Proceedings of ICRC 2001: 1264 © Copernicus Gesellschaft 2001

ICRC 2001

Hydro-acoustic detection of ultra-high and extremely high energy neutrinos

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Abstract. Hydro-acoustic detection of ultra-high (10^{15}eV) and extremely high ($> 10^{18}$eV) energy cosmic neutrinos in the world's oceans, employing existing hardware is considered.

The results of simulations of acoustic signals emitted by neutrino induced cascades with energies 10^{20-21}eV, with realistic signal propagation in the ocean, are presented. We have demonstrated that it is possible to develop a hydro-acoustic detector of 10^{20-21}eV neutrinos (for example topological defect neutrinos) with an effective detection volume of tens of cubic kilometers using an existing array of 2400 hydrophones in the Pacific Ocean near the Kamchatka Peninsula.

We further discuss the prospects of using a converted portable hydro-acoustic station of 132 hydrophones as a basic module for a deep-water acoustic neutrino telescope in the Mediterranean Sea, or elsewhere. Such a device can have a relatively low detection energy threshold of $\sim 10^{15}$eV, enabling a search for AGN and GRB neutrinos.

1 Introduction

During recent years the target mass scale of the underground neutrino telescopes has grown to 10^4tons (Super-Kamiokande). However to search for ultra-high energy (UHE, ¿1015 eV) astrophysical neutrino sources (Active Galactic Nuclei - AGNs and Gamma Ray Bursts - GRBs, for example), sites of the most energetic processes (accelerators) in the Universe, neutrino telescopes of effective detection volumes of a cubic kilometer or more (KM3) are necessary (Learned, 1993; Learned and Mannheim, 2000).

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Neutrino telescopes with a KM3 target mass scale have also been proposed for studies of the upper boundary of the energy spectrum of cosmic neutrinos. For example, if elementary particles of unification scale (even Planck scale) masses 10^{24-28}eV do exist, their interactions and decays could produce neutrinos (and other particles) of super-high (extremely-high) energies (SHE, EHE) up to 10^{24-28}eV (Markov and Zheleznykh, 1980, 1986).

Speculations upon the unknown sources of the observed highest energy cosmic rays with energies above the GZK-limit have led to the appearance of several current models which include significant or even dominant neutrino fluxes. For example, in the framework of some GUT models with X-particle masses of 10^{23}eV, and in topological defect (TD) models, calculations of cosmic neutrino fluxes with energies up to 10^{23}eV have been performed (Sigl 2000; Kuzmin 2000; and references therein).

Since the mid-1970's deep underwater acoustic neutrino detection (Askaryan and Dolgoshein, 1976; Bowen, 1977; Learned, 1979) has been discussed and developed as an alternative method to optical DUMAND-type experiments for studying UHE cosmic neutrino fluxes. The energy thresholds for acoustic detection are a few orders of magnitude greater than the $10 - 50$ GeV threshold typical for the deep underwater (Baikal, NESTOR, ANTARES) and under-ice (AMANDA) optical detectors. However the target mass scale of acoustic detectors can be (affordably) a few orders of magnitude greater than that of optical detectors, because distances of tens of kilometers characterize the sound attenuation-length in the water. Moreover the hardware and techniques for ocean acoustics are relatively inexpensive and well developed.

The bipolar acoustic pulse production arises from the rapid expansion of the region of material traversed by the neutrino induced particle cascade, which ionizes and slightly heats the

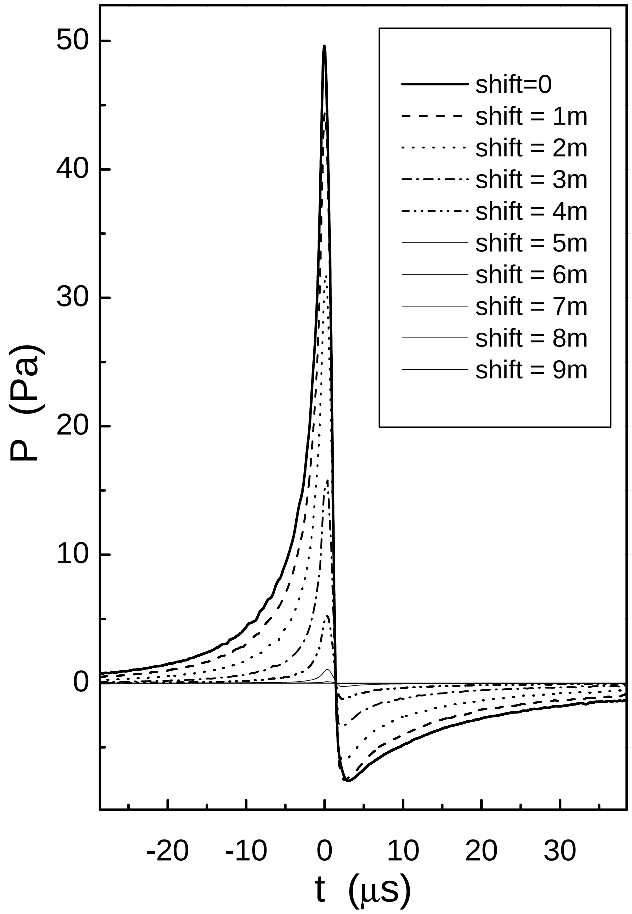

Fig. 1. Acoustic pulse amplitudes at an equivalent distance of 1 m from a 10^{20}eV electron-hadron cascade axis. Various offsets from shower maximum are indicated.

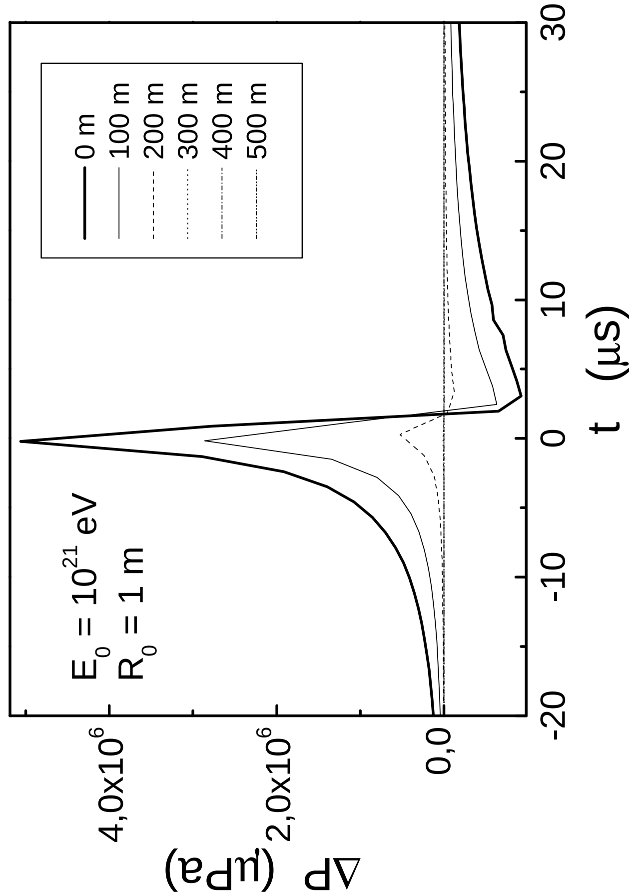

Fig. 2. Acoustic pulses at an equivalent distance of 1 m from the 10^{21}eV electron-photon cascade core, for several displacements from shower maximum.

medium. An acoustic signal is emitted by a neutrino-induced cascade mainly in the direction perpendicular to the cascade axis in a rather narrow solid angle. The initial spectrum peaks at a few tens of kHz.

2 Acoustic Pulses Produced by EHE Neutrinos in Water

The results of calculations of the UHE neutrino induced acoustic pulses in water were given in a series of articles (Dedenko, et al, 1995; Dedenko, et al., 1997; Butkevich, et al., 1999). In this paper we present the results of new and improved calculations of acoustic signals emitted by EHE electron-hadron and electron-photon cascades.

Fig. 1 shows the results of calculations of acoustic pulses caused by an electron-hadron cascade with an energy of 10^{20}eV in seawater ($14\,\mathrm{deg}$C temperature, deep Mediterranean), scaled ($1/r^2$) to a reference distance of 1 meter from the cascade core. Calculations were performed for different deviations from the shower maximum along the cascade axis.

At super-high energies the Landau - Pomeranchuk - Migdal effect (decreasing cross sections for pair production and brems-strahlung) should be taken into account. Due to this effect the longitudinal development of electron-photon cascades in water increases by factors of tens or even hundreds compared to cascades with energies less than 10^{15}eV. At a cascade energy of 10^{20}eV the cascade length increases to 500 m; at energy 10^{21}eV to 1-1.5 km. Counterbalancing this, the density of deposited energy is decreased by 100 times compared to the Bethe-Heitler showers. The advantage of greater length however is larger near-field volume.

Fig. 2 shows acoustic pulses caused by the electron-photon cascades with energy 10^{21}eV in seawater and $14\,\mathrm{deg}$C temperature, scaled to a distance of 1 meter from the cascade core. Calculations were performed for different deviations from the shower maximum along the cascade axis.

The reference amplitude of the acoustic signal at this distance can be as much as 5 Pa. Strong acoustic emission is localized in a divergent disk of 200 m thickness, which is perpendicular to the cascade axis. In contrast, the density of deposited energy in a hadron cascade would be about 50 Pa as its length is of a few tens meters.

Table 1. Acoustic detection volumes estimates in cubic kilometers for cascade energies (10^{20}eV)/(3.16×10^{20}eV)/(10^{21}eV), and various false alarm rates and summer season wind velocties, employing the Kamchatka array . ("-" denotes not calculated).

False Alarm Rate	1/Day	1/Week	1/Month
Summer Wind Vel.			
2 m/sec, calm	11/-/-	9.5/-/-	6.6/-/-
5.5 m/sec	3.9/5.3/81	2.2/4/-	1.3/2.2/-
10.2 m/sec	0.98/1.3/24	0.73/1.4/-	0.56/0.98/-

3 Kamchatka Array as a KM3 Detector of EHE Neutrinos

One of the goals of our SADCO (Sea-based Acoustic Detector of Cosmic Objects) collaboration is to consider the use of already existing stationary sonar facilities, such as those placed in the Kamchatka region, as an acoustic detector of neutrinos (Karlik et al., 1997; Dedenko et al., 1997). This Kamchatka sonar installation has a large planar phased array, with 2400 hydrophones. The array is installed on a sea shelf and connected with on-shore equipment by cable. The sector of view is $120\,\mathrm{deg}$. The angular resolution in the horizontal plane is $0.8\,\mathrm{deg}$ in each of 150 (virtual) parallel fan-shaped beams. The vertical angular width is $7\,\mathrm{deg}$. The gain of this array is 2500 at 1400 Hz.

Evaluations of the effective detection volume of the Kamchatka array were performed for three cascade energies (10^{20}eV, 3.16×10^{20}eV, 10^{21}eV), for realistic ocean noise conditions and for different probabilities of false alarm (false impulse signal). It is seen from the Table 1 that in summer time and under calm wind conditions, the Kamchatka array can have a significant detection volume (tens of cubic km) for seeking acoustic signals from 10^{21}eV cascades. Employing the Kamchatka array, it is possible to develop special software to search for electron-hadron cascades induced by EHE (topological defects) cosmic neutrinos with E$>$ 10^{20-21}eV and higher energies in water volumes of tens cubic kilometers and more.

4 Prospects for Hydro-acoustic Monitoring with An Optimal Frequency Response

The frequency range of the Kamchatka array (1.0 - l.5 kHz) is not optimal because of low signal/noise input ratio and pulse noise from other sources of sound. However there is the opportunity for creation of acoustic detectors of even greater volume using an optimal bandwidth (2-20 kHz) for the signals generated by UHE and EHE neutrino induced cascades.

In particular, we consider, a hydro-acoustic system designated MG-10M, formerly used by the USSR Navy, now withdrawn from service. The interest in this station (or to its receiving array) is due to the fact that this array has amplification about 1700 at an average frequency of 15 kHz, i.e. approximately what is necessary for optimal neutrino detection. Moreover, the receiving array is not large - a cylinder of 1.6 meters diameter and 1 meter height. The array contains 132 hydroacoustic sensors directed in a vertical plane on a cylindrical surface. The mass of the array is about 1200 kg and it is designed for depths up to 500 meters. The frequency band is (4-25) kHz. The sensitivity is about 170 (V/Pa). This array practically matches the parameters desired of a basic module of an acoustic neutrino detector with a "low" energy detection threshold of $\sim 10^{15}$eV.

Measurements of the hydro-acoustic background are planned in the Mediterranean Sea at several potential deployment sites for an acoustic neutrino telescope. An acoustic array of 6 high-sensitivity hydrophones for deep-water measurements of noise in the frequency band $3 - 50$ kHz with threshold sensitivity about $10^{-5} Pa/\sqrt{Hz}$ has been designed and constructed.

5 Conclusions

We have considered the possibilities of acoustic neutrino detection in the deep ocean using two existing sonar arrays with great amplification 1500: a fixed Kamchatka hydro-acoustic array for long waves (frequencies less than ~ 1.5 kHz), and a compact portable military surplus system with frequency band of 5-15 kHz. Neutrino telescopes based upon such systems can make competitive searches for neutrinos of extreme energies. The further advantages of this approach are that years of experience have resulted in high reliability acoustic systems, and the necessary expenses for modern electronics are not large compared to design and construction of new hydro-acoustic systems or to the costs for optical Cherenkov instruments with similar sensitive volumes.

Acknowledgements. These investigations are supported by the RFBR-INTAS grant IR-97-2184 and the RFBR grant 00-15-96632.

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