KM3NeT sensitivity to neutrino bursts from galactic supernovae

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Abstract

A very large volume Mediterranean neutrino telescope (KM3NeT), designed and optimised for detection of Cherenkov light from interactions of neutrinos with energies above about 100 GeV, could be sensitive to an intense neutrino burst from the core collapse of a massive star in our Galaxy. In a short time interval during the burst (∼10 s) the total amount of Cherenkov photons produced by low-energy (∼10 MeV) neutrino interactions in the sea water rises well above the usual background level. The main source of these photons are positrons from interactions of electron anti-neutrinos with the free protons in water. The KM3NeT detector could be considered as a potential member of the SuperNova Early Warning System (SNEWS), an international network of neutrino experiments with the goal of providing an early warning in case of a Galactic supernova. The possibilities for the detection of a supernova signal with KM3NeT will be discussed in this paper.

Key words:
Supernova, core collapse, neutrino burst, neutrino telescope, KM3NeT

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1. Introduction

A supernova of type II, which is a core collapse and explosion of a massive star above 8 solar masses, produces a short and very intense flux of neutrinos of all types. Almost all gravitational binding energy of the progenitor star (∼ 99%) is released in this neutrino burst, which lasts only few tens of seconds. 25 neutrino events from the supernova SN1987A, detected simultaneously in 3 neutrino detectors [1] provide a strong evidence of this core-collapse supernova mechanism. However, for establishing a comprehensive stellar collapse model, more neutrino data is necessary. The current model for this phenomenon can be found, for example, in the review [2].

Supernova explosions are very rare events, with typical rate expectations of 3 events per century in the Milky Way. The location and time of these events cannot be predicted, therefore 100% duty cycle is needed for the detection of a neutrino burst signal. This can be achieved with a network of neutrino detectors working in parallel. The current neutrino experiments, which are sensitive to supernova neutrino bursts, are forming the SNEWS (SuperNova Early Warning System) network [3]. The primary goal of this network is to provide a

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prompt alert on Galactic supernovae to the astronomical community. Such an early alert will allow for studying the complex phenomenon of stellar collapse and explosion from the very beginning.

The high energy neutrino telescopes are designed to detect neutrinos with energies above about 100 GeV. Even though the neutrino energies from the core-collapse supernova are not exceeding few tens of MeV, the luminosity of the neutrino burst may be large enough to generate a detectable signature in the neutrino telescopes. For example, the IceCube neutrino telescope, which is currently under construction at the South Pole [4], is sensitive to a SN1987A-type neutrino burst from the Galaxy and beyond (up to 30 kpc) and is a member of SNEWS network [5].

The sensitivity to supernova neutrino bursts of the future Mediterranean neutrino telescope KM3NeT is discussed in this paper.

2. A supernova neutrino signal in the neutrino telescope

In the current picture of core-collapse supernovae the neutrinos are produced in two stages. In a first stage, which lasts less than a second, up to 20% of energy is released in electron neutrinos, which are produced from $e^-p \to n\nu_e$ interactions. The rest of the energy is emitted in a second stage, which is associated with the cooling phase of the core (neutron star). During this phase all neutrino types are produced with similar luminosities in the process $e^+e^- \to \nu_l + \overline{\nu}_l$, where $l = e, \mu, \tau$. These neutrinos have thermal energy spectra, with steadily decreasing temperature. Typical time-integrated energy spectra of supernova neutrinos are given in Fig. 1. The details of the underlying calculations can be found in [6].

The detection method for a supernova neutrino burst in a high energy neutrino telescope was first proposed for the AMANDA telescope [7] and later tested with experimental data [8]. This method is based on a prompt and statistically significant increase of the overall counting rates in the telescope's optical modules (OM) in a short time interval, typically taken to be $\Delta t \sim 10$ s. The rate

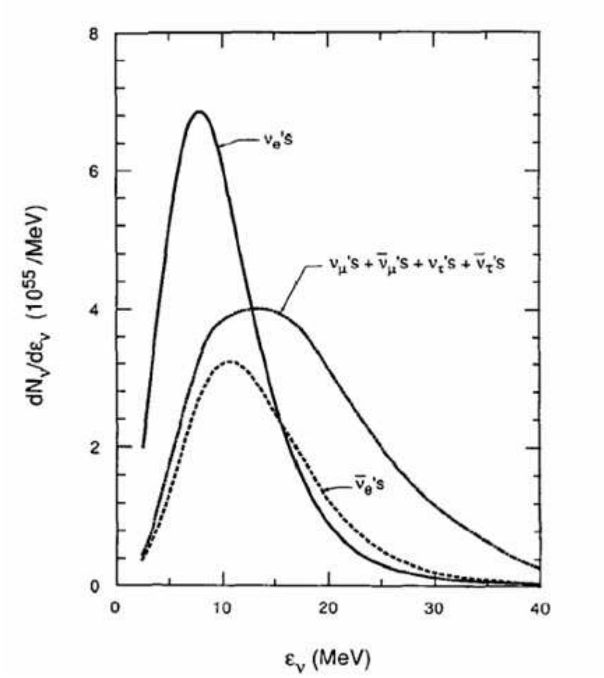

Fig. 1. The time integrated neutrino energy spectra from the core-collapse of a massive star. Taken from [6].

increase is mainly caused by $\overline{\nu}_e$ interactions with the free protons of hydrogen atoms (ice or water) in the telescope volume,

$$\overline{\nu}_e + p \to e^+ + n. \tag{1}$$

Other reactions, like νe or neutrino interactions with the atomic nuclei in the water, have significantly smaller cross-sections and can be neglected [9].

The sensitivity to the supernova neutrino burst can be calculated as an excess of total OM rates in the neutrino telescope over an average background rate, expressed in standard deviations. In this paper all rates correspond to 1 photon-electron signals in OMs. In the case of Poissonian statistics for the signal and background rates, the detection sensitivity can be expressed as

$$S = \frac{\Delta R}{\sigma}, \tag{2}$$

where ΔR is the overall photo-electron count increase in all N_{OM} optical modules in the time interval Δt ($\Delta R = N_{OM}\Delta R_{OM}\Delta t$), and the standard

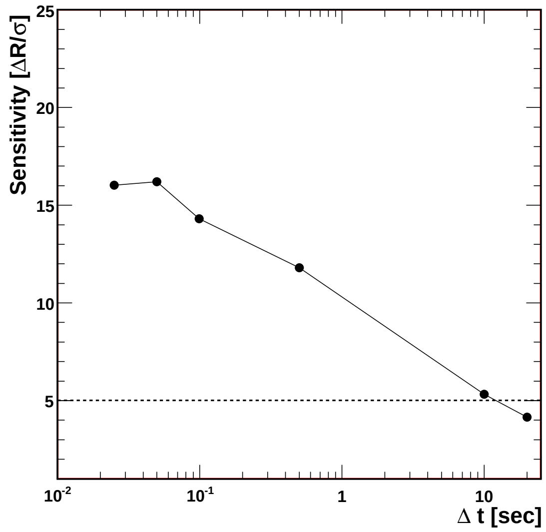

Fig. 2. Sensitivity to a supernova neutrino burst signal for different time intervals for the KM3NeT reference detector. A supernova SN1987A-type burst is assumed at a distance d=10 kpc.

deviation of the background is $\sigma = \sqrt{R_B \Delta t}$, where R_B is the background rate averaged over N_{OM} in an appropriate time interval before Δt. Note that the sensitivity to the neutrino burst signal is proportional to $\sqrt{N_{OM}}$. A similar dependence is expected for the overall photo-cathode area times quantum efficiency of the photo-detectors used.

SNEWS is setting a certain sensitivity limit for a neutrino experiment. For example, the false alert rate based on a 10 s coincidence signal from 2 detectors should be below 1 event per century [3]. This condition is fulfilled for experiments with a false rate below 1 event per week. Taking into account that a 5σ fluctuation above average background corresponds to a probability $< 2.85 \times 10^{-7}$ per 10 s interval, i.e. 0.017 false alerts per week, a 5σ level of sensitivity for a supernova neutrino signal is assumed to be a sufficiently stringent requirement in this paper. The non-Poissonian background fluctuations expected from bioluminescence may contribute significantly to the false alert rate and should be considered separately.

3. KM3NeT sensitivity to a neutrino burst

KM3NeT is a next-generation Mediterranean high-energy neutrino telescope with at least 1 km^3 of instrumented volume. The final configuration for KM3NeT will be selected at the end of the current design study project, which is supported by the EU through the FP6 program [10].

The KM3NeT detector assumed in this study corresponds to the reference detector model from the KM3NeT Conceptual Design Report [11]. It includes 8325 OMs, each with 21 PMTs of 3" diameter. This multi-PMT OM has a significantly larger ($\times$1.8) photo-cathode area than a standard 10" PMT, which is used in the IceCube [12] and ANTARES [13] neutrino telescopes.

The KM3NeT sensitivity to a supernova neutrino burst was studied with a help of parametric Monte Carlo simulations and compared to a previous ANTARES study, where the OM rates were evaluated with a help of the ANTARES simulation software based on GEANT 3.21 [14]. A SN1987A-type explosion at a distance close to the Galactic center (d=10 kpc) was considered in both cases. The differential neutrino flux was simulated according to the model from [15]. This flux will produce $\sim$170 events of type (1) per kiloton of water target mass in a 20 s interval. More then half of these events will be produced in the first second, and about 14% in the first 25 ms.

The sensitivity of KM3NeT is presented in Fig. 2 as a function of Δt. The dashed line corresponds to the 5σ level. Assuming similar deep-sea conditions and the same OM characteristics, the sensitivity ratio of the KM3NeT and ANTARES neutrino telescopes can be calculated as $r_s = \sqrt{1.8 \times (N_K/N_A)} \simeq 4$, where $N_K = 8325$ and $N_A = 900$ are the number of OMs in KM3NeT and ANTARES, respectively.

It should be noted that the ANTARES data acquisition system (DAQ) is based on the "all-data-to-shore" concept [16]. It allows for temporary storage of all raw data (OM hits) in a case of an internal or external trigger. Currently the ANTARES raw data is stored for the external triggers from the GRB coordinates network (GCN). The same DAQ concept is considered for the KM3NeT telescope.

An internal or external supernova trigger (for example the SNEWS alert) could be used for the raw data storage and thus allow for the detailed study of the supernova signal evolution.

The main difference in sensitivity to supernova neutrino signals between the Mediterranean KM3NeT telescope and IceCube is the higher background rate due to the deep-sea environment. The dominant background source in the deep sea is a steady, isotropic radiation from ^{40}K. The rate considered in these calculations corresponds to the ANTARES site, i.e. an isotropic flux of ∼350 photons/cm^{2}s .

Other major background sources in the deep-sea are the continuous bioluminescence from bacteria and localised bioluminescence bursts connected to macroscopic organisms [17]. These contributions depend on the deep-sea environment (for example currents) and can not be predicted in advance. However, they may be separated from a supernova signal, as the bacteria luminescence is not characterised by prompt increase of the rates, while the bioluminescence bursts can be localised in the detector.

More information on the bioluminescence background is expected from the ANTARES pilot project, where background rates are under constant monitoring and included in the recorded neutrino data.

4. Conclusions

A first study indicates that the KM3NeT neutrino telescope can detect a supernova neutrino burst as a significant excess of counting rates ($> 5\sigma$) in a time interval of 10 s or shorter, for a SN1987A-like supernova explosion at a distance $d <10$ kpc. An implementation of all-data-to-shore concept in KM3NeT and the storage of the raw data upon an internal or external supernova trigger will open the possibility for the detailed study of the recorded signal.

Constant monitoring of the deep-sea environment will be necessary to keep the false supernova event rates caused by the bioluminescence bellow a limit of 1 event/week, which is accepted by the SNEWS network. A supernova neutrino trigger for a deep-sea neutrino telescope fulfilling this condition can be designed and tested using the data collected in the ANTARES pilot project.

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