Possibility that high energy neutrino telescopes could detect supernovae

F. Halzen and J. E. Jacobsen
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

E. Zas
Departamento de Física de Partículas, Universidad de Santiago, E-15706 Santiago de Compostela, Spain
(Received 25 June 1993)

We have simulated the response of a high energy neutrino telescope to the stream of low energy neutrinos produced by a supernova. The nominal threshold of such detectors is in the GeV energy range. The passage of a large flux of MeV neutrinos during a period of seconds will nevertheless be detected as an excess of single counting rates in all individual optical modules. Detectors under construction, which consist of roughly 200 modules, will be able to detect a galactic supernova at or above the 5σ level. The rate of fake signals is, however, too large for the telescope to serve as a neutrino watch. Such capability requires detectors with roughly 3 times the number of optical modules; thus, this will be within easy reach of the next generation detectors.

PACS number(s): 95.55.Vj, 97.60.Bw

The neutrino events detected in the Kamiokande [1] and IMB [2] detectors prior to the optical display of Supernova 1987A represented a most remarkable birth of neutrino astronomy. Some argue, however, that the data have left us with some lingering questions and uncertainties. Most prominent is our inability to understand the time of the possible Mont Blanc detection [3] and the directionality of the IMB events [4]. This underscores the importance of collecting as much information as possible when presented with the rare opportunity of observing the next nearby supernova. We show here that high energy neutrino detectors, presently under construction [5], can observe the neutrino bursts from galactic supernovae even though they have nominal thresholds of GeV energy, i.e., almost three orders of magnitude above the MeV energy of supernova neutrinos.

First generation high energy neutrino telescopes consist of approximately 200 optical modules (OM's) deployed in deep, clear water or ice shielded from cosmic rays [5]. Coincident signals between the OM's detect the Čerenkov light of muons with energy in excess of a few GeV. Also electromagnetic showers initiated by very high energy electron neutrinos are efficiently detected. The idea has been debated for some time [6] whether these instruments have the capability to detect the neutrinos from a supernova despite the fact that they have only MeV energy. The production of copious numbers of positrons of tens of MeV energy in the interaction of $\bar{\nu}_e$ with hydrogen will suddenly yield signals in all OM's for the 10 sec duration of the burst. Clearly such a signal, no matter how weak, will become statistically significant for a sufficient number of OM's. We here perform a complete simulation of the signal and its detection and conclude that the 200 OM's of detectors such as the Deep Underground Muon Detector (DUMAND) and Antarctic Muon and Neutrino Detector Array (AMANDA) are sufficient to establish the occurrence of a neutrino burst in coincidence with the optical display of a supernova. We also show that the same detectors can actually serve as a supernova watch, i.e., a "fake" signal occurs less than once a century, by increasing the number of OM's by a factor of 3. This is much less than the roughly 7000 OM's which are projected for a next-generation detector [7]. Clearly these observations will not provide the quality and range of information obtained by dedicated low-threshold detectors.

We will focus here on the DUMAND and AMANDA detectors. They typify the techniques used by other detectors such as BAIKAL and NESTOR, which are under construction [5].

DUMAND is positioned under 4.5 km of ocean water, below most biological activity and well shielded from cosmic ray muon backgrounds. One nuisance of the ocean is the background light resulting from radioactive decays, mostly ^{40}K, plus some bioluminescence, yielding an OM noise rate of 50–100 kHz. On the other hand, deep ocean water is very clear, with an attenuation length of order 40 m in the blue. The deep ocean is stable, quiet, and completely shielded from electromagnetic interference.

AMANDA is operating in deep clear bubble-free ice. The ice provides a convenient mechanical support for the detector. The immediate advantage is that all electronics can be positioned at the surface. Only the optical modules are deployed into the deep ice. Polar ice is a sterile medium with a concentration of radioactive elements reduced by more than 10^{-4} compared to sea or lake water. The low background results in an improved sensitivity which allows for the detection of high energy muons with very simple trigger schemes, which are implemented by off-the-shelf electronics. Being positioned under only 1 km of ice it is operating in a cosmic ray muon background which is over 100 times larger than the one for DUMAND. The challenge is to reject the down-going muon background relative to the up-coming neutrino-induced muon signal by a factor larger than 10^6.

Although aspects of the observations of SN 1987A left some lingering doubts about supernova models [3,4], they remarkably confirmed the established ideas for the supernova mechanisms [8]. At collapse the core is expected to release energy in a prompt ν_e burst lasting a few

0556-2821/94/49(4)/1758(4)/$06.00

milliseconds. Most of the energy is, however, liberated after deleptonization in a burst lasting about ten seconds. Roughly equal energies are carried by each neutrino species. The time scale corresponds to the thermalization of the neutrinosphere and its diffusion within the dense core [9].

Since the $\bar{\nu}_e$ cross section [10] for the inverse β decay reaction on protons in the detector exceeds the characteristic cross sections for the other neutrino flavors, $\bar{\nu}_e$ events dominate by a large factor after including detection efficiency. In this reaction, free protons absorb the antineutrino to produce a neutron and a positron which is approximately isotropically emitted with an energy close to that of the initial neutrino. For the purpose of this paper we use typical parameters, derived from SN 1987 observations, which are consistent with those previously estimated in supernova models. From the energy distributions of the observed events the average temperature of the neutrino sphere in SN 1987A was deduced to be 4.0 MeV [8].

Before discussing our detailed Monte Carlo simulation, we present a back-of-the-envelope derivation of our final result. After convoluting the 4 MeV thermal Fermi distribution of the neutrinos with a detection cross section rising with the square of the neutrino energy, one obtains an event distribution peaked in the vicinity of 20 MeV. The track length of a 20 MeV positron in ice is roughly 12 centimeters and therefore over 3000 Čerenkov photons are produced. This number, combined with a typical quantum efficiency of 25%, leaves 800 detected photons in each event. We assume that these photons are emitted uniformly over an average solid angle Ω, which represents a convolution of the Čerenkov cone and a random particle track. This is an adequate approximation since multiple scattering bends the positron tracks thus spreading the emitted photons over an angle comparable to the Čerenkov angle. In the end the value of Ω will actually drop out of our approximate calculation.

We can therefore approximate the positron as a point source (order 10 cm over a detection radius which is expected to be of order meters) emitting photons uniformly in a solid angle comparable to the Čerenkov angle. The detection probability becomes a simple function of both the module collection area A_M and the distance to the positron shower R:

$$P(R) = 1 - e^{-800\ A_M \cos\theta / \pi\ R^2}, \tag{1}$$

where θ is the relative angle between the axis of the OM and the position vector of the neutrino event. When R is less than R_d ($\simeq \sqrt{250\ A_M \cos\theta}$) the OM is likely to trigger on the positron while for larger R the probability falls off rapidly. We next calculate an effective volume $V_{\rm eff}$ associated with each OM by integrating the probability function over volume:

$$V_{\rm eff} \sim \frac{\Omega}{4\pi} 2\pi \int_0^{R_{\rm att}} P(R) R^2 dR d(\cos\theta). \tag{2}$$

The first factor corresponds to the probability that the arbitrarily oriented solid angle points in the direction of the OM. We conservatively assume that the OM has 2π acceptance and integrate up to the attenuation length $R_{\rm att}$ of the medium which is ultimately responsible for limiting the effective detection volume $V_{\rm eff}$. The integration can be performed analytically by approximating $P(R)$ as

$$P(R) = \begin{cases} \frac{800\ A_M \cos(\theta)}{\Omega\ R^2} & \text{for } R > R_d, \\ 1 & \text{for } R < R_d. \end{cases} \tag{3}$$

The largest contribution to $V_{\rm eff}$ comes from large R where the approximation is adequate. Keeping only the $R > R_d$ part of the integral we obtain, after angular integration,

$$\begin{aligned} V_{\rm eff} &\sim \frac{1}{4} \int_{R_d}^{R_{\rm att}} 800 A_M dR \\ &\sim 200 A_M (R_{\rm att} - R_d). \end{aligned} \tag{4}$$

It is interesting to note that the effective volume is proportional to both the collection area of the OM and the attenuation length and, as previously stated, it is quite insensitive to the solid angle over which the Čerenkov photons are distributed (Ω). For OM's such as those used in the AMANDA detector with a collecting area $A_M = 0.028$ m^2 and for an attenuation length $R_{\rm att} =$ 25 m typical of ice [11], we obtain $V_{\rm eff} \sim 130$ m^3. This result can be used to rescale SN 1987 observations to a supernova at a distance $d_{\rm kpc}$. From 11 events observed in the 2.14 kton Kamiokande detector we predict

$$N_{\rm events} \sim 11\ N_M \left[\frac{\rho\ V_{\rm eff}}{2.14\ \text{kton}}\right] \left[\frac{52\ \text{kpc}}{d_{\rm kpc}}\right]^2 \tag{5}$$

for a detector with N_M optical modules. For a 130 m^3 effective volume of each of the 200 OM's we obtain 5300 events.

We now require a meaningful detection of this signal in the presence of the continuous background counting rate of all phototubes. Over the 10 s duration of the delayed neutrino burst from a supernova, the rms fluctuations of the combined noise from all the OM's is

$$\sigma_{\rm 1pe} = \sqrt{10\ \nu_{\rm 1pe}\ N_M}, \tag{6}$$

where the background counting rate in each module at the 1 photoelectron level is represented by $\nu_{\rm 1pe}$. The probability that the noise in the OM's fakes a supernova signal can be estimated assuming Poisson statistics. The expected rate of supernova explosions in our Galaxy is about 2×10^{-2} yr^{-1}. If the detector is to perform a supernova watch we must require that the frequency of fake signals is well below this rate. The signal should therefore exceed $n_\sigma \geq 6$ which corresponds to a probability of 9.9×10^{-10}. The corresponding number of 10 s intervals indeed exceeds a century. Clearly the requirement can be relaxed if we just demand that the detector can make a measurement in the presence of independent confirmation. For an average noise rate of 1 kHz, a typical value for the OM's in AMANDA, the rms fluctuation of the 2 million hits expected in an interval of 10 s is 1400. This implies that detection of a galactic supernova is near the 4σ level for the 200 module configuration, while detection should not represent a problem for the next generation detector which consists of 7000 OM's. Since the signal in the present detector is marginal, it is necessary to do a more realistic calculation of the event rate. We will conclude that our rough estimate is somewhat conservative.

Background noise in the modules clearly plays a critical role so that low noise environments such as ice have an intrinsic advantage. Signal to noise is proportional to the ratio $V_{\text{eff}}/\sqrt{\nu}$. Obviously, increased attenuation length in the medium and larger effective area of the OM results in an enhanced effective volume. Considering parameters appropriate for DUMAND, an attenuation length of 40 m in water and OM's with double diameter, we expect a factor of 10 increase in effective volume per optical module. This should readily compensate for a noise rate higher by a factor of 100. This would imply that DUMAND and AMANDA have comparable sensitivity as supernova detectors. It has unfortunately been shown that bioluminescence in a deep ocean detector is the origin of backgrounds with seconds of duration which make the observation of supernova difficult. The background problems can be overcome, however, by reconfiguring the detector [6].

For a complete calculation we have combined a detailed electromagnetic shower Monte Carlo, initially developed to evaluate the radio emission by cascades in ice [12], with the AMANDA Monte Carlo simulation. The shower Monte Carlo program is a fast three-dimensional routine which simulates the dominant low energy processes: Møller, Bhabha, and Compton scattering as well as electron-positron annihilation, continuous energy loss, and multiple elastic scattering, as well as the bremsstrahlung and pair production processes which dominate at high energy. We added the capability to simulate the emission of Čerenkov photons by cascade particles. Our event file consists of over 10 000 events sampled from a 4 MeV temperature Fermi-Dirac neutrino distribution weighted by a cross section rising with the square of the neutrino energy. Photon detection is simulated using the AMANDA Monte Carlo simulation to correctly account for the effects of attenuation in deep polar ice, optical module efficiency as a function of photon wavelength and detector geometry [13].

The final result can be quoted as an effective volume for the entire detector of 23 000 m^3 $\pm$ 2 000 for the first stage AMANDA configuration of 10 strings arranged in a nine 30 m side polygon with one at the center. Each string has 20 modules spaced at 10 m intervals [14]. We therefore obtain an effective volume of 115 m^3 per module, close to our crude estimate. Single OM's have a lower threshold than the Kamiokande and IMB experiments which reconstruct Čerenkov cones. This is taken into account by correction factors multiplying the event rates to be entered in Eq. (3), which we evaluated to be 1.4 (5.4) for Kamiokande (IMB). We thus obtain 7700 (9070) events in the 200 modules of the 9+1 configuration of AMANDA. A trigger could be implemented by monitoring the sum of all singles rates in ~ 1 s intervals, and requiring positive fluctuations in this sum for several such intervals.

At the 2 pe level we obtain an effective volume of 5 900 m^3 $\pm$ 1 400. If the OM's noise rate is reduced by over a factor 16, signal-to-noise will actually be improved by working at the 2 pe level. Triggering at the 2 pe level is likely to be impractical in the present experiments.

Typical noise rates for AMANDA modules imply that $\sigma_{1\text{pe}} \sim 1400$. The calculated event rates for a supernova bursts in the center of the galaxy therefore correspond to a 5.4 (6.4) sigma effect when rescaling the observed signals from SN 1987A at Kamiokande (IMB). This should provide a sufficiently clean signal. We can combine Eqs. (2) and (3), including the correction factor, to obtain the expected signal

$$n_\sigma = 0.35\sqrt{N_M}\left[\frac{10^2}{\sqrt{10\nu_{1\text{pe}}}}\right]\left[\frac{V_{\text{eff}}}{125\ \text{m}^3}\right]\left[\frac{8\ \text{kpc}}{d_{\text{kpc}}}\right]^2 . \tag{7}$$

Here we scaled to the Kamiokande event number. The constant is 0.42 for IMB. The results are encouraging since an AMANDA supernova watch can be performed at the 6 σ level with only 340 (240) optical modules according to Kamiokande (IMB) observations of SN 1987A. A next-generation detector with over 7 000 modules should provide a sharp signal for a supernova at the galactic center and should operate as a supernova watch to twice the distance to the galactic center, i.e., covering all the galactic disk.

We end with a warning about the statistics. Clearly in a realistic analysis penalty factors will be associated with various trials made to identify a burst. This will, however, not alter our positive conclusions. A modest increase the number of OM's can absorb the effect of a large number of trials, e.g., associated with a sliding window to identify the 10 s burst.

We are grateful to J. Hauptman, R. Morse, and J. Learned for helpful discussions. This work was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881, in part by the Texas National Research Laboratory Commission under Grant No. RGFY93-221, and in part by the "Comité Conjunto Hispano-Norteamericano" and CICYT.

[1] K. Hirata *et al.*, Phys. Rev. Lett. **58**, 1490 (1987); Phys. Rev. D **38**, 448 (1988).

[2] R.M. Bionta, G. Blewitt, C.B. Bratton, and D. Casper, Phys. Rev. Lett. **58**, 1494 (1987).

[3] M. Aglietta *et al.*, Phys. Rev. Lett. **58**, 1490 (1987); Europhys. Lett. **319**, 136 (1987).

[4] C.B. Bratton *et al.*, Phys. Rev. D **37**, 3361 (1988).

[5] J.G. Learned, in *Proceedings of the 13th European Cosmic Ray Symposium*, Geneva, Switzerland, 1992, edited by B. Patterson and P. Grieder (CERN, Geneva, 1992),

and references therein.
[6] C. Pryor, C.E. Roos, and M.S. Webster, Astrophys. J. **329**, 335 (1988).
[7] F. Halzen and J.G. Learned, in *Proceeding of the Fifth International Symposium on Neutrino Telescopes*, Venice, Italy, 1993, edited by M. Baldo-Ceolin (INFN, University of Padua, Padua, 1993).
[8] H.A. Bethe, Rev. Mod. Phys. **62**, 801 (1990).
[9] A. Burrows, Annu. Rev. Nucl. Part. Sci. **40**, 181 (1990).
[10] D.N. Schramm, Comments Nucl. Part. Phys. **17**, 239 (1987).
[11] T. Miller *et al.*, *in Proceedings of the 23rd International Cosmic Ray Conference*, Calgary, Canada, 1993, edited by D. A. Leahy (University of Calgary, Calgary, 1993).
[12] E. Zas, F. Halzen, and T. Stanev, Phys. Rev. D **45**, 362 (1992).
[13] S. Tilav *et al.*, in *Proceedings of the 23rd International Cosmic Ray Conference* [11].
[14] D.M. Lowder *et al.*, in *Proceedings of the 23rd International Cosmic Ray Conference* [11].