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Radio Detection of Neutrinos from Behind a Mountain

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Abstract: We explore the sensitivity of a neutrino detector employing strongly directional high gain radio antennae to detect the conversion of neutrinos above 10^{16} eV in a mountain or the earth crust. The directionality of the antennae will allow both, the low threshold and the suppression of background. This technology would have the advantage that it does not require a suitable atmosphere as optical detectors do and could therefore be deployed at any promising place on the planet. In particular one could choose suitable topographies at latitudes that are matched to promising source candidates.

Introduction

Identifying the sources of the highest energy Cosmic Rays (CR) is a fundamental and unsolved problem in astroparticle physics. If they are accelerated in astrophysical objects, high energy neutrino emission should be associated with this acceleration [1]. Since these neutrinos would neither interact with intergalactic or interstellar media nor be deflected by magnetic fields, neutrino astronomy carries the hope of identifying these elusive sources of highest energy CRs.

Various detectors have been proposed for neutrino energies above 10^{16} eV, most of them relying on mountains to provide suitable target mass for ν_τ with the ensuing τ lepton decay providing a detectable air shower (AS) after the τ leaves the target [2]. As high energy neutrinos get absorbed in the earth, geometries for such events are restricted to within a few degrees of horizontal [3].

Optical detectors exploiting the fluorescence emission of horizontal showers as well scintillator telescopes have been proposed to measure the promising ν_τ signature [4]. Here we explore what could be a simpler and cheaper technology in the field: strongly directional (high gain, low threshold) radio antennas. All they require is a rigid mechanical support structure and like all the other detectors some electronics. But no optical components have to be calibrated and maintained, and the detector could be made largely insensitive to the local climate at a promising detector site. The challenge for our detector will lie in isolating the signal.

Geosynchrotron radio signals

AS produce geosynchrotron radio emission due to the deflection of secondary shower electrons and positrons in the earth's magnetic field [5]. In this study for the first time such radio signals are studied from horizontal showers. Using the REAS2 Monte Carlo code [6] we calculate the radio emission from 10^{15} eV and 10^{16} eV horizontal, π^+ induced AS propagating through a constant density atmosphere of 1.058×10^{-3} g cm^{-3}, corresponding to approximately 1500 m above sea level. The magnetic field was set to a strength of 0.4 Gauss with an inclination of $60°$, a conservative estimate for Central Europe and Northern America. The AS were simulated as propagating from north to south; the corresponding geomagnetic angle is thus $60°$. This is the most conservative choice, as it effectively minimizes the field component perpendicular to the propagation direction of the AS. Atmospheric curvature can be neglected here, as the AS need only a few kilometers to develop in the lower atmosphere. The AS simulations were carried out using CORSIKA 6.502 [7], with shower-to-shower fluctuations taken out by simulating 25 air showers per parameter set and then selecting a shower with a typical longitudinal evolution profile for the radio simulations.

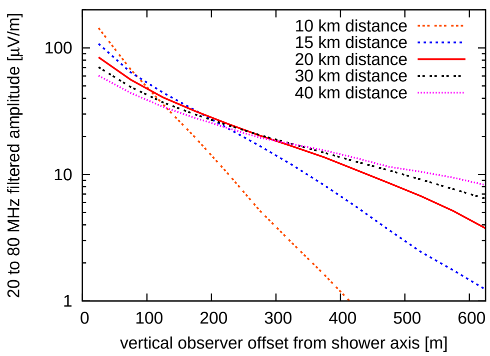

Figure 1: Lateral dependence of geosynchrotron radio emission field strenghts of 10^{16} eV horizontal air showers for different observer distances from the τ decay point. 10^{15} eV values are lower by approximately a factor of 10.

One important question is which observer distance is suited best for radio observations of these horizontal AS. Figure 1 illustrates how the lateral profile of the radio signal spreads out as the distance from the starting point of the AS increases. Despite strong relativistic beaming of geosynchrotron radiation, the lateral slope changes significantly with the distance of the observer from the τ decay point. An observing distance of 20 km seems to constitute a good compromise: the signal in the center region is still strong while its lateral spread does not require too dense an array of antennae.

Also important is the selection of a suitable observation frequency band. This clearly depends on the actual noise situation at the selected observing site. In the absence of man-made radio interference, atmospheric and galactic noise set the limits. In Fig. 2 we show what signal-to-noise ratios (SNR, defined as peak power of the signal divided by power of the noise in the band of interest) can be expected for 10^{16} eV AS at 20 km observing distance and 225 m vertical observer offset from the shower axis. The values are calculated for an isotropic radiator and a combination of day-time atmospheric noise and galactic noise

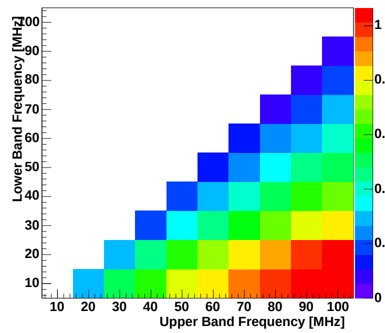

Figure 2: Expected SNR as a function of observing frequency band for 10^{16} eV showers initiated at 20 km distance and 225 m vertical observer offset from the shower axis, calculated for an isotropic radiator. 10^{15} eV values are lower by approximately a factor of 100.

based on measurements by the CCIR/ITU-R (International Telecommunication Union). As geosynchrotron emission has a steeply falling frequency spectrum, it is important to include low frequencies. As can be seen in Fig. 2 an observing bandwidth from 20 to 80 MHz would be desirable. Below 20 MHz, atmospheric noise gets very strong, and above 80 MHz FM radio transmitters could pose problems.

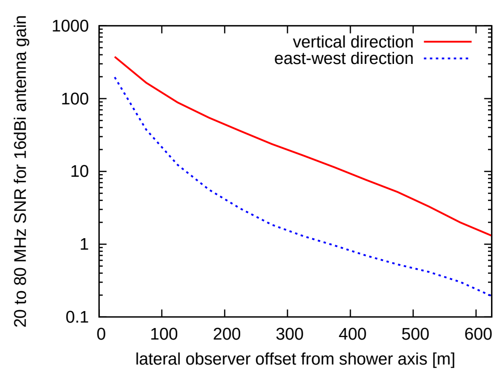

Figure 3: Expected SNR as a function of observing frequency band for 10^{16} eV showers at 20 km distance, calculated for an antenna with 16 dBi antenna gain. 10^{15} eV values are lower by approximately a factor of 100.

SNR of order unity are too low for self-triggered measurements of geosynchoton radiation. Using directional antennae pointing at the target mass will significantly improve the SNR. For the envisioned broad-band measurements, logarithmic-periodic dipole antennae (LPDAs) can achieve antenna gains of 10 dBi. If three such antennae are phase coupled, effective gains of up to 16 dBi can be reached. This boosts the SNR into a region where measurements seem feasible up to axis offsets of ~ 300 m, as illustrated in Fig. 3.

For the specific relative geometry of AS and magnetic field explored here the lateral distribution of the radio signal is very different along the horizonatal and the vertical axis. As multiple measurements along the vertical also allow to place additional constraints on the zenith angle of the observed shower and as the signal falls off more slowly along the vertical axis, more than one antenna should be used along the vertical direction.

The SNR required for self-triggered operation of an antenna array depends on many factors such as the multiplicity of antennae used in coincidence and the required detection efficiencies. These issues would have to be addressed in a specific proposal for such a detector.

Neutrino event rates

A threshold close to 10^{16} eV for horizontal AS is well matched to the effective threshold beyond which τ leptons can escape from significant depth inside a rock mass: at 10^{15} eV the decay length of a τ (in vacuum) is only $\sim$50 m. At 10^{17} eV this decay length will have grown to 5 km, which allows for τ from a reasonable amount of target mass to escape the rock before they decay, and on the other hand constrains the decay volume needed behind the rock to be reasonably small.

Using a modified ANIS [8] code we examine the probability that a ν_τ interacts in rock with the ensuing τ decay initiating an AS outside of the rock. In ANIS we use the option of CTEQ5 deduced cross-sections. A smooth approximation for the energy loss of the τ leptons in rock and air is included in the calculation. Depending on the energy of the incoming ν_τ, an equilibrium is reached at some point inside the rock between ν_τ interactions producing new τ leptons and the decay of τ leptons that were produced in neutrino interactions further upstream. Our simulations show that for standard rock this equilibrium is reached after 1 km at 10^{15} eV, 2 km at 10^{16} eV, and 10 km at 10^{17} eV.

25 M ν_τ were injected at each of the energies mentioned above. From the above simulations of radio signals we infer an effective threshold of 8×10^{15} eV for AS detection to estimate how many neutrinos we might detect. Fig. 4 shows the distributions of decay vertices above that energy from the 10^{16} eV and 10^{17} eV simulations.

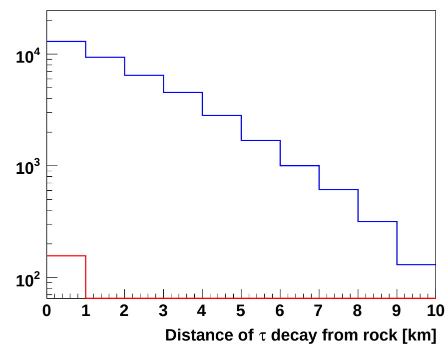

Figure 4: Distribution of decay vertices that result in showers with an energy above 8×10^{15} eV. The blue histogram is for a ν_τ energy of 10^{17} eV, the red one for 10^{16} eV.

Within the first 10 km after the mountain we see less than 200 decays for the lower ν_τ energy and about 40,000 for the higher one. At higher energies efficiency will be affected by τ decaying behind the detector "volume". The detection efficiency for 10^{17} eV ν_τ is $\epsilon = 0.0016$. A detector element of two stations separated vertically by 200 m would allow to collect data over a vertical range of 400 m. Working with a 200m horizontal displacement between such detector elements one would hope to have a decent efficiency for threefold coincidences over an area of roughly 160,000 m^2 for two such elements, and each vertical expansion of the array by one additional element would add roughly 80,000 m^2. The exposure of an eight antenna array accumulated over one year would be $31,536,000\ \mathrm{s} \times 320,000\ \mathrm{m}^2 \approx 10^{17}\ \mathrm{cm}^2\ \mathrm{s}$ for a pointlike source. As the LDPAs typically have an opening angle of $65°$, detectors situated 30 km from a 1.5 km high mountain range would cover a solid angle of 5.7×10^{-2} sr.

A source would only be seen if it is behind a target mass at the local horizon of the detector. The time any given source spends near the horizon depends on its declination. Figure 5 summarizes the total observation times that can be expected if the source can be followed within $\pm 1.5^\circ$ of the horizon and gives the azimuthal coverage required to follow the source along that segment of its path. If a source were to just rise or set vertically through a $\pm 1.5^\circ$ detector aperture, it would be visible for less than 1% of the total time. If the location was chosen to accommodate the requisite azimuthal coverage shown in Fig. 5, then one would expect to "see" the source about 15% of total time for a latitude of 45°. The proposed antennae will cover the requisite 30° in azimuth. Putting all this together, if we can measure ν_τ between 10^{16} eV and 10^{17} eV, with the efficiencies estimated above and linearly interpolated between the two energies, it would take an array of a little more than 130k antennae to observe one event per year from Galactic sources [9].

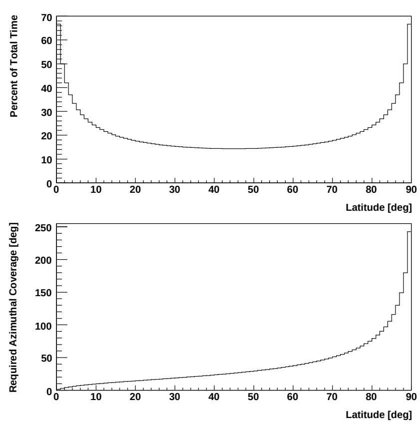

Figure 5: Upper panel: Percent of total time spent in a $\pm 1.5^\circ$ band around the horizon if the upper or lower culmination point is arranged to be 1.5° above or below the horizon. Lower panel: total number of degrees that have to be covered in azimuth in order to attain that maximal time.

To give an example of the sensitivity reach to the diffuse neutrino flux we consider, $\phi_{\nu_\tau} \simeq 10^{-3}\,(E_\nu/\mathrm{GeV})^{-2.54}\quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, which is expected if extragalactic cosmic rays (from transparent sources) begin dominating the observed spectrum at energies as low as $\sim 10^{17.6}$ eV [10], as suggested by recent HiRes data [11]. For such a ν_τ-flux, the expected number of events (with $E_\nu > 10^{17}$ eV) per year per eight antennae is about 0.003.

Conclusions

The energy range at which the detector works is well matched to the problem of ν_τ detection through τ decay in the atmosphere. Cosmic ray detectors with upward of a thousand detector stations are proven, keeping open in principle the possibility of deploying an antenna array big enough for the isotropic fluxes. To further pursue this route, emphasis will have to be put on developing inexpensive and reliable detector stations for such a detector. Radio detection carries that promise.

Acknowledgements

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References

[1] F. Halzen and D. Hooper, Rept. Prog. Phys. **65**, 1025 (2002).
[2] D. Fargion, Astrophys. J. **570**, 909 (2002).
[3] K. Martens for the HiRes Collaboration, in these Proceedings (2007).
[4] Z. Cao *et al.*, J. Phys. G **31**, 571 (2005); M. Iori *et al.*,, arXiv:astro-ph/0602108.
[5] T. Huege and H. Falcke, Astron. Astrophys. **412**, 19 (2003).
[6] T. Huege, R. Ulrich and R. Engel, Astropart. Phys. **27**, 392 (2007).
[7] D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz, and T. Thouw. FZKA Report 6019, Forschungszentrum Karlsruhe, 1998.
[8] A. Gazizov and M. P. Kowalski, Comput. Phys. Commun. **172**, 203 (2005).
[9] M. D. Kistler and J. F. Beacom, Phys. Rev. D **74**, 063007 (2006).
[10] M. Ahlers *et al.*, Phys. Rev. D **72**, 023001 (2005).
[11] R. U. Abbasi *et al.* [HiRes Collaboration], Phys. Rev. Lett. **92**, 151101 (2004).