for the first time, well below the Waxman - Bahcall bound for neutrinos and, in addition, we would be able to rule out a subset of theoretical Top–Down model.

In Figure 2.b the flux limits are compared with those of other experiments, like ANITA (Balloon mission) [19],

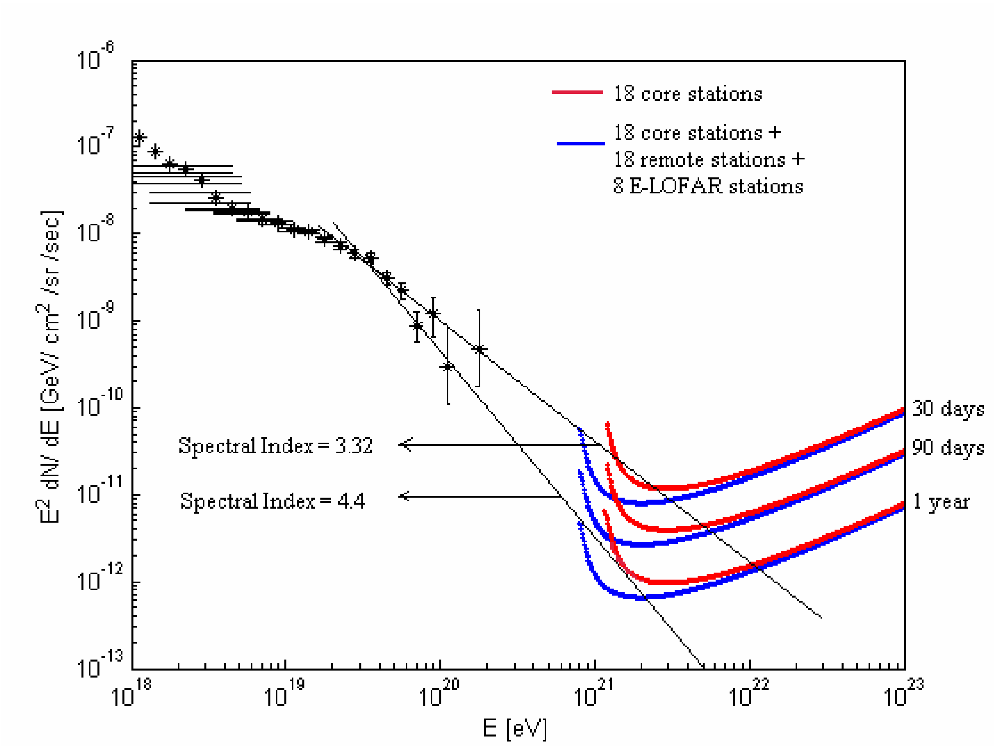

Figure 2.a: Limits on cosmic ray flux with LOFAR. Flux limit for core stations are plotted in red color, however it is plotted in blue color for beams, formed including all core stations, remote stations and international stations of LOFAR.

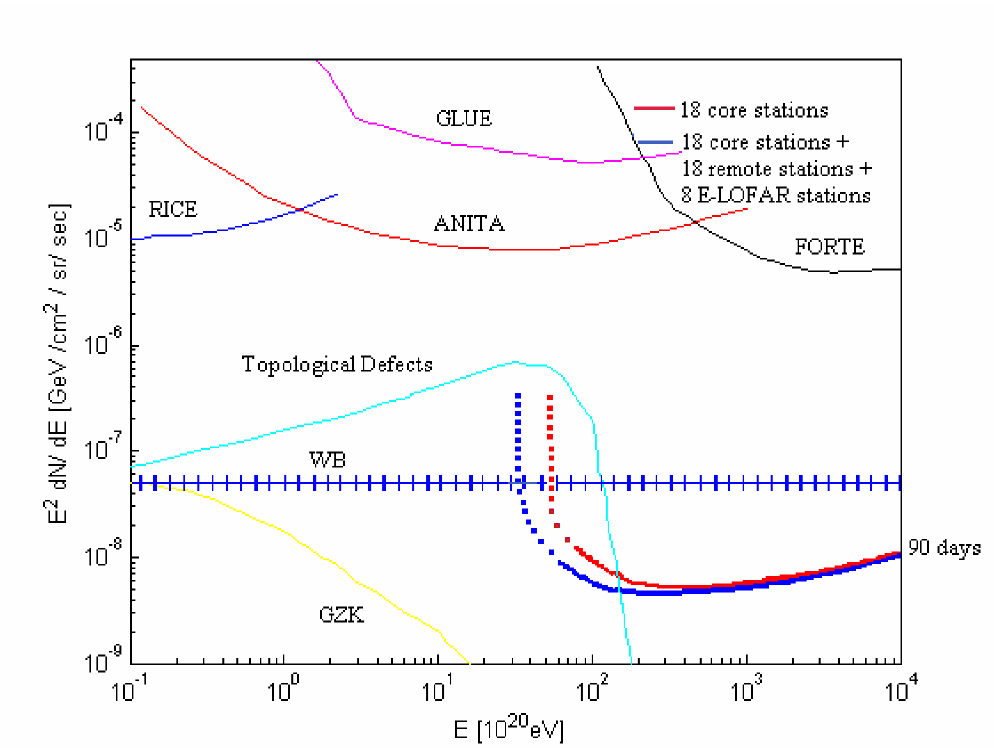

Figure 2.b: Sensitivity limit expected for detection of Ultra High Energy Neutrinos.

FORTE (satellite mission) [20], and GLUE (NASA space network antenna) [21]. With 90 days of observation time we will be able to improve the limit on the flux of UHENs by two orders of magnitude over the present one determined from WSRT [22, 23] or three orders of magnitude compared to the FORTE limit [20].

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