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A Simple Model for Neutrino Cooling of the Large Magellanic Cloud Supernova

D. N. SPERGEL, T. PIRAN, A. LOEB,* J. GOODMAN, J. N. BAHCALL

A simplified analytic model of a cooling hot neutron star, motivated by detailed computer calculations, describes well the neutrinos detected from the recent supernova in the Large Magellanic Cloud. The observations do not require explanations that invoke exotic physics or complicated astrophysics. The parameters in this simple model are not severely constrained: $6.1^{+3.5}_{-3.6} \times 10^{52}$ ergs emitted in electron antineutrinos, a peak temperature of $4.2^{+1.2}_{-0.8}$ megaelectron volts, a radius of 27^{+17}_{-15} kilometers, and a cooling time of $4.5^{+1.7}_{-2.0}$ seconds.

THE DETECTION OF NEUTRINOS from the Large Magellanic Cloud (LMC) supernova (SN1987a) by the Kamiokande II (*1*) and the Irvine-Michigan-Brookhaven (IMB) (*2*) detectors was an epochal event in astronomy and physics. Most of the energy of the recent LMC supernova was emitted in neutrinos, a confirmation of the standard picture of core collapse (*3, 4*).

The physics of the explosion was complicated and requires detailed models for a correct description. However, the success of the simplified model described here suggests that the data from the LMC supernova are too sparse to discriminate among more sophisticated models or to justify inventing exotic new physics. In order to test in more detail our understanding of stellar collapse, we must await detection of a galactic core collapse [~50 times as many events expected at a rate of order one collapse event every 8 years (*5*)] or the availability of much larger detectors to observe stellar collapses in other galaxies.

The fluences and temperatures inferred from the neutrino observations were consistent with pre-supernova expectations (*6, 7*). However, there is one unexpected feature of the LMC supernova neutrino data: the 7.3-second gap between the first eight and last three events in the Kamiokande II data. The Kamiokande II detector observed eight events in the first 1.9 seconds, followed by a quiet period of 7.3 seconds, and then three events were detected within 3.2 seconds. The IMB detector observed six events in the first 2.7 seconds, followed by a quiet period of 2.4 seconds, and then two events were detected within 0.6 second. Many investigators have claimed that exotic new physics or complicated astrophysics is required to understand the arrival times of the neutrinos (*8–10*). Figure 1 shows that the average energy of an event appears to decline with time and shows the agreement of the data with a cooling blackbody model. We show that a cooling hot neutron star model fits well all the observed data and provides an estimate of the radius of the hot neutron star. We focus on this simple model to show that it is not necessary to invent new physics to explain the observation; the observations can be fit by a simple model motivated by detailed calculations performed before the occurrence of SN1987a.

We combine the IMB and Kamiokande data sets with the assumption that the first neutrino in IMB arrived at the same time as the first neutrino observed by Kamiokande; the offset time is not known precisely. Given the observed rates, the expected time lag is ≈0.25 second. Our conclusions do not change if we include a time lag of this order. We also neglect neutrino scattering events. Bahcall *et al.* (*6*) considered the angular distribution and concluded that zero to three of the first Kamiokande events (2% significance) and zero to two of the IMB events (5% significance) may have been the result of scattering; the inclusion of scattering did not alter the estimates of neutrino temperature and would not change any of the conclusions of this report. These significance levels represent the fraction of Monte Carlo simulations of the angular distribution of events that have a larger Kolmogorov-Smirnov (KS) measure than the observations.

The temporal structure of the combined data can be fitted by an exponentially decaying flux $F \propto \exp[-(\ln 2)t/t_{1/2}]$, where $t_{1/2} = 2^{+0.9}_{-0.8}$ seconds is the decay constant (see Fig. 2). (All numbers in this report are quoted with 95% confidence limits.) Monte Carlo simulations of data drawn from this function show that a worse fit for the KS measure would be obtained in 10% of the cases. The exponential decay is not unique, and other functional forms {such as $F \propto \exp[-(t/\tau)^{1/2}]$ with the first half of the events arriving in the first $t_{1/2} = 2.8\tau = 1.4^{+0.8}_{-0.5}$ seconds} can provide even better fits to the data (see Fig. 2). Although these functions fit the observed temporal structure, they do not explain the apparent relation between time of arrival and average energy of the events.

When the core of a massive star can no longer support itself, it collapses rapidly on a dynamical time scale of milliseconds. When the density in the core reaches nuclear densities, nuclear pressure stops the collapse, and in this core bounce the gravitational binding energy is converted into thermal energy.

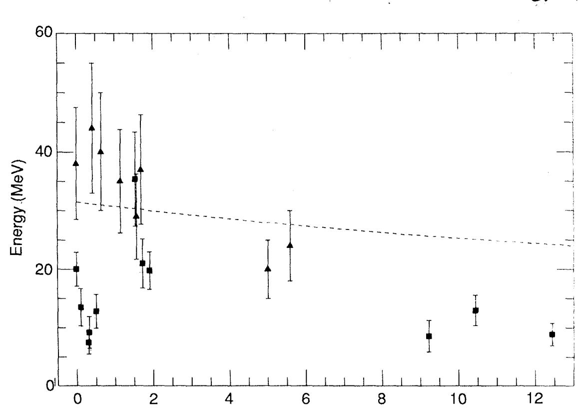

Fig. 1. Energy of the observed neutrino events in Kamiokande II (▲) and IMB (■) as function of time of arrival. The dashed line shows the expected average energy of an event in IMB based on the cooling blackbody model with $T_0 = 4.2$ MeV and $\tau = 4.5$ seconds. The dotted line shows the expected average energy of an event in Kamiokande. [Data and error bars from (*1, 2*).]

D. N. Spergel, A. Loeb, J. Goodman, J. N. Bahcall, Institute for Advanced Study, Princeton, NJ 08540.
T. Piran, Institute for Advanced Study, Princeton, NJ 08540, and Racah Institute for Physics, Hebrew University, Jerusalem, Israel.

*Permanent address: Soreq Nuclear Research Center, Yavne, Israel.

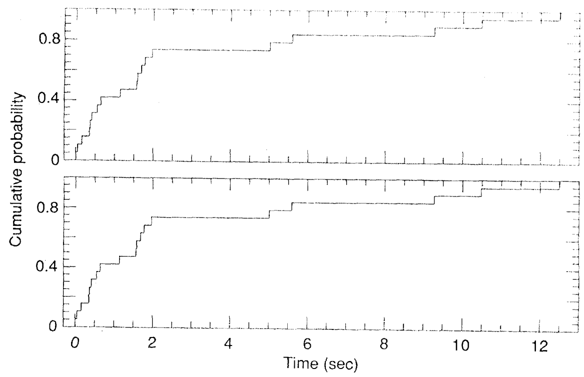

Fig. 2. Observed and fitted cumulative probability of time of arrival in the combined data. The solid line shows the cumulative number of events detected before a given time. (**Top**) Dotted line is fitted probability for $F \propto \exp[-(t/\tau)^{1/2}]$ with $\tau = 0.5$ second and $T_{1/2} = 1.4$ seconds. (**Bottom**) Dotted line is fitted probability for $F \propto \exp(-t/\tau)$ with $\tau = 2.9$ seconds and $T_{1/2} = 2$ seconds. Half of the events are expected to arrive before $T_{1/2}$ in each model.

The hot neutron star is so dense that it can cool only by neutrino emission. The densities achieved during core collapse are so large that the core is no longer transparent to neutrinos (*11*) and the characteristic antineutrino emission time is not the collapse time of milliseconds but rather the neutron diffusion time (seconds). Detailed calculations of neutrino transport before the supernova (*4*) out of the cooling hot neutron star suggest that the bulk of the energy is emitted in all flavors of neutrinos over several seconds. Because of this long cooling time, theories that evoke several neutrino mass eigenstates to explain the observed time structure (*10*) are unnecessary.

Motivated by detailed calculations in the literature, we have fitted the observed energy-time data pairs (E_i, t_i) to a phenomenological model where the neutrino source is a blackbody ($F \propto T^3$) with an exponentially decaying temperature: $T = T_0 \exp(-t/4\tau)$. (The energy density at the surface is proportional to T^4, thus τ is the cooling time scale for the hot neutron star.) Since the neutrino optical depth in the supernova is large and the density drops by several orders of magnitude at its surface, the neutrino spectrum is nearly thermal. Although multigroup diffusion calculations (*4*) suggest that the high energy tail is nonthermal, the data are too sparse to reveal the nonthermal character of the spectrum: they can be fit by a single temperature (*6*). Following Bahcall *et al.* (*6*), we simulate the detector response to a thermal electron antineutrino ($\bar{\nu}_e$) flux including the energy dependence of the absorption cross section ($\sigma \propto E^2$), the uncertainties in estimating the energy of the events, and the energy-dependent efficiencies of the different detectors. The assumption of an exponential functional form for the cooling function is not essential; other decreasing functions of time would also be suitable. The likelihood function is maximized at $T_0 = 4.2$ MeV and $\tau = 4.6$ seconds. The total number of observed events corresponds, with these parameters, to an initial flux of $0.23 \times 10^{10}\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ and a total fluence of $1.3 \times 10^{10}\ \bar{\nu}_e\ \mathrm{cm}^{-2}$. We use the multidimensional KS test (*12*) to estimate the significance of this fit. The two-dimensional KS measure is the maximum difference between the observed and the expected fraction of events in each of the four quadrants: $(E < E_i, t < t_i)$, $(E > E_i, t < t_i)$, $(E < E_i, t > t_i)$ and $(E > E_i, t > t_i)$ where i ranges over all the observed events. With the above parameters the two-dimensional KS measure is 0.21. Using a Monte Carlo code, we simulate synthetic data and estimate the maximum likelihood parameters for it and their two-dimensional KS measure. The observed KS measure is better than 55% of the cases obtained from the synthetic data. At 95% confidence level we obtain the following: $T_0 = 4.2^{+1.2}_{-0.8}$ MeV, $\tau = 4.5^{+1.7}_{-2.0}$ seconds and $F_0 T_0^2 = 4.0^{+2.4}_{-2.0} \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{MeV}^2\ \mathrm{sec}^{-1}$ where F_0 is the initial neutrino flux. Because of the strong correlation of the estimated flux with temperature, we have quoted $F_0 T_0^2$. For a larger effective volume for IMB (6500×10^3 metric tons) (*13*), the 95% confidence temperature range drops to $4.1^{+1.1}_{-0.7}$ MeV and the flux and time scale ranges do not change significantly. The fit obtained for this larger volume is better than 63% of the cases obtained from synthetic data. The Kamiokande data alone yield a peak temperature of $2.9^{+1.3}_{-0.5}$ MeV, and the IMB data alone yield a peak temperature of $4.9^{+4.2}_{-1.9}$ MeV.

Both the cross section, σ, and the energy-dependent detector efficiencies influence the event rate in the detectors. Thus, the event rate is proportional to T^{η} with $\eta \approx 5$ to 8 in the temperature range considered. The characteristic decay time of the event rate is $4\tau/\eta$ and we expect that half of the events will arrive in the first 2.0 seconds (see Fig. 3). Since the event rate drops much faster than the temperature, Bahcall *et al.* (*6*) were justified in fitting one temperature to the early events.

The luminosity (in electron antineutrinos) of a blackbody of radius R can be equated to the product of the detected flux, F, and the average energy of a neutrino, $3.15T$,

$$L_{\bar{\nu}_e} = \frac{7\pi}{4}\sigma_B T^4 R^2 = 4\pi D^2 F(3.15T) \quad (1)$$

where D is the distance to the LMC and σ_B is the Stefan-Boltzmann constant. This yields an estimate of the radius (in kilometers) of the cooling neutron star,

$$R = 27^{+17}_{-15} D_{50} \quad (2)$$

where $D_{50} \equiv D/(50\ \mathrm{kpc})$. The smaller values for the radius correspond to the higher temperatures, whereas the larger values correspond to the lower temperatures obtained from the simulated data. This neutrinosphere radius will decrease as the neutron star cools.

The total energy emitted by the hot neutron star (in ergs), is

$$\int L_\nu\, dt = N_\nu F_0(3.15T_0)(4\pi D^2)\tau = 6.1^{+3.5}_{-3.6} \times 10^{52} N_\nu D_{50}^2 \quad (3)$$

where N_ν is the ratio of energy emitted in all neutrino species to the energy emitted in electron antineutrinos and L_ν is the luminosity (in all neutrino species). The estimate of the energy emitted is very uncertain due to the small number of events. This estimate is consistent with that obtained by other groups (*7*). The need to estimate N_ν exacer-

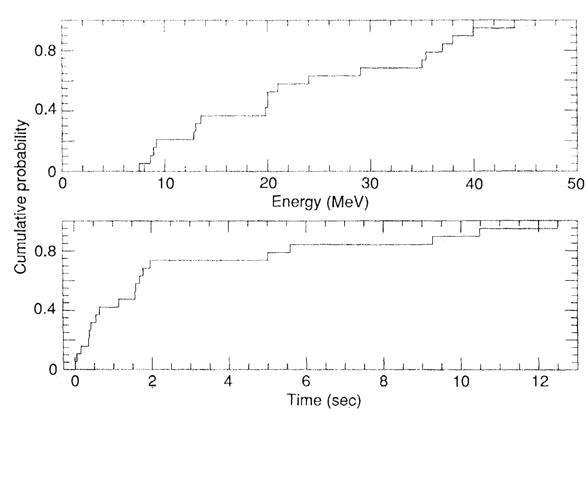

Fig. 3. (**Top**) Solid line shows the cumulative number of events detected in both detectors below a given energy. The dotted line shows the expected cumulative distribution calculated for a model with $T_0 = 4.2$ MeV and $\tau = 4.5$ seconds. (**Bottom**) Solid line shows the cumulative number of events detected before a given time. The dotted line shows the expected cumulative distribution for the same model.

bates the uncertainties in the total luminosity. Several investigators have suggested that since N_ν is expected to exceed 6, the observations are consistent only with very hard equations of state or with the formation of a black hole (*9*). These researchers have not included the uncertainties in the energy arising from small number statistics. Equation 3 shows that even if we assumed $N_\nu = 8$, the total energy emitted would still be consistent with the binding energy of a $1.4M_\odot$ neutron star (where $M_\odot$ is the solar mass) and a wide range of equations of state (*14*).

The success of this simplified model implies that it will be difficult to use the observed neutrino flux to confirm more detailed models. The supernova has confirmed the general picture of core collapse; however, it has not provided sufficient data to discriminate between equations of state or to validate specific detailed models. There is no need to evoke new particle physics or complicated astrophysical scenarios to explain the observed data. When a supernova is observed in our own galaxy, the detectors should record many hundreds of events and neutrino spectroscopy may then reveal surprises about stellar collapses and weak interaction physics.

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Differential Expression of c-*myb* mRNA in Murine B Lymphomas by a Block to Transcription Elongation

TIMOTHY P. BENDER, CRAIG B. THOMPSON, W. MICHAEL KUEHL

Expression of c-*myb* proto-oncogene messenger RNA (mRNA) and protein has been detected principally in tumors and in normal tissue of hematopoietic origin. In each hematopoietic lineage examined, expression of the c-*myb* gene is markedly downregulated during hematopoietic maturation. However, the mechanism by which differential expression of the c-*myb* gene is regulated is not known. In murine B-lymphoid tumor cell lines, the amount of steady-state c-*myb* mRNA is 10 to more than 100 times greater in pre-B cell lymphomas than in B cell lymphomas and plasmacytomas. The downregulation of c-*myb* mRNA correlates with events at the pre-B cell–B cell junction. Differential expression of c-*myb* mRNA levels detected between a pre-B cell lymphoma and a mature B cell lymphoma is now shown to be mediated by a block to transcription elongation in the first intron of the c-*myb* locus. In addition, this developmentally regulated difference in transcriptional activity is correlated with alterations in higher order chromatin structure as reflected by changes in the patterns of hypersensitivity to deoxyribonuclease I at the 5′ end of the c-*myb* transcription unit. Regulation of transcription elongation may provide a more sensitive mechanism for rapidly increasing and decreasing mRNA levels in response to external stimuli than regulation of the initiation of transcription.

THE C-*myb* PROTO-ONCOGENE, which encodes a nuclear DNA binding protein (*1*), is the normal cellular homolog of the transforming gene of avian myeloblastosis virus (*2*). Although its normal function is unknown, the c-*myb* gene is expressed predominantly at immature stages of development in the hematopoietic system (*3*). Levels of c-*myb* messenger RNA (mRNA) are markedly decreased during chemically induced differentiation of several hematopoietic tumor cell lines (*4*). Steady-state levels of c-*myb* mRNA in murine pre-B cell lymphomas are 10 to more than 100 times greater than those in B cell lymphomas and plasmacytomas, and the difference correlates with events at the pre-B cell–B cell junction (*5*). The steady-state level of c-*myb* mRNA in the pre-B cell lymphoma line 70Z/3B is 10 to 20 times greater than that expressed by the mature B cell lymphoma A20.2J (Fig. 1A) (*6*).

To examine the possibility that differences in steady-state levels of c-*myb* mRNA expression are due to differences in message stability, we measured the half-life of c-*myb* mRNA in these two cell lines after inhibition of RNA synthesis by actinomycin D. We found that the stability of c-*myb* mRNA does not differ significantly between these two cell lines (Fig. 1B). From this experiment, we estimate the half-life of c-*myb* mRNA to be approximately 3 hours in each cell line. For comparison, we determined the half-life of histone protein 2B mRNA to be approximately 30 minutes in each cell line, in good agreement with previously reported estimates (*7*). Thus, the 10- to 20-fold difference in c-*myb* mRNA expression between the 70Z/3B pre-B cell lymphoma and the A20.2J B cell lymphoma is not due to differences in c-*myb* mRNA stability.

To investigate the possibility that the difference in c-*myb* mRNA expression in these two lines is transcriptionally regulated, we used a nuclear run-on assay. When a plasmid containing a 2.4-kb murine c-*myb*

T. P. Bender and W. M. Kuehl, National Cancer Institute/Navy Medical Oncology Branch, Naval Hospital, Bethesda, MD 20814.
C. B. Thompson, Howard Hughes Medical Institute, University of Michigan, Ann Arbor, MI 48109.