ACOUSTIC DETECTION OF HIGH-ENERGY ASTROPHYSICAL NEUTRINOS*

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Neutrinos are mysterious elementary particles due to their tiny masses, electrical neutrality, and interaction only through gravitational and weak force, which makes their detection challenging. Their astrophysical origins and the production mechanism remain unclear. This contribution will presents the prospect of the acoustic simulation to detect ultra-high-energy (UHE) neutrinos with KM3NeT. KM3NeT, the Cubic Kilometer Neutrino Telescope located in the Mediterranean Sea, is equipped with state-of-the-art hydrophones and digital optical modules. To investigate the high-energy astrophysical origins of neutrinos, a study of tidally disrupted events as potential candidates is proposed.

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1. Introduction

Neutrinos are the best probes for studying the ultra-high-energy (UHE) universe, since they do not deviate from their trajectories while traveling through the space. When UHE neutrinos interact with a medium, such as ice or water, they may produce secondary particles, leading to instantaneous transfer of energy along the cascade. The energy deposited can create bubbles through microscopic-scale explosions (shown in Fig. 1 (c)). These explosions generate cavities and bubbles, which in turn produce a shock wave propagating in the medium [1, 2]. The sound propagation can be described by the pressure transfer ΔP as

$$\Delta P = \frac{1}{c_{\mathrm{s}}^2}\frac{\partial^2 P}{\partial t^2} = -\frac{\alpha}{C_{\mathrm{p}}}\frac{\partial^2 q(\boldsymbol{r},t)}{\partial t^2}\,, \tag{1}$$

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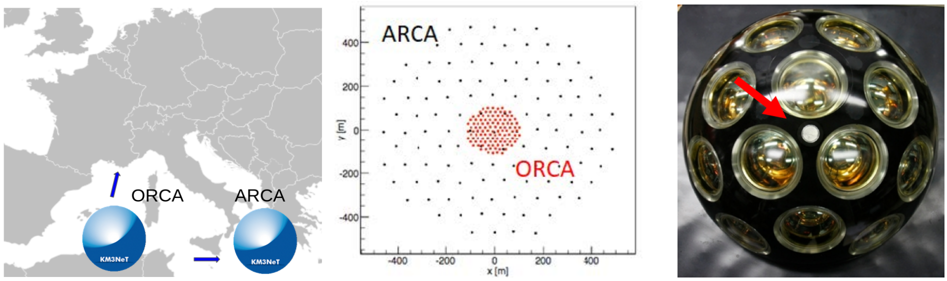
where, c_s is the speed of sound, α is the thermal expansion coefficient, C_p refers to the specific heat capacity of the medium, $q(\boldsymbol{r}, t)$ denotes the instantaneous deposition of the energy density along the position vector $\boldsymbol{r}$ and time t [3].

The acoustic UHE neutrino detection technique has not been widely adopted due to computational and technological challenges, such as the lack of sensitive hydrophones and reliable acoustic signal simulations. To provide a comprehensive overview of this investigation, Section 2 discusses the exceptional detector capabilities of the KM3NeT observatory. The foundation of the acoustic simulation groundwork is presented in Section 3, and Section 4 discusses the selection of candidates for tidally disrupted events (TDE) and the reasoning behind studying this class of transients as a potential source of high-energy neutrinos (HE). Finally, the future steps and the approach of this study are summarized in Section 5.

2. Detector

KM3NeT is a km^3 seawater Cherenkov neutrino telescope comprised of two infrastructural sites, ORCA (Oscillation Research with Cosmics in the Abyss) offshore Toulon, France, and ARCA (Astroparticle Research with Cosmics in the Abyss) offshore Capo Passero, Italy.

The objectives of this experiment are to determine the neutrino mass hierarchy and to discover the origins of the HE neutrinos with ORCA and ARCA, respectively. ORCA is designed for detecting neutrinos in the GeV range, while ARCA targets astrophysical neutrinos with energies up to hundreds of PeV. The primary difference between the detectors is the spacing of the optical modules and detection units (DU); at the ORCA site, the DUs are placed closer together, and the overall detector is smaller in size. In contrast, at ARCA, a horizontal spacing between two detection units is approximately 95 m. Each detection unit consists of 18 digital optical modules (DOMs), with a vertical spacing of 36 m for ARCA and 9 m for ORCA (Fig. 1 (b)). KM3NeT is a large European neutrino telescope infrastructure, which will consist of 6000 piezoelectric hydrophones [4, 5]. The piezoelectric hydrophone, composed of ceramic sensors, is shown in Fig. 1 (c). These hydrophones are primarily used for the underwater positioning of DOMs. This well-designed experimental setup results in an angular resolution of point-like sources for ARCA as fine as 2° in the case of neutrino-induced shower events and 0.1° for track events [6]. The detection of a 220 PeV neutrino by ARCA is a remarkable demonstration of the detection capacity of KM3NeT [7].



(a) (b) (c)

Fig. 1. Design layout of KM3NeT. (a) Sites in the Mediterranean Sea of both ORCA and ARCA. (b) ARCA and ORCA size and the horizontal spacing between DUs comparison [4]. (c) Red arrow pointing at piezoelectric hydrophone (white circle) in the DOM [5].

3. Acoustic simulation

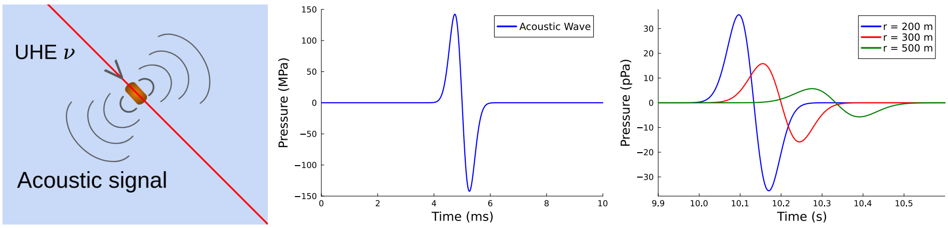
The thermo-acoustic signals produced by the interactions of 100 TeV neutrinos in the Mediterranean Sea can be approximated by Gaussian heat deposition and Poisson energy deposition in bounded and semi-bounded environments. However, both the propagation of the acoustic pulse and precalibration of the signal present significant challenges. Considering pulse propagation, the simulation comprises two primary theories: the wave theory and the ray theory of wave propagation.

The equation below, taken from [3], describes the case of the sound wave as a symmetric monopole and Gaussian-distributed heat deposition with radial distance r radius, and the pressure pulse can be expressed as

$$p\left(r \approx 0, t'\right) = -\frac{\beta}{4\pi C_{\mathrm{p}}\sqrt{2\pi}} \frac{t' E_0}{r} \exp\left(-\frac{t'^2}{2\sigma^2}\right) , \tag{2}$$

where β the bulk coefficient, C_{p} specific heat capacity, and $t' \approx t - \frac{r}{c}$ is the time at the observation point for the E_0 energy of the particle.

To understand the acoustic phenomena at the KM3NeT ARCA site, we compiled the following parameters: salinity, temperature, density, and coefficients of thermal expansion, and used them to estimate the signal shown in Fig. 2 (b) [3, 8]. Figure 2 (c) shows the significant decrease in pressure pulse at various distances.



(a) (b) (c)

Fig. 2. Acoustic signal production from UHE neutrinos. (a) Illustration of the Cherenkov radiation (visible blue light) produced perpendicular to acoustic signal. (b) Pressure pulse behavior at a distance of 0.01 m from a 100 TeV neutrino interaction. (c) Gaussian pressure dispersion at distances of 200 m, 300 m, and 500 m.

4. Tidally disrupted events

A tidal disruption event (TDE) occurs when a supermassive black hole (SMBH) of a mass of 10^6–$10^{12}\,M_\odot$ rips apart a star (1–10 $M_\odot$) in a tidally bound system, resulting in the spaghettification of the star. A main-sequence star can become tidally trapped in the vicinity of SMBH. The stripping of plasma from the captured star begins at $t = t_{\rm fb}$ [9]. As time passes, the plasma starts to fall back (fb) towards the SMBH. The remaining partially ripped star and consecutive plasma fb create shocks onto SMBH. These shocks produce non-thermal X-ray and radio emissions. An accretion disk is formed at $t = t_{\rm acc}$, and shock accretion can result in plasma winds [9]. The formation and mechanism of TDEs are derived from their multi-wavelength characteristics. The stellar evolution of these main-sequence stars can be determined by their emission lines of H and He in the optical regime. These stars may also contain heavy nuclei from stellar nucleosynthesis, which makes them a unique class of transients and potential candidates of sources of UHE cosmic rays and neutrinos [10]. To study TDEs as potential sources of astrophysical neutrinos, we selected 44 raw samples from various catalogs [11]. These selected sources lie within the field of view of the KM3NeT ARCA detector (shown in Fig. 3). To study these sources and their emission processes, we investigate their spectral energy density. From the primary multi-wavelength investigation, less than 1% of the sources exhibit gamma-ray and X-ray emission [10].

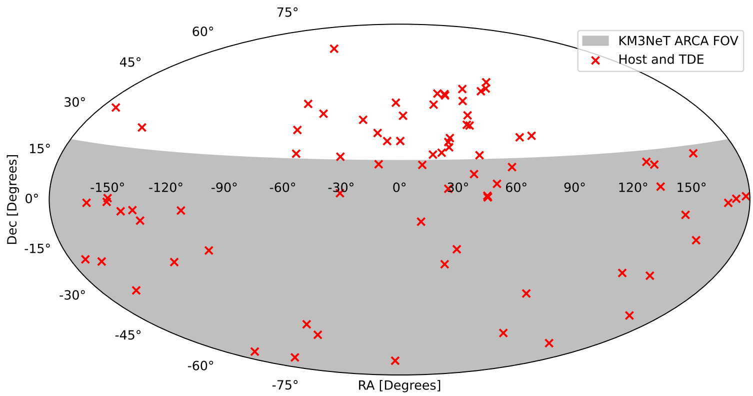


Fig. 3. TDE positions in the equatorial sky. The shaded region (covering $\approx 70\%$ of the sky) marks the field of view (FOV) of the KM3NeT ARCA sky.

5. Future outlook

Acoustic signals are sensitive to the properties of the medium, and the next steps will accommodate the propagation of the signal shown in Fig. 4. We will investigate the reflection of the signal from the seabed and use sound speed profiling to measure the Doppler shifts of the signal. For the TDEs study, we are working on fitting a physical model to the spectral energy distribution. In addition, we plan to calculate the bolometric luminosity to estimate the accretion efficiency of the jets. We will perform a directional reconstruction of the neutrino events. The subsequent step will involve conducting a likelihood analysis using the KM3NeT ARCA data.

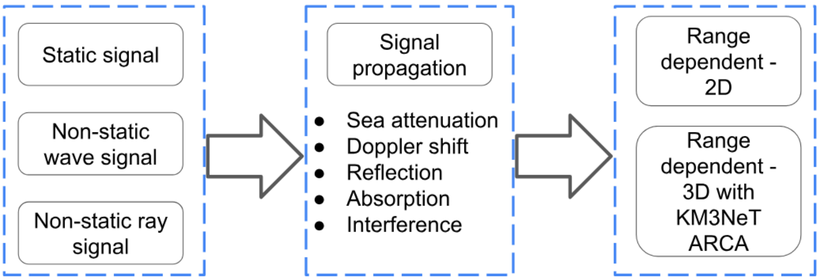


Fig. 4. Flow of the future steps of acoustic signal modeling.

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