Online Search for Neutrino Bursts from Supernovae with the AMANDA Detector

Thomas Feser[1] for the AMANDA Collaboration[2]
(1) Institute for Physics, Mainz University, D-55099 Mainz, Germany
(2) complete author list in G. C. Hill et al., these proceedings

Abstract

Although designed to detect neutrinos with energies of 100 GeV and above, the AMANDA neutrino telescope is also capable of detecting multi-MeV antielectron neutrinos from supernovae. Embedded in the deep, cold and sterile ice of the South Polar glacier, photomultiplier noise is of the order of only a few hundred Hz. The signature of supernova neutrinos is the simultaneous increase in rate in all optical sensors in the detector. We outline improvements in the reduction of correlated noise and describe a fast and robust filter that has been developed to allow participation in SNEWS.

1. Introduction

AMANDA (Antarctic Muon And Neutrino Detector Array) utilizes the large volume of transparent glacial ice available at the South Pole as a Cherenkov medium. The optical modules (OMs) are buried 1500-2000 m deep in the Antarctic ice sheet. Each OM is made up of a photomultiplier tube (PMT) enclosed in a pressure-resistant glass vessel and connected to the surface electronics by cables supplying power and transmitting PMT signals. The shortest spacing between any two OMs in the array is 10 m. This limits the track reconstruction ability to particles with energies above few tens of GeV.

Current models assume that a type-II supernova (SN) transforms $> 99\,\%$ of the gravitational energy released by the stellar collapse ($\sim 10^{46}$ J) into an intense burst of neutrinos with nuclear energies. They leave the SN core within a few seconds after the collapse, hours before visible light. A small fraction then interacts within the AMANDA detector volume. The dominant detection mechanism for such neutrinos in water or ice is the inverse β-decay reaction on protons $\bar{\nu}_e + p \rightarrow n + e^+$ leaving positron tracks of ~ 10 cm-length. The Cherenkov light radiated along these tracks can be seen in nearby PMTs. A SN neutrino burst will produce positrons throughout the detector, which will increase the counting rates of all PMTs above their average value. This collective behavior can be seen clearly even if the increase in each individual PMT is not statistically significant - see fig. 1. The observation of such an event could therefore provide the detection

pp. 1325–1328

of a supernova hours before the corresponding electromagnetic radiation would reach Earth. It has been shown that the AMANDA-B10 detector, which consists of 302 OMs, can detect SN collapses of type-II with 90 % efficiency for 70 % of the stars in our galaxy allowing one fake event per year [1]. In the austral summer of 1999/2000 the AMANDA-II detector was completed to include 677 OMs. At that time, the SN data acquisition system (SNDAQ), which monitors the rates measured by the OMs continuously, was significantly modernized [3]. It can now read out the detector in 10 ms time bins, compared to 500 ms before. However, due to limited resources in satellite bandwidth and tape storage capacity at the South Pole, the data were rebinned and archived in 500 ms bins. Only when the sum of the rates of a subset of especially stable OMs showed a fluctuation of at least 3 standard deviations, the data were recorded in 10 ms resolution. This method produced too many false alerts and was thus unable to contribute to SNEWS (Supernova Early Warning System [4]). This changed in 2003, when a sophisticated online analysis software embedded in the data acquisition framework was installed.

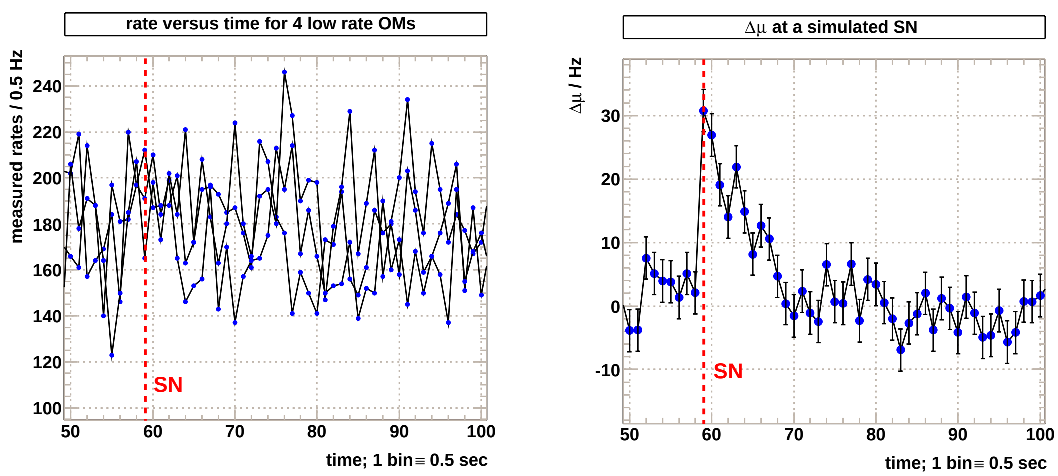

Fig. 1. The rate increase induced by a simulated SN in the galactic center - yielding a rate increase of 110 $\frac{\text{counts}}{10\,\text{sec}}$ in each OM [2] - is hardly visible in the rates of individual OMs. The analysis observable $\Delta\mu$, however, shows a significant deviation.

2. Likelihood-based Data Analysis

Assuming that the measured OM rates r_i (i being the OM index) are Gaussian variables - with a a mean estimated by μ_i and a width estimated by σ_i - one defines an observable $\Delta\mu$ as signal-induced deviation from these expectation values yielding the maximum likelihood for a set of measured rates at a given time [1]. This is equivalent to a minimization of

$$\chi^2 \equiv \sum_{i=1}^{n_{\mathrm{OMs}}} \frac{(r_i - \mu_i - \epsilon_i \, \Delta\mu)^2}{{\sigma_i}^2} \quad . \tag{1}$$

ϵ_i denotes the relative photon sensitivity of each OM; the rates r_i are taken in 500 ms time bins. The resulting formula for $\Delta\mu$ can be derived analytically, and an error can then be estimated by $\sigma^2_{\Delta\mu} = \sum_i (\frac{\partial}{\partial r_i}\Delta\mu)^2 \sigma_i^2$. The coherence of the rate increase is tested by the χ^2 value defined above. In a typical situation with ~ 460 OMs contributing to our analysis, any $\frac{\chi^2}{\mathrm{n.d.f.}} > 1.3$ suggests a pathologically unlikely event that can be rejected.

The estimate of μ_i is done by calculating a moving average over the rates $r_i(t)$ measured before and after the particular r_i in formula 1. The estimate of σ_i is handled similiarily, but using the sum over the squared $r_i(t)$ as well. Simulations indicate that the separation of supernova induced $\Delta\mu$ values from the background reaches a flat maximum for moving average times above 5 min. For the online analysis an interval of 10 min was chosen.

3. Correlated Noise and OM Qualification

Unfortunately, the OM noise rates in AMANDA are not Poissonian variables. Instead, one observes an increased probability for short time differences between adjacent pulses, increasing the total noise rate by $60 - 70\,\%$ compared to Poissonian behaviour. The intensity of this afterpulsing is measured by $f \equiv \frac{\sigma_i}{\sqrt{r_i \, \Delta t}}$. For Poissonian behaviour, one can assume $\sigma_i = \sqrt{r_i \, \Delta t}$ and thus $f = 1$. The reasons for afterpulsing are not fully understood. The AMANDA OMs have large cathode areas and operate in a very cold environment. Measurements were, therefore, performed in situ and at low temperatures in the lab. It is known that ion clouds drifting back to the cathode after an initial photon hit may knock out additional electrons and, hence, produce correlated follow-up pulses. This effect can indeed be observed, but it is not the dominant cause. It is speculated that luminescence from the decay of excited atomic states within the OM glass sphere accounts for most of the correlated noise.

The measurements also showed that photon-induced pulses cause $\sim 70 - 85\,\%$ fewer afterpulses than noise pulses. This gives a strong argument for a lengthening of the $10\,\mu$s artificial deadtime that was previously applied in the hardware of the scalers which measure the rates. Monte Carlo studies showed an optimal separation of simulated supernova signals from background induced $\Delta\mu$ values for a dead time of $\sim 250\,\mu$s. OMs that still show strong afterpulsing after the implementation of the deadtime are excluded from the analysis. This is not done in advance of the analysis as described in [1], but dynamically within. The qualification is based on the estimators for μ_i and σ_i introduced in the previous section. Both estimators do not take into account a time window of the expected

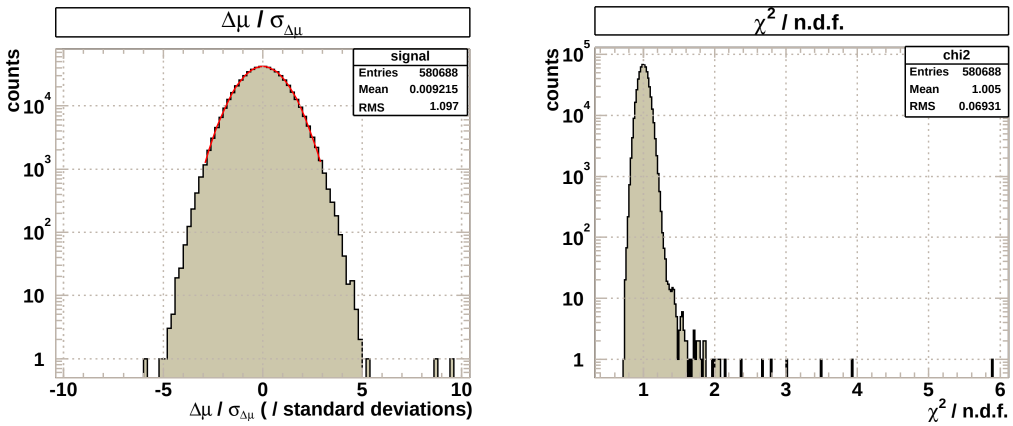

Fig. 2. In a preliminary analysis of roughly 80 hours of 2003 data, the analysis found no SN candidate. The two events with $\Delta\mu/\sigma_{\Delta\mu} \sim 10$ failed to pass the χ^2 cut. Fitting a Gaussian to the left histogram yields $\chi^2_{\rm fit}$/n.d.f. $= 41/27$.

signal length ($\sim 15\,$s) following the tested rate r_i. This prevents the disqualification of OMs due to the increased rate variations induced by a SN. As a result of our current qualification requirement of $f < 3$, we usually find ~ 460 OMs employed to find $\Delta\mu$ and $\sigma_{\Delta\mu}$.

4. Summary and Outlook

Currently any event with $\Delta\mu/\sigma_{\Delta\mu} > 5.5$ and with a χ^2-probability $\geq 10^{-4}$ is classified as SN candidate event. In a preliminary analysis of $\sim 80\,$hours of data (shown in fig. 2) we found no fake events. From a gaussian fit to the shown distribution we expect 15 fake candidates per year. This rate is sufficiently low to allow the analysis to contribute to SNEWS. It can detect 90 % of the supernovae at a distance of 9.4 kpc. The analysis is not yet optimized to a specific SN signal shape or duration. An improved sensitivity can therefore be expected in the future. After thorough long time stability checks, the information on SN candidate events will begin to be transmitted to the SNEWS network.

5. References

1. Ahrens, J. et al. 2002, Astrop. Phys. 16 p. 345, arXiv: astro-ph/0105460
2. Halzen, F. et al. 1994, Phys. Rev. D49 No. 4 p. 1758
3. Neunhöffer, T. et al. 2001, Proc. of the 27th ICRC p.1125
4. Scholberg, K. 1999, arXiv: astro-ph/9911359, http://hep.bu.edu/~snnet