Supernova Burst Analysis with the Amanda Neutrino Telescope

R. Wischnewski for the AMANDA Collaboration [1]
DESY Zeuthen, D-15738 Zeuthen, Germany (email: wischnew@ifh.de)

Abstract

The High Energy Neutrino Telescope AMANDA is capable of searching for bursts of low energy neutrinos originating from Supernova (SN)-collapses. We present data taken with AMANDA-B10 in 1997. We find satisfactory long term stability for a subset of PMTs and runs. A Likelihood description of the combined counting rates efficiently removes non-statistical fake events. With 51 low noise PMTs, the currently operated telescope is sensitive to SN bursts of up to $\sim$8.5 kpc distance. A future upgrade to AMANDA-II can extend the visibility radius to $\sim$12 kpc.

1 Detection Principle:

The AMANDA High Energy Neutrino Telescope is currently made of 424 photomultipliers (PMTs) with spacings of tens of meters, deployed into the antarctic ice sheet at the geographic South Pole. The main goal of the experiment is muon/neutrino detection at the TeV-energy scale with angular resolution of a few degrees. AMANDA has an intrinsic muon threshold of $\sim$50 GeV.

Monitoring of a huge ice volume permanentely with a few hundred PMTs, allows however also to search for bursts of low energy neutrinos, originating e.g. from gravitational stellar collapses. Supernova (SN) neutrinos which interact inside the detector close enough to a given PMT will cause an enlarged counting rate for the duration of the SN neutrino burst (typically 10 sec). Once these noise rate changes are sampled with a large number of PMTs, coherent fluctuations much smaller than one standard deviation per PMT will become significant. Such a SN search with the AMANDA detector, as proposed by Halzen et al (1994), would detect the dominant reaction channel $\bar{\nu}_e + p \rightarrow e^+ + n$ with the positron's Cerenkov light triggering a PMT.

The effective detection volume V_{eff} per optical module is determined by the optical properties of the ice, and is calculated to be $V_{eff} \approx 410\,\mathrm{m}^3$ (Jacobsen, 1995). For a SN of the same luminosity as SN1987A, located at the center of our galaxy (8.5 kpc), this yields about 100 counts per PMT.

The background to this signal is determined by the noise fluctuation of all PMTs. For the ideal situation of identical, uncorrelated and purely Poissonian noise of the PMTs, the fluctuation of noise hits N_{HIT} per 10 secs, is given as $\sigma_N = (10\,\mathrm{sec} \cdot R \cdot n_{pmt})^{1/2}$, with n_{pmt} the total number of PMTs and R their noise rate. Under this assumption, a SN1987A-type supernova at the galactic center would yield an 11σ effect (90% signal efficiency) for 50 PMTs with R=320 Hz. The above assumption simplifies the experimental situation, the most dramatic change being non-Poissonian single PMT noise fluctuations. A SN1987A 8.5 kpc signal is at the $1\sigma_N$ level for each PMT, which requires a well understood detector.

With the very low rate of SN-bursts in our galaxy (10^{-1}-$10^{-2}/\mathrm{yr}$, Totsuka et al (1991)), and the few existing SN-detectors, a continuous SN-monitoring is essential. We are considering to join the 'SN Early Alert Network' (Habig et al, 1999).

Results of a SN-analysis using the AMANDA-A detector located at 800m-1000m depth have been presented earlier (Wischnewski et al, 1995). This shallower detector turns out to be inferior to the AMANDA-B telescope due to higher noise and less stability.

2 Experimental Setup:

The AMANDA detector currently consists of 13 vertical strings equipped with Optical Modules (OMs). Each OM consists of a pressure glass vessel with a 8"-Hamamatsu R-5912 PMT inside. PMTs are operated at a gain of $\sim 10^9$ over 2 km of cable. All front-end electronics are in a laboratory building on the ice-surface.

[1] see talk of F.Halzen (HE 6.3.01) for the full author list

Detailed detector descriptions can be found in Andrés et al (1999) and Biron et al (1997). We distinguish **AMANDA-B4**, with the first 4 strings with a total of 86 OMs (deployed 1996, readout via coaxial cable), **AMANDA-B10**, with 302 OMs, with the B4-strings and strings 5-10 (deployed 1997, twisted pair readout), and **strings 11-13** with 122 OMs (1998, mainly optical fiber readout).

The **data acquisition (DAQ)** of the relevant SN-information, i.e. of the counting rates of all PMTs in 0.5 sec intervals, is done with a dedicated DAQ system for the B10-detector. This system (Biron et al, 1997), which is independent of the main Muon-DAQ, uses custom made SN-counter boards that sample the discriminator output pulses. The SN-counter are FPLA-chip based CAMAC boards; for suppression of PMT afterpulses they are programmed to a deadtime of 10 μsec, applied after each counted pulse. Absolute time synchronisation is given by a GPS clock, interfaced to a CAMAC-GPS latch module. The system is controlled by a Power Macintosh.

For strings 11-13, a new DAQ-system for the permanent acquisition of the PMT counting rates is operating since 1999. It is part of the modernized VME-based main Muon-DAQ, and consists of a set of 200 MHz 20 bit VME Multiscalers SIS3808 (SIS-Struck), modified for afterpulse suppression with a programmable deadtime. These counters are externally strobed by a custom made, GPS-synchronized VME-Clock board. The currently used noise sampling window of 0.5 sec can be reduced to msec-scale, to allow for higher resolution measurement of the SN-onset. In a future upgrade, all AMANDA-B10 PMTs could be read out through that system.

SN-data is fully accessible online for strings 11-13, B10-information is accessed on a weekly basis. The full set of data for each run period (February-November) is shipped back from South Pole only once per year. A subset of data is available remotely via satellite also during the Antarctic winter.

3 Data Analysis:

This analysis is a first pass through the full SN-data set of 1997 AMANDA-B10. A total of 156 effective lifetime days have been analyzed for the time interval March–November 1997. All data were analyzed in terms of fixed 10 sec time intervals, obtained by summing over adjacent 0.5 sec time intervals. We note, that a SN-signal will be asynchronously located with respect to this time scale, thus reducing the signal efficiency.
To find a detector subset that is stable for the whole observation period, we apply a PMT classification as 'good/bad' for every run. The classification is specific to this analysis, it does not neccessarily apply to muon analysis. Then a selection algorithm (Bouchta et al, 1999) removes bad PMTs or runs with many bad PMTs until all remaining runs are with good PMTs only. Rejected runs are due to calibration, transient phenomena and major malfunctioning. We are left with a subset of 170 'good' PMTs (51 PMTs from B4) and 185 runs, corresponding to 107.5 lifetime days.
Average noise rates for PMTs in AMANDA-B4 are found to be $\sim$320 Hz. PMTs on string 5–10 have noise rates of $\sim$1.1 kHz, roughly 3.4 times higher than for strings 1-4. This is shown in fig.1, giving the noise rate, R_i, as function of PMT number for all selected PMTs. Recent laboratory measurements found a ^{40}K contamination of the glass vessel, which is responsible for the additional noise in all 338 PMTs on string 5-13. For the selected set of 170 good PMTs and all good runs within the full operation period of 240 days we observe only a small 2% drift of the summed absolute counting rate, as displayed in fig.2.

The **width of the noise distribution**, σ_N, for all PMTs is clearly above the Poisson expectation $\sigma_{pois} = \sqrt{N_{HIT}}$. For strings 1-4 and 5-10 we find for the ratio $r_{pois} = \sigma_N/\sigma_{pois}$ $\sim$1.6 and $\sim$1.8 respectively. For the selected PMTs, we present in fig.1 σ_N as function of number of hits for 10 sec intervals, N_{HIT}. Note, that for a stable detector it is entirely σ_N that determines the signal-to-noise for a SN-analysis. The two large cluster at N_{HIT} $\sim$3000 and $\sim$11000 correspond to strings 1-4 and strings 5-10. The noise distributions are reasonably described by Gaussian fits.

SN signal search: A SN-signal would show up as a fluctuation in the sum $\sum R_i(t)$ of the counting rates of all PMTs. We consider for every 10 sec time interval t the difference $d_{ma}(t)$ between this sum and the moving average, $S_{ma}(t)$: $d_{ma}(t) = (\sum R_i(t)) - S_{ma}(t)$. The moving average accounts for PMT drifts and uses a

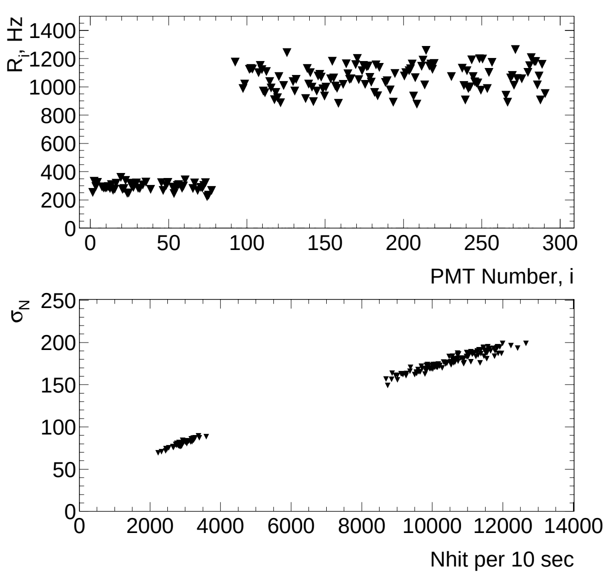

Figure 1: (Upper:) The average noise rate, R_i, for the selected PMTs; Strings 1-4: *i*= 1-80, strings 5-10: *i*= 87-302. (Lower:) Width of the noise hit distribution, σ_N, as function of the average number of hits N_{HIT} in 10 sec intervals.

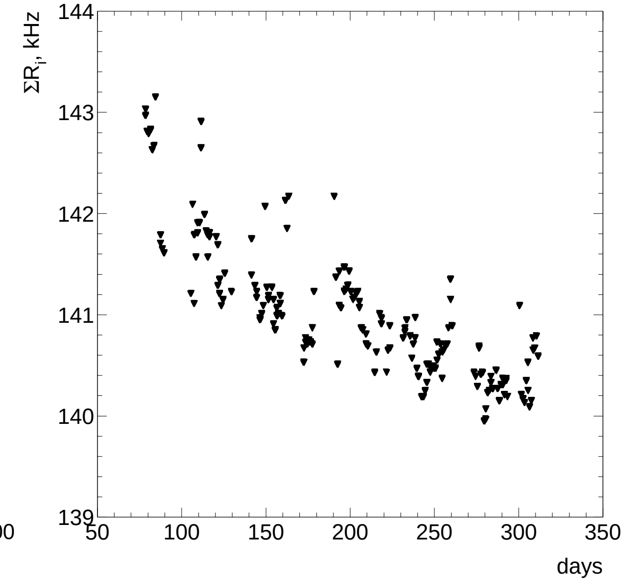

Figure 2: Summed counting rate for all selected PMTs from March-November 1997. The drop is a 2% effect.

centered 250 sec wide window.

To separate potential SN-signal candidates from non-statistical fluctuations, faking signals by e.g. electronic noise in a few PMTs with a large $d_{ma}(t)$, we consider a Maximum-Likelihood approach. The Likelihood $\mathcal{L}$ of the system of n_{pmt} PMTs, each following a Gaussian distribution, is $\mathcal{L} \sim \prod(exp(-(R_i - r_i)^2/2/\sigma_i^2))$, where r_i and σ_i are the average and standard deviation of the noise distribution for PMT *i*. In the case of an external signal applied to all PMTs, the expectation values r_i must be replaced by $\bar{r_i} = r_i + d_{ma}/n_{pmt}$. In the Gaussian limit, the Likelihood can be equivalently replaced by $\chi^2 = \sum((R_i - \bar{r_i})^2/\sigma_i^2)$. The experimental χ^2distribution is compatible with a χ^2 distribution with NDF=51. Figure 3 shows the contour plot for χ^2/NDF versus d_{ma} for AMANDA-B4 for the observation period. A few large χ^2 events are observed, some also at $d_{ma} \geq 2000$ (not shown). They are rejected with a cut $\chi^2/NDF \leq 1.5$ (99.9% signal efficiency).

With this cut applied, the d_{ma} distribution for AMANDA-B4 is shown in fig.4. Arrows indicate the cut values (for 90% detection efficiency) for a SN1987A type event occuring at 6 kpc and 8.5 kpc distance. The cut values assume a SN-neutrino luminosity with a time profile $I(t) = I_0 \cdot exp(-t/\tau)$ with $\tau = 2.5 - 3.5\mathrm{sec}$ and account for the sampling inefficiency. For 107 days in 1997, the detector is background-free for a 6 kpc signal, for 8.5 kpc we observe $\sim$1 event (consistent with noise statistics).

We note, that the experimental results are (apart from the fake events) in agreement with a MC model of the detector with uncorrelated PMTs.

For a 250 PMT array with the same low noise OMs as those used in AMANDA-B4, a conservative prediction yields a fake event rate of $\leq$1 event/year for a distance of $\sim$12 kpc, for 1000 adn 5000 PMTs the limit is 17 kpc and 26 kpc.

The performance of strings 5-10 with respect to a SN-signal search is worse than for AMANDA-B4. The combined signal-to-noise for the selected 119 PMTs is only 65% of that of the 51 B4-PMTs. At this level of analysis, we find non-Gaussian tails in the d_{ma}-distributions, and therefore limit this presentation to B4-data. An upcoming analysis will treat these PMTs separately as well as combined with B4.

To summarize, we

- developed a method to select good quality runs and OMs, yielding a stable detector configuration of 170 out of 302 PMTs over the 9 month observation period for ∼69% of the runs (also confirmed by a dedicated muon analysis by Bouchta et al (1999));
- present the first SN analysis for AMANDA-B, which yields a sensitivity limit for distances of $d_{SN} \sim 8.5$ kpc at fake event rates ∼4 events/year. This is obtained on the basis of a subset of 51 low noise AMANDA-B4 PMTs;
- predict for a detector upgrade to 250 (1000) Optical Modules of AMANDA-B4 type an increase of the sensivity range to $d_{SN} \sim 12\,(17)$ kpc.

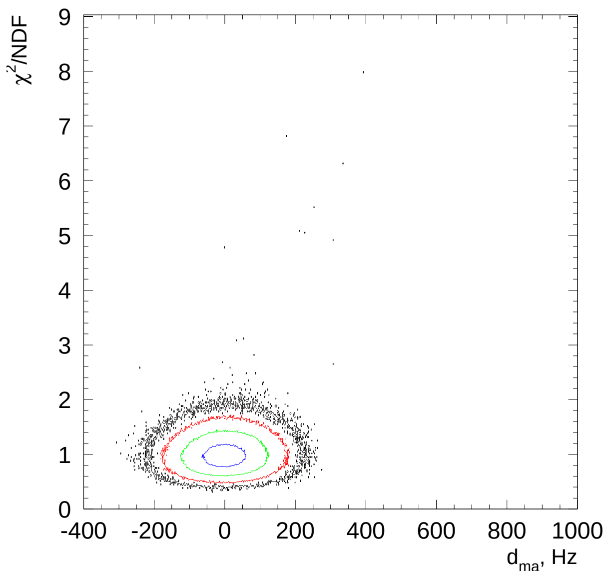

Figure 3: χ^2/NDF versus $d_{ma}(t)$, the deviation of the summed noise rate from the moving average for AMANDA-B4 for 107.5 days. Large χ^2/NDF values indicate fake events.

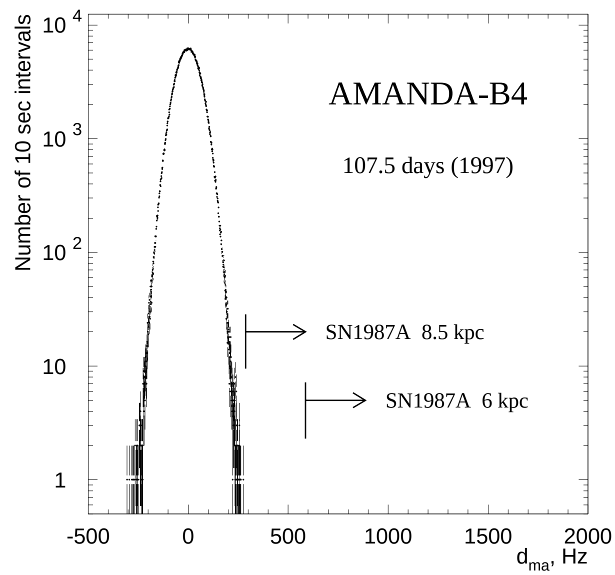

Figure 4: Deviation $d_{ma}(t)$ of the summed noise rate from the moving average for the selected 51 PMTs of AMANDA-B4 and a selected life time of 107.5 days in 1997, with a cut in $\chi^2/NDF \leq 1.5$. Indicated are the cut-values for signals expected for SN1987A-type Supernova at 6 kpc and 8.5 kpc.

References

Andrés, E., et al., submitted to Astrop Phys.; Hill, G., HE.6.3.0.2, these proceedings

Biron, A., et al., Proposal for the AMANDA-II Detector, DESY-PRC 97-05, 1997.

Bouchta, A., et al., HE.3.2.11, these proceedings.

Habig, A., et al, http://hep.bu.edu/∼snnet/

Halzen, F., Jacobsen,J.E. and Zas, E., Phys.Rev.D 29 (1994) 1758

Jacobsen, J.E., PhD Thesis, Univ.Madison, 1996.

Totsuka, Y. and Schramm, D.N., in Neutrino Physics, K.Winter (ed.), Cambridge University Press, 1991

Wischnewski, R. et al., Proc. 24th International Cosmic Ray Conference, Vol.1, 658, Rome 1995.