Detection of Galactic supernovae with the KM3NeT neutrino telescope

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***Abstract*. A core collapse supernova produces a short and very intense flux of neutrinos of all flavours. In a short time interval the total amount of Cherenkov photons produced by low-energy ($\approx$ 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. A km^3 size neutrino telescope in the Mediterranean (KM3NeT), designed and optimised for detection of Cherenkov light from interactions of neutrinos with energies above several 100 GeV, could be sensitive to this intense neutrino burst from supernovae in our Galaxy. The possibilities for the detection of such a supernova signal with KM3NeT and a possible contribution to the SuperNova Early Warning System (SNEWS) is presented.**

***Keywords*: core-collapse, neutrino, KM3NeT**

I. INTRODUCTION

KM3NeT is a future Mediterranean deep-sea research infrastructure, which will host a high-energy neutrino telescope with an instrumented volume of at least 1 km^3. The configuration of this telescope will be selected at the end of the current design study (DS) project, which is supported by the EU through the FP6 program [1]. The conceptual design of this Mediterranean research infrastructure was released in April 2008 [2] by the KM3NeT consortium. KM3NeT is designed to detect high-energy cosmic neutrinos (E_ν above about 100 GeV). However, it could be also sensitive to a short and very intense flux of the low-energy (E_ν <100 MeV) neutrinos from a core-collapse of a massive star. A core-collapse event (supernova of type II) produces an intense flux of neutrinos of all flavors. Almost all gravitational binding energy of the progenitor star ($\sim 99\%$) is released in this neutrino burst, which lasts only few tens of seconds.

The first and so far only evidence of the neutrino emission from the core-collapse supernova is based on a simultaneous detection of about 25 neutrino events in 3 neutrino detectors [3]. These neutrinos were produced in SN1987A, which took place in the Large Magellanic Cloud, about 52 kpc away.

Supernova explosions are very rare events, with typical rate expectations of 3 events per century in our Galaxy. These events play a very important role in the evolution of Universe. For example, the heavy elements (above iron) are produced in these explosions. The conditions set by the supernova and its remnants could furthermore lead to a cosmic acceleration and the production of cosmic rays. To develop the comprehensive stellar collapse model further, more neutrino data is necessary. The current status of the supernova modeling can be found, for example, in the review [4].

The location and time of the SN events cannot be predicted in advance and therefore 100% duty cycle is necessary 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 [5]. The primary goal of this network is to provide a 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 IceCube high energy neutrino telescope, which is currently under construction at the South Pole [6], is a member of SNEWS network. This telescope is sensitive to a SN1987A-type neutrino burst from the Galaxy and beyond.

In this paper the sensitivity of the Mediterranean neutrino telescope KM3NeT to supernova neutrino bursts in our Galaxy is discussed.

II. A SUPERNOVA NEUTRINO SIGNAL IN THE NEUTRINO TELESCOPE

In the current picture of core-collapse supernova the neutrinos are produced in two stages. In a first stage, which lasts less than a second, up to 20% of the overall energy is released in electron neutrinos, which are produced from $e^- p \rightarrow n\nu_e$ interactions (neutronisation). 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 flavors are produced with similar luminosities through the process $e^+e^- \rightarrow \nu_l + \overline{\nu}_l$, where $l = e, \mu, \tau$. The exact model of neutrino emission in a core-collapse event is difficult to access, as available data from SN1987A is not sufficient to discriminate the different scenarios of neutrino production. This is the reason for the large number of models, consistent with the neutrino data from SN1987A. All these models contain a component associated with the cooling of the newly formed neutron

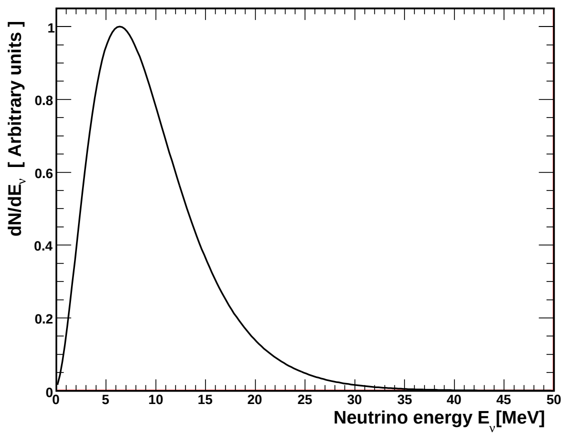

Fig. 1. Time integrated neutrino energy spectrum for the exponential cooling model

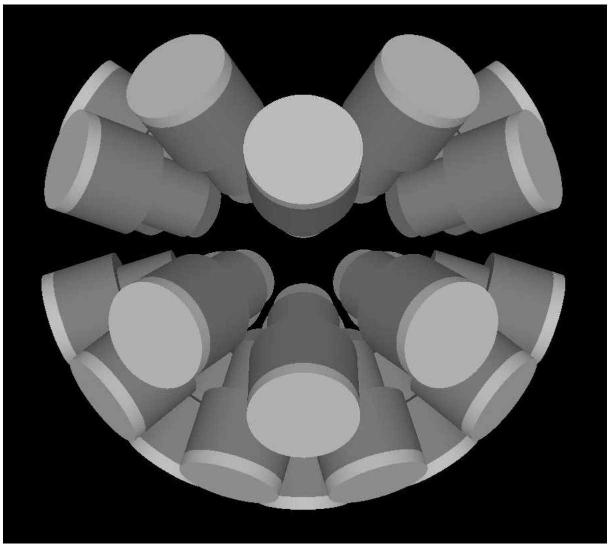

Fig. 2. The GEANT4 model of the KM3NeT Multi-PMT optical with 31 PMTs.

star. The neutrino emission models used in this study were taken from [7] and [8]. It should be noted that an improved analysis of SN1987A antineutrino events was published recently [9].

One of the simple, single-component cooling models of neutrino emission, is called "exponential cooling model" (for details see [8]). In this model the neutrino flux is described by three parameters: R_c - which describes the intensity of the emission, initial temperature T_0 and the luminosity time scale τ_c. The neutrinos have thermal energy spectra, with a steadily decreasing temperature

$$\frac{dN_c}{dtdE} = A_c(R_c) \cdot \frac{E^2}{1 + exp[E/T_c(t)]}, \quad (1)$$

where A_c normalization parameter is a function of R_c and the core temperature is decreased as

$$T_c(t) = T_0 \cdot \exp[-t/4\tau_c]. \quad (2)$$

The parameters for the exponential cooling model were obtained from the fit to SN1987A data [8]:

$$R_c = 40.2 \text{ km}, \quad T_0 = 3.81 \text{ MeV}, \quad \tau = 4.37 \text{ s} \quad (3)$$

The time-integrated neutrino energy spectrum for the exponential cooling model is given in Fig. 1. In the neutrino flux at the Earth, neutrino propagation effects in the exploding star and in the interstellar medium play an important role. However, these effects are beyond the scope of the paper and are not discussed here in the text.

From all neutrino flavors produced in the cooling phase, electron anti-neutrinos ($\overline{\nu}_e$) are most efficiently detected in the considered energy range (2.2-100 MeV). These neutrinos produce positrons in the process of inverse beta decay (IBD):

$$\overline{\nu}_e + p \rightarrow e^+ + n. \quad (4)$$

Other reactions, like νe or neutrino interactions with the atomic nuclei in the water, have significantly smaller cross-sections and can be neglected [10]. The positrons produced in IBD reactions are the main source of signals in neutrino telescopes. Almost all events of SN1987A detected in 3 different detectors were produced by this process.

The detection method for a supernova neutrino burst in a high-energy neutrino telescope was first proposed for the AMANDA telescope [11] and later tested with experimental data [12]. 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 increase is caused by the Cherenkov photons radiated from the positrons produced in reaction (4).

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

$$S = \frac{\Delta R}{\sigma}, \quad (5)$$

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 deviation of the background is $\sigma = \sqrt{N_{OM}R_B\Delta t}$, where R_B is the averaged background rate. The sensitivity to the neutrino burst signal is thus proportional to $\sqrt{N_{OM}}$. A similar dependence is expected for the overall photo-cathode area and quantum efficiency of the photo-detectors.

To be accepted in the SNEWS network, a neutrino experiment should pass a certain sensitivity test. For example, SNEWS requirs, that the false alert rate based on a 10 s coincidence signal from 2 detectors should be below 1 event per century [5]. This condition is fulfilled for experiments with a false signal rate below 1 event per week. This translates into a probability $< 2.85 \times 10^{-7}$ for a 10s interval, corresponding to a 5σ fluctuation of a Poissonian background. For this reason, for the KM3NeT telescope only burst signals above 5σ are considered. It should be noted that the non-Poissonian background fluctuations expected from bioluminescence in the Mediterranean neutrino telescope may significantly increase the false alert rate and should be considered separately.

III. KM3NeT SENSITIVITY TO A NEUTRINO BURST

The KM3NeT neutrino telescope configuration considered in this paper is based on a new type of optical module (OM) developed during the KM3NeT Design study. In this OM 31 PMTs with 3” diameter are mounted in a 17” glass sphere. This multi-PMT OM has a significantly larger photo-cathode area than conventional OMs of ANTARES and IceCube, with single 10” PMTs.

Up to 300 detection units, each with 20 multi-PMT OMs, could be used in the KM3NeT neutrino telescope. The detection unit is a basic, vertical structure of the KM3NeT neutrino telescope. The total number of 3” PMTS in this case would be 186000, distributed in 6000 multi-PMT OMs.

The KM3NeT sensitivity to the supernova neutrinos previously was estimated for the detector configuration which was presented in the KM3NeT CDR [13]. In this configuration 174825 similar PMTs are mounted in 8325 OMs. Each OM is hosting 21 downward-looking PMTs.

The KM3NeT sensitivity to the supernova neutrinos was calculated by two different methods. In the first method the rates calculated for the ANTARES neutrino telescope were rescaled for KM3NeT. The supernova signal in ANTARES was evaluated with a help of GEANT 3.21 based simulations [14]. The model used in these simulations [7] predicts ~ 200 positron events per kiloton of water target mass in a 20 s interval. This rate corresponds to a burst (similar to SN1987) in our Galaxy, at a distance d=10 kpc. According to the model, half of these events are produced in the first second, and about 14% in the first 25 ms.

The KM3NeT sensitivity was evaluated for a constant background rate, corresponding to 50 kHz for the ANTARES OM. The signal rate was rescaled according to the KM3NeT OM characteristics (photo-cathode area and quantum efficiency). The KM3NeT sensitivity to neutrino burst signals is increased by a factor of 5 with respect to ANTARES. Here we assume that KM3NeT is equipped with $N_K = 6000$ multi-PMT OMs, while the corresponding number is $N_A = 900$ for ANTARES. with conventional 10” PMTs.

The quantum efficiency of the 3” PMTs is expected to be higher by a factor of 1.3 in comparison to the 10” PMTs used in ANTARES OMs.

In the second method the supernova burst signal was studied with the help of GEANT-4 simulations. The model of the multi-PMT OM which is used in the simulations is shown in Fig. 2. The calculations are based on the exponential cooling, with a set of parameters given by (3) . This model predicts a similar number of positron events per kton of detector target as was obtained for ANTARES. The GEANT-4 simulations are still in progress and the results obtained will eventually replace the results from previous calculations.

The KM3NeT sensitivity obtained with the first method is presented in Fig. 3. As it can be seen from the figure, the signal sensitivity depends on observation time window Δt. The dashed line corresponds to the 5σ level.

A. *The KM3NeT Data model*

The KM3NeT data model is based on a ”all-data-to-shore” concept. This concept is successfully implemented in the ANTARES data acquisition system (DAQ) and allows a flexible data handling [15]. For example, in the case of internal or external trigger all raw data (OM hits) corresponding to the fixed time interval (currently about 2 min in ANTARES) could be stored on a disk. The ANTARES raw data is stored for external triggers from the GRB coordinates network (GCN). Recently SNEWS alerts were also included in the ANTARES DAQ. The raw data can then be used for the detailed study of the supernova signal evolution. This will allow the testing for different models of neutrino production and propagation.

The main limiting factor to the sensitivity of the supernova neutrino signal in the Mediterranean KM3NeT telescope is the deep-sea environmental optical background and in particular the localised bioluminescence bursts connected to macroscopic organisms [16]. 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 bioluminescence bursts could be localised in the detector.

The data on a bioluminescence background is available from the ANTARES pilot project. These rates are under constant monitoring and included in the recorded neutrino data.

IV. 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. The implementation of the all-data-to-shore concept in KM3NeT and the storage of the raw data upon an internal or external supernova trigger (SNEWS alert) will open the possibility for a detailed study of the recorded signal. Constant monitoring of

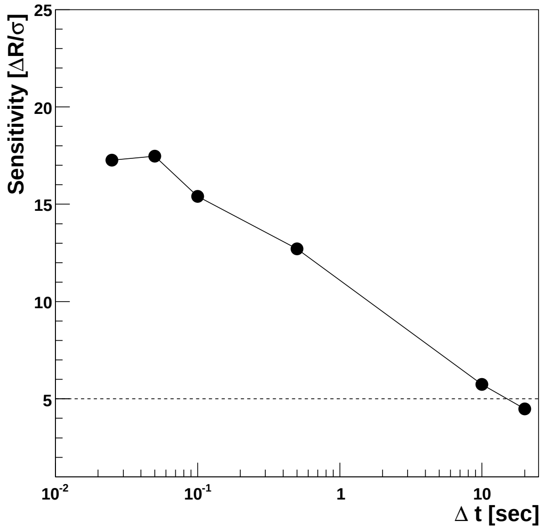

Fig. 3. Sensitivity to a supernova neutrino burst signal for different time intervals for the KM3NeT reference detector. A supernova SN1987A-type burst is assumed at a distance d=10 kpc.

the deep-sea environment will be necessary to keep the false supernova event rates caused by bioluminescence below a limit of 1 event/week, which is accepted by the SNEWS network. An internal 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.

V. Aknowledgment

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References

[1] http://www.km3net.org
[2] *KM3NeT Conceptual Design Report for a Deep-Sea Research Infrastructure in the Mediterranean Sea Incorporating a Very Large Volume Neutrino Telescope.*, KM3NeT Consortium, ISBN 978-90-6488-031-5
[3] K. Hirata *et al.*, Phys. Rev. Lett. 58(1987) 1490.
R.M. Bionta *et al.*, Phys. Rev. Lett. 58(1987) 1494.
E.N. Alexeyev *et al.*, Phys. Lett. B205 (1988) 209.
[4] H. T. Janka *et al.*, Phys. Rept. 442 (2007) 38.
[5] P. Antonioli *et al.*, New J.Phys. 6(2004) 114.
[6] IceCube Collaboration (A. Achterberg *et al.*), Astroparticle Physics 26(2006), 155
[7] A. Burrows, Astrophys. J 334 (1988) 891.
[8] T. J. Loredo and D.Q. Lamb, Phys. Rev, D65 (2002) 063002.
[9] G. Pagliaroli *et al.*, Astroparticle Physics, 31(2009), 163.
[10] A. Burrows, K. Klein, and R. Gandhi, Phys. Rev. D45 (1992) 3361.
[11] F. Halzen, J. E. Jacobsen and E. Zas, Phys. Rev. D49 (1994) 1758.
[12] AMANDA Collaboration (J. Ahrens *et al.*), Astropart. Phys. 16 (2002) 345.
[13] R.Shanidze (for the KM3NeT Consortium), Nucl. Instrum. Meth. A620 (2009) 120.
[14] Y. Becherini, G. Ramadori, M. Spurio, ANTARES-PHYS-2002-002 (ANTARES note, unpublished)
[15] ANTARES Collaboration, (J. A. Aguilar *et al.*), Nucl. Instrum. Meth. A570 (2007) 107.
[16] J. Craig *et al.*, Nucl. Instrum. Meth. A620 (2007) 224.