Supernova neutrino detection in the ANTARES neutrino telescope.

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Abstract: Neutrinos of all flavours are produced during a Supernova (SN) explosion. The antineutrinos can interact in the medium surrounding the underwater ANTARES telescope and produce positrons emitting Cerenkov radiation which is recorded by the optical modules (OMs) of the detector. The signature of this event is a simultaneous increase of the counting rate in the detector. The aim of this work is to develop several methods to detect the SN signal in ANTARES detector. In particular this analysis, using the specific geometrical configuration of the OMs, minimizes the noise effect introduced by the bioluminescence during the measurement. The significance as a function of the number of active OMs and of the distance to SN is also evaluated.

Keywords: ANTARES, neutrino, supernovae.

1 Introduction

The ANTARES neutrino telescope [1] is a large water Cerenkov detector that could provide the opportunity to detect the Cerenkov light produced by positrons from SN antineutrinos via reaction $\bar{\nu}_e + p \rightarrow n + e^+$. To investigate this possibility we evaluate the response of the ANTARES optical modules to SN neutrinos with a help of Geant4 simulations and compare the possible SN signal rates to the ANTARES OM rates, which are recorded during the normal run operations. The ANTARES detector is made of detection lines that consist of 25 storeys, a group of a 3 OMs that are arranged close to each other (distance is less than 1m). This configuration provides an opportunity to reduce the background using only hits that are in coincidence between OMs in the same storey. A method to minimize the effect of the bioluminescence burst is discussed in the Section 3 while the statistical analysis based on singles rates, double coincidences and triple coincidences in one storey is presented in Section 4, 5 and 6. The performance of the three different methods is also compared, and significance is evaluated.

2 Simulation

We performed the simulations using Geant4 with the detailed OM description. In these simulations we included the full 3 OMs ANTARES storey configuration while for the positrons we used the energy spectrum and the flux obtained averaging in time the distributions from the model 57 of A.Burrows [2] for a SN1987A like event at a 10 kpc distance. As a result we have obtained an excess of 14 hits in a 105ms time interval on each OM. The time interval of 105ms was chosen because it both corresponds to the standard time slice of the data flow in ANTARES detector and to the period of SN explosion where the highest neutrino flux is produced according to [2]. To fully exploit the geometry of ANTARES detector, we have also obtained the number of coincidences produced by the positron light between two or three OMs of the same storey in a 25ns time window. The possibility to use these multi coincidences will be described in the next sections. To evaluate the number of hits from an event at a distance $R$ different from the 10 kpc we used a simple proportion, knowing that $\Phi \times 4\pi R = \text{const}$.

3 The bioluminescence filter

In addition to the Cerenkov light produced by muons, neutrino telescopes also detect Cerenkov light from the decay of radioactive elements and light from luminescent organisms. Fig. 1 represents the time variation of the optical background rate detected in one OM. One of the main contributions comes from the radioactive decay of $^{40}\text{K}$. The frequency of this noise is evaluated by MC
calculations to be around 40kHz and does not change since the $^{40}$K concentration depends on the salinity that is almost constant on time and sea depth. However in fig. 1 the mean rate is about 80kHz, the additional contribution being due to a constant bioluminescent activity.

A maximum significance of 5 for SN at the 4 kpc is obtained at low bioluminescence level (run #39656) for the estimated by the formula:

\[ S = \frac{h_{\text{signal}}N_{\text{OM}}}{\sqrt{h_{\text{background}}N_{\text{OM}}}} \approx 4.8 \]  

In case of 14 signal hits ($h_{\text{signal}}$) and of 80kHz of background for 900 active OMs ($N_{\text{OM}}$) the significance can be estimated by the formula:

\[ S = \frac{h_{\text{signal}}N_{\text{OM}}}{\sqrt{h_{\text{background}}N_{\text{OM}}}} \approx 4.8 \]  

the main idea of all methods described here being to measure the increase of the total hits in the detector in one time slice and to compare it with the previous measurements. For single hits in the specific case of ANTARES detector, this cannot be directly applied due to the bioluminescence bursts that have been therefore excluded using the filter as described above. The procedure we have used is the following:

a) The data collected in a 45 min time interval, sufficiently large to have good statistics, were used to determine the fit $h_{i,\text{exp}}$ of the hit count distribution for each $i$th OM in the detector. $h_{i,\text{exp}}$ can be seen as the probability density function (PDF) of the hits in OM$_i$. The results from the fit were also used to define quality cuts. In particular only OMs for which the hit distribution follows the next criteria where accepted for the analysis: the fit converges, $\lambda \geq 2000$, the area of the Poisson component is larger than 30% of the total area (in other words: there is less than 70% of the bio-burst hits).

b) The data are then analysed time slice by time slice. At each time slice the hits of all the OMs that have passed the bioluminescence cut are summed together to determine the total hit count of the detector in that particular time slice.

c) The total hit count of the detector should be described by the "detector PDF" distribution, which is different for every time slice because OMs which have passed the bioluminescence cut are different. The detector PDF distribution can be evaluated using the PDFs for every OM, but this is a very time consuming procedure. To simplify we have made a simulation using all the parameters from fits of the single PDFs which proved that detector PDF is still a Gaussian with an average $M = \sum m_i$ where $m_i$ is mean of PDF for $i$th working OM and with a sigma $S = \sqrt{\sum \sigma_i^2}$ where $\sigma_i$ is a variance for $i$th PDF.

To estimate the significance two runs were selected. One of them was #39656, recorded on 16 May 2009, where bioluminescence conditions were good (rate: 80kHz for the bottom, 60kHz - middle, 60kHz - top), another one was #40154 recorded on 13 April 2009 when bioluminescence was higher (rate 200-160-140kHz).

The parameters of the fit ($\lambda$, $A$, $j_{\text{max}}$) were then extracted from the experimental distributions as deduced from the analysis of the 2 runs. In order to compare with the other methods described in the note, we have calculated the significance assuming 900 working PMTs and keeping the same mean characteristics of the background of the two previous runs.

The results of these simulations are shown in fig. 2 where the significance is plotted as a function of the distance of the SN. 900 OMs in the same conditions of the runs 39656 and 40154 were simulated. The decrease of the significance with the increase of the SN signal (from distance 3.5 kpc and closer) is due to the bioluminescence filter: when the SN signal is very high a lot of OMs are excluded from the analysis. The dotted lines with a 1.7$\sigma$ label in the same figure are obtained when the effect due to the long-term fluctuations is included in the calculation. This effect is probably ascribed to the baseline rate which is slightly changing during the analysis time of 45 min and which increases the width of the distribution by a factor of about 1.7.

A maximum significance of 5 for SN at the 4 kpc is obtained at low bioluminescence level (run #39656) for the
full working detector when the long-term fluctuation is included.

Figure 2. Simulated significance for 900-OM detector in dependence of the distance from SN explosion. OMs signal is simulated according to run #39656(solid) and #40154(dotted) conditions. Dashed and dot dashed lines represent calculations with the 1.7 increase of sigma to account for long term fluctuations.

5 Supernova signal for double coincidences between OMs.

The ANTARES configuration allows the light from $^{40}$K decay to be simultaneously seen by a couple of OMs in a storey. This fact is rather well known and it is used in the detector calibrations [3]. Later on by the couple of OMs we assume only OMs from the same storey.

For every couple of OMs the plot of the time difference between every two hits from both OMs can be determined. One example of this time distribution is shown in fig. 3.

Figure 3. Example of the time coincidence distribution for storey 1635, OM 1 and 2. Dashed line represents random coincidence level. The area of the Gaussian accounts for the number of hits from $^{40}$K coincidences.

We can distinguish a plateau due to the random coincidences in the time window $\tau$ of 20 ns and a Gaussian shaped distribution due to $^{40}$K decays seen by the both modules (later we call them “true coincidences” to distinguish from the random coincidences). To extract these two components the distribution was fitted with a Gaussian plus a constant. The rate of the true coincidences extracted from the fit is about 16Hz for a couple of OMs and it is independent from the bioluminescence activity. The rate is thus stable in time, but it depends from the couple of OMs since efficiency of the OMs is different.

To understand how the uncertainty on the true coincidence rate from the fit depends on the statistics i.e. on the number of the summed time slices, we performed a simple simulation of the time difference distribution for one couple of OMs assuming an 80Hz random background on each OM and a Gaussian distribution with 16Hz for the coincidences. These simulations gave the uncertainty on the extracted true coincidence rate as reported in fig. 4 for various number of time slices $N_{TS}$.

In this method we calculate the global rate of the coincidences in the detector at any time slice and compare it with the sum of the rates of each couples. The global detector rate was determined from the time differences between all coincidence hits of every OM couple that were collected in a common distribution. This distribution was then fitted with the same procedure described above and the error evaluated as in fig. 4 where the number of couples instead of the number of time slices was assumed. The true coincidence detector rate extracted from the fit is stable in time and equal to the sum of the every OM couple rates in case of normal work or higher in case of SN explosion.

Figure 4. Uncertainty on the coincidence rate extracted from the fit of the simulated distribution for different time slice numbers (solid curve). Dotted curve represents error in absence of the random background.

We verified this procedure on real data. To this purpose one period with a 450 OM couples was analysed and the rate for every couple was calculated from 20000 time slices of the data to provide as seen from fig. 4 an uncertainty less than 5%. The global detector true coincidence rate was then obtained from the fit for every time slice. The difference between this rate and the sum of the true coincidence rates of every couple was evaluated and normalized to the detector rate. As expected, the distribution of this normalized difference has a mean 0 and sigma 17%, in good correspondence with the expected error from fig. 4 for 450 $N_{TS}$.

Simulations with Geant4 estimates a value of 22Hz for the true coincidence rate, the difference with respect to the measured 16Hz being ascribed mostly to the description of the lateral region of the OM. Geant4 simulations...
also show that the light produced by the positrons induced by SN neutrinos may simultaneously hit two and even three OMs in the same storey. These additional events increase the coincidence rate during the SN explosion. The Geant4 simulation of this effect gives a rate of about 2.8Hz in the first 100ms time window i.e. an increase of 0.28 events for each pair of OMs in the considered 105 ms time slice for a 10 kpc SN1987A. The measurement of this small increase, which was reduced down to 2Hz to take into account the difference between MC and data, can extend the significance to the SN explosion in ANTARES detector.

The 5σ significance obtained from the simulations of 900-OM detector is reported in fig. 5 as a function of the SN distance for various bioluminescence rates. For an event occurring at 4 kpc the significance is comparable to the previous method for a background rate of the 100kHz. Given the ANTARES geometry, a triple coincidence in each storey can occur whenever a single event (light from a track, a 40K decay) is simultaneously seen by the 3 OMs. In our approach we require that 3 hits, one for each OM, are detected during a 20ns time window. This means also that in every pair of the hits in the triple coincidence, the time difference is less than 20ns. In order to obtain the time difference distribution like for doubles it was decided to use three dependent distributions: \( t_1 - t_2 \), \( t_2 - t_3 \) and \( t_3 - t_1 \), where \( t_i \) is time of hits from OM. In this case the random coincidences do not form a plateau in the time difference distribution. This is because, for example, the difference \( t_1 - t_2 \) is constrained by the condition that both \( t_1 \) and \( t_2 \) must be close to \( t_3 \) by less than 20 ns. Using Bayes’ theorem one can evaluate the shape of the random coincidences part:

\[
f_{\text{rand}}(\Delta t) = \frac{2}{\sigma} \frac{|\Delta t|}{\sigma^2}
\]

The fit is thus done adding the Gaussian of the true coincidences to the random part (4). True coincidences rate for the storey is calculated as a mean value of the true coincidence rates extracted from the fit of the three distributions \( t_1 - t_2 \), \( t_2 - t_3 \) and \( t_3 - t_1 \).

To find the true triple coincidence rate, one month of data was analysed. It was found that the mean storey rate is about 0.065Hz and it is stable during 3 months. Simulations with Geant4 give a higher value: 0.2Hz. This large discrepancy can be explained considering the already observed behaviour in the double coincidence case where the simulations give a value around 22Hz against the observed 16Hz. In case of a triple coincidence this inefficiency is additionally amplified. The Geant4 simulation also estimates the total number of triple coincidences from SN to about 0.035 per storey in a time slice. Assuming the same damping in the detection efficiency as for 40K rates (0.2Hz MC against 0.065Hz experimental), the SN triple coincidence rate is expected to be about 0.11Hz.

Similarly to the double, the coincidences rate of the triple coincidences in the detector during one time slice is calculated. Unfortunately the number of triples is much less than the doubles, the fitting procedure is not applicable so that the significance is affected by the random coincidences (4). The simulated significance as a function of the SN distance and background is shown in the fig. 5.

### 6 Conclusion

We have investigated different possibilities for detecting SN neutrinos with the ANTARES telescope. The significances estimated for the three methods we have described are comparable (fig. 2, fig. 5). Double and triple coincidences seem preferable because significance increase with the SN signal and they do not strongly suffer from the bioluminescence activity. Of course the simultaneous acquisition of an external SN trigger like the one provided by the SNEWS collaboration will strengthen our analysis. The study to implement this possibility is now in progress.