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First results on UHE Neutrinos from the NuMoon experiment

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Abstract: When high-energy cosmic rays impinge on a dense dielectric medium such as the lunar regolith, radio waves are produced through the Askaryan effect. At frequencies of the order of 100 MHz this is a very efficient way to detect Ultra-High Energy cosmic rays or neutrinos. The radio signals can be measured using the Westerbork Synthesis Radio Telescope (WSRT) which consists of fourteen 25m parabolic dishes. A first analysis of the present 100 hour observations at the WSRT will be presented.

Introduction

When high-energy cosmic rays or neutrinos impinge on a dense medium the leading part of the shower will have a large excess of electrons. The velocity of these electrons is almost equal to the light velocity while the propagation velocity of electromagnetic waves in the dielectric medium is much smaller. Cherenkov radiation is thus emitted. At wavelength comparable to or smaller than the typical size of the leading cloud of electrons the emission will be coherent; this is called the Askaryan effect [1]. At wavelength much shorter than the length of the shower the coherent Cherenkov radiation is emitted in a rather narrow cone around the Cherenkov angle. At wavelengths comparable to the typical longitudinal size of showers produced by Ultra-High Energy cosmic rays or neutrinos the radiation is still coherent but dispersed over almost the complete solid angle [2].

The number of electrons in the leading charge cloud increases linearly with the primary energy of the cosmic particle to a good approximation. The intensity of the radio waves thus grows quadratically with primary energy. In addition lunar rock and the Earth's atmosphere is rather transparent to radio waves at frequencies in excess of 100 MHz. Impacts of ultra-high energy (UHE) cosmic rays on the complete surface of the Moon facing the Earth will thus be detectable from the Earth which makes these longer wavelength radio signals an extremely efficient way to detect these particles. The lower intensity of the emitted radiation, which implies a loss in detection efficiency, is compensated by the increase in detection efficiency due to the near isotropic emission of coherent radiation. The net effect is an increased sensitivity by several orders of magnitude, for the detection of UHE cosmic rays and neutrinos [2]. Including the LPM effect for hadronic showers [3] does not change the basic picture.

For observation of the emitted radio waves one should use radio telescopes working in the 100-300 MHz frequency regime which are able to detect transients with a duration of less than 1 ns. The Westerbork Synthesis Radio Telescope (WSRT) is such a telescope and we will report here on the current status of the observations. In addition we will report on the progress of forthcoming observations with the LOFAR telescope.

WSRT Observations

The WSRT consists of fourteen 25 m parabolic dishes located on an east-west baseline extending over 2.7 km [4]. It is normally used for super-synthesis mapping, but elements of the array can also be coherently added to provide a response equivalent to that of a single 94 m dish. Observing can be done in frequency bands which range from about 115 to 8600 MHz, with bandwidths of up to 160 MHz. The low frequency band which concerns us here covers 115-170 MHz [5]. Each WSRT element has two receivers with orthogonal dipoles enabling measurement of all four Stokes parameters. In tied-array mode the system noise at low frequencies is 600 Jy. To observe radio bursts of short duration, the new pulsar backend (PuMa II) is used. It can provide dual-polarization base-band sampling of eight 20 MHz bands, enabling a maximum time resolution of approximately the inverse of the bandwidth.

During an actual observation four of the eight available bands are beamed to one side of the Moon and the remaining four to the other. Each beam, when the Moon is at the zenith, will cover a section of the sky of length 5° and width 0.1°. When the Moon is off the zenith the width of the section will increase due to baseline foreshortening. Since the Moon has a diameter of 0.5°, the total Moon coverage will be approximately 30%.

Dispersion

An important aspect for the observations is the dispersion of the radio pulse in the ionosphere of the Earth. The magnitude of the dispersion is determined by the number of free electrons along the line of sight. For a tenuous plasma with density ρ_e the plasma frequency is given by $\nu_p^2 = \rho_e e^2/(4\pi^2 m_e \varepsilon_0)$. For the case under consideration, the plasma frequency is much smaller than the frequency of interest and the frequency dependent phase shift can be written as

$$\phi(\nu) = \int \frac{2\pi\nu}{c}\Big(1 - \frac{\nu_p^2}{2\nu^2}\Big)dz \;, \qquad (1)$$

where z is the distance along the line of sight. The first term corresponds to a frequency independent time shift. The second term gives rise to a dispersion of the signal which can be expressed as

$$\Delta\phi(\nu) = \frac{e^2}{4\pi\varepsilon_0 m_e c}\frac{S_t}{\nu} = 2\pi 1.34\frac{S_t}{\nu} \;, \qquad (2)$$

where the slanted total electron content (STEC), $S_t = \int \rho_e dz$, is expressed in units of TECU (1 TECU=10^{16} electrons/m^2) and ν in GHz.

Pulse Signature

For a typical observation the time sampled data (8 frequency bands, two polarizations, sampled at 40MHz) are stored on disk to be analyzed at a later time. The analysis consists of several steps. First the time-sequence data are fourier transformed to frequency spectra where radio-frequency interference (RFI) lines are filtered out. A frequency dependent phase-shift is subtracted to correct for the ionospheric dispersion of the Moon signal (see Eq. (2)). The dispersion is calculated on the basis of the STEC value. The de-dispersed signal and RFI subtracted spectrum is converted back into time sequence data. A signal from a cosmic ray impact on the Moon should show now as a sharp peak while before dispersion correction it was a rather broad pulse covering many sampling times. After dispersion correction, due to the large bandwidth of the signal from the Moon, the pulse should be visible in all four frequency bands which were directed at the same side of the Moon and not in the others.

WSRT Data Reduction

The RFI is eliminated from the WSRT data after fourier transforming the Nyquist sampled data with a resolution of 2 kHz. The WSRT system is equipped with an automatic gain control which is affected by the presence of strong RFI. Since RFI strongly varies over time, the dynamic range for the signal of interest will depend on this. For this reason we have restricted our analysis to those times where the gain remained within 30% of a preset value. From the analyzed 36 hours a total of 13.3 hours of data, with a 30% Moon coverage, passed this criterion.

Due to uncertainties in the actual STEC value at the precise time of observation, we expect that the

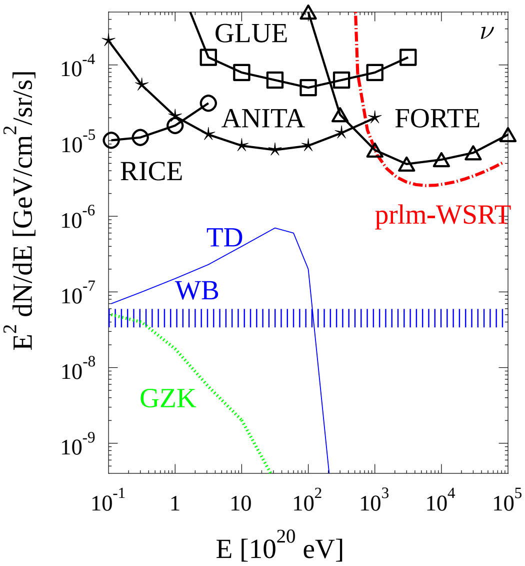

Figure 1: Preliminary flux limits on UHE neutrinos determined with WSRT (labeled as 'prlm-WSRT') are compared with various models, in particular, WB [6] (vertical bars), GZK [7] (thin dotted), and TD [8, 9] (drawn). Limits from the RICE [10], GLUE [11], ANITA [12], and FORTE [13] experiments are also shown.

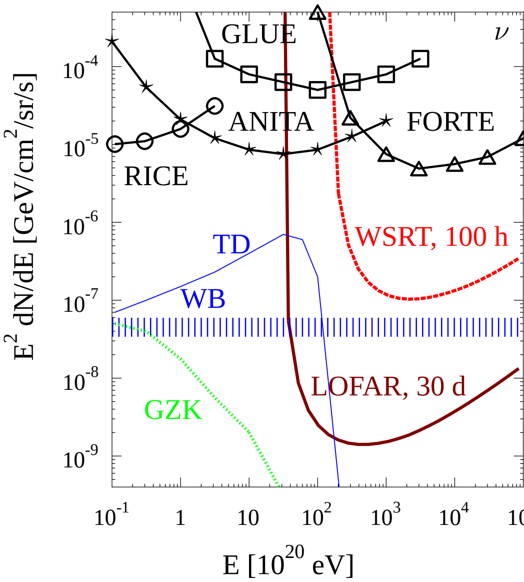

Figure 2: Flux limits on UHE neutrinos as can be determined with WSRT and LOFAR observations. Other curves are the same as in Fig. 1.

pulse, after dispersion correction based on the approximate STEC value, may acquire a small width of not more than 5 sampling times (125 nsec at a sampling frequency of 40 MHz). To efficiently search for such a peak the power in a sliding 125 nsec wide window is calculated. If this exceeds the background level by a certain factor, X, the power in corresponding time windows in other frequency bands is calculated. Due to a possible in-accuracy in the STEC value the calculated times for the pulse in the other bands can be trusted up to a certain accuracy which is taken into account in the search procedure. Only when a significant pulse is found in all four frequency bands will it be labeled as a possible event.

Using this procedure we have verified that there was no single pulse detected with a power larger that $200\times F_{noise}$ in this data set. As can be seen from Fig. 1 this limit is still well above the Waxman-Bahcall limit [6] for UHE neutrinos even though it is already competitive with the limits set by other experiments such as FORTE [13].

Future

A full analysis of WSRT observations, which is ongoing, should set limits as shown in Fig. 2 should no neutrino signals be observed. The limits are tighter than those obtained from this preliminary analysis due to a lower limit on the power in the pulse due better constraints and a longer observation time.

An even more powerful telescope able to study radio flashes from the Moon will be the LOFAR array [14]. With a collecting area of about 0.05 km^2 in the core (which can cover the full Moon in a series of beams), LOFAR will have a sensitivity about 25 times better than that of the WSRT. LOFAR will operate in the frequency bands from 30-80 and 115-240 MHz where it will have a sensitivity of about 600 Jy and 20 Jy, respectively. The Galactic background noise will become the dominant source of thermal noise fluctuations at frequencies below about 100 MHz. It therefore appears that the optimal radio window for the detection of cosmic ray or neutrino induced radio flashes from the Moon will be around 100-150 MHz.

Conclusions

We have presented the results of a preliminary analysis of part of the recent data obtained from observations with the WSRT. Even though this represents only a rough analysis of a fraction of the data the limit is comparable to that set by other experiments.

Future observations with the LOFAR telescope, which is now in the stage of being rolled out, will be able to cut through the Waxman-Bahcall limit and will have a realistic possibility of seeing the first UHE neutrinos ever.

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