SN1987a: CALCULATIONS VERSUS OBSERVATIONS

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In this report the results of old calculations (Mayle 1985; Woosley, Wilson, Mayle 1986; Mayle, Wilson, Schramm 1987) of collapse driven explosions and new calculations of the Kelvin-Helmholtz proto-neutron star cooling will be compared with the neutrino observations of supernova 1987a. The calculations are performed by a modern version of the computer model of Bowers and Wilson 1982. (See Mayle 1985 for more recent improvements).

First we give the results of the old calculations. In the collapse, bounce and cooling of the central iron core of a massive star, about 0.1% of the binding energy of the eventual neutron star is emitted in a short deleptonization burst as the bounce shock passes through the photosphere; 5% is emitted in the total deleptonization process; and 95% is released as thermal emission in all neutrino species. In a survey of a wide range of stellar masses, stars in the range 20 to 30 $M_\odot$ are found to have the most energetic antineutrino spectra ($<\epsilon_{\bar{\nu}_e}> \sim 15$ MeV). In calculations where black holes were formed (Woosley, Wilson, Mayle 1986 and Wilson 1971) very little neutrino emission was found associated with black hole formation. The neutrinos associated with BH formation also have low energies. The time history of the neutrino pulse is sensitive to the explosion mechanism. If the mechanism is a prompt exiting through the star of the bounce shock wave, the pulse has a high peak as the shock wave passes near the photosphere. It falls rapidly for the next first few tenths of a second and then declines slowly over several seconds to effectively zero. If no prompt explosion occurs then the shock becomes an accretion shock and matter continues to fall onto the proto-neutron star keeping up the luminosity. After the late time mechanism ejects the envelope the luminosity drops several fold to the luminosity associated with the bare proto-neutron star. During the accretion phase the average antineutrino energy is about 10 MeV while during the cooling phase the energy rises to about 15 MeV.

We have made three new calculations following the cooling of proto-neutron stars until the luminosity fell below an observable level. In the first model a soft equation of state (EOS) was used (gravitational critical mass 1.50 $M_\odot$). The proto-neutron star was selected by taking a post bounce calculation of the core of a 25 $M_\odot$ star and removing all the mass but for the inner 1.64 $M_\odot$. The second model was made with a stiffer EOS using the same core as the first model. The third model was made by

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following the collapse of a 15 $M_\odot$ model of Woosley that had a 1.27 $M_\odot$ iron core. This model gave a prompt explosion with an energy of 3×10^{50} ergs. In Figure 1 we see the energy emitted in antineutrinos versus time for these three models. We note that only the high mass soft EOS model can sustain an appreciable luminosity for the

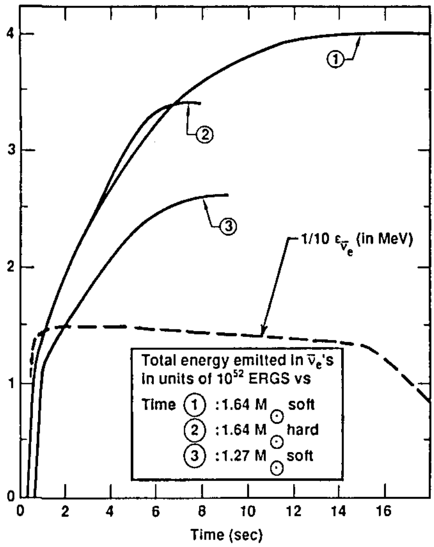

Figure 1. Cooling curves for the three models studied. Also shown is the average antineutrino energy for the 1.64 $M_\odot$ core evolved with the soft equation of state.

12 seconds needed to explain the observations (Hirato et al. 1987 and Bionta et al. 1987). The antineutrino energy peaks a few tenths of a second after bounce and only falls slightly until the neutron star has almost stopped emitting neutrinos. At the photosphere the antineutrino energy is always rising except near the very end. The red shift at the photosphere is 1.30 for the 1.64 $M_\odot$ soft EOS model at the end of the calculation. The mean energy of the antineutrinos is considerably greater than 3.15 times the matter temperature at the photosphere at late times because the antineutrinos exchange energy with matter principly through electron scattering since the density of protons near the photo is quite low. In Figures 2a, b the time integrated number spectrum for the 1.64 $M_\odot$ soft EOS model is given along with the spectra multiplied by the detector responses, Q, and the capture cross section for antineutrinos, σ. We see that our expected energy for Kamiokande is somewhat high and for IMB it is somewhat low. Statistical studies by the Kolmogorov-Smirnov method show that our spectra can account for both the Kamiokande and IMB results with good confidence.

Table 1 gives a summary of results of the three model calculation and Table 2 gives the expected observational results from our models. We estimate the neutron

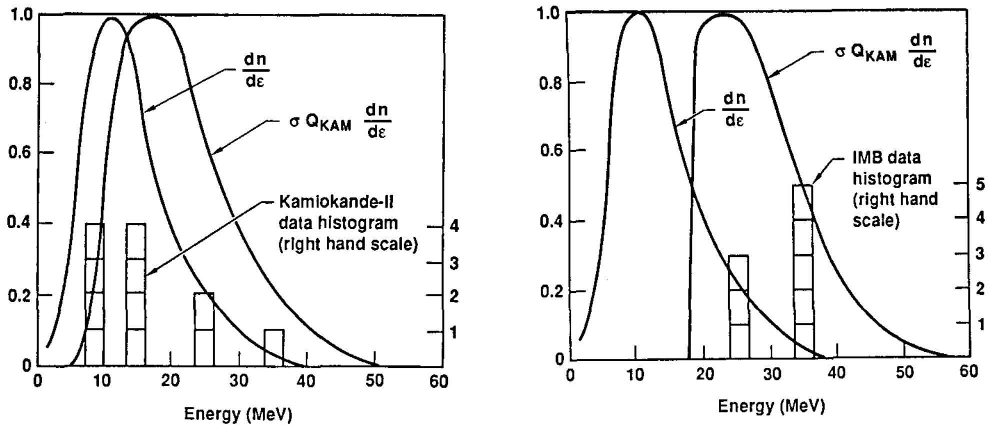

Figure 2a, b. Antineutrino number distribution function for the 1.64 $M_\odot$ core evolved with the soft EOS. The maximum is normalized to unity, as only the shape of the curve is being considered. Also shown is the shape of the expected positron number spectrum that would be produced by electron antineutrino capture on protons taking into account detector characterestics.

$M/M_\odot$	EOS	ρ_c (10^{15} g/cc)	r (km)	Time (sec) $L \geq 5\times10^{51}$ erg/sec	B.E. at end of calculation (10^{53} erg)	Total B.E. (10^{53} erg)	ε_{ν_e} (MeV)	$\varepsilon_{\bar{\nu}_e}$ (MeV)	ε_μ (MeV)	% B.E. in ν_e's	% B.E. in $\bar{\nu}_e$'s	% B.E. in $\nu_{\mu,\tau}$'s
1.27	Soft	1.3	10.7	7.7	1.65	2.3	10.5	13.9	23.5	15	17	68
1.64	Hard	0.74	20.0	6.5	2.17	2.7	7.2	12.0	18.4	15	16	69
1.64	Soft	1.5	9.8	13.2	3.08	4.1	10.5	14.0	23.3	12	14	74

TABLE 1

$M/M_\odot$	EOS	# $\bar{\nu}_e$ Absorb. Kam.	# $\bar{\nu}_e$ Absorb. IMB	# e^- Scatt. Kam.	# e^- Scatt. IMB	ε_{e+} Kam.	ε_{e+} IMB	# ν_e Absorb. C_2Cl_4
1.27	Soft	9.5	5.7	1.3	0.45	20.3	28.7	.10
1.64	Hard	10.4	3.9	1.5	0.49	17.4	26.0	.09
1.64	Soft	14.8	8.9	2.1	0.84	20.2	27.9	.16

TABLE 2

star binding energy by comparing the observed counts to the number predicted by our calculation. We do this both for Kamiodande and IMB and average the two results. We add 20% to this number because when the luminosity for the 1.64 $M_\odot$ soft EOS model had fallen to the point it would be very difficult to observe, it still contains 20% of the total binding energy appropriate to the EOS used. We assumed a distance to the

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LMC of 52 Kps. We arrive at an estimate of the binding energy of $(3.0 \pm 1.0) \times 10^{53}$ ergs. The uncertainty arises from Poisson statistics and distance uncertainties. We may also estimate the binding energy by the core mass and EOS required to account for a 12 second signal. Our 1.64 $M_\odot$ soft EOS has a binding energy of 4.0×10^{53} ergs and was the only model to produce an antineutrino signal that lasted as long as 12 seconds. The largest uncertainty in the calculation is the shape of the EOS function above nuclear density. Because a soft EOS is indicated, a black hole remnant is still a possibility.

If we plot the Kamiokande and IMB data together as in Figure 3, we see that for the first two seconds a fairly high luminosity is followed for 10 seconds by a much lower luminosity. We infer from this fact that there may have been a 2 second period of accretion, followed by the explosion and subsequent Kelvin-Helmholtz cooling of the proto-neutron star.

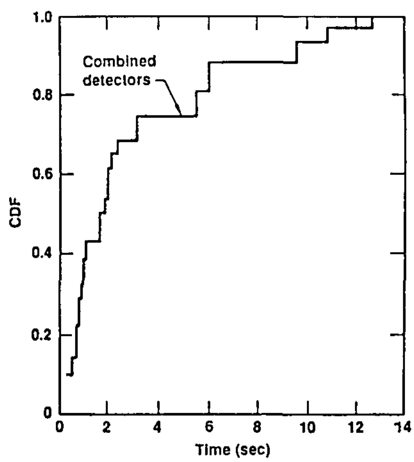

Figure 3. The stair step curve is the detected sample cumulative distribution function (CDF) for the combined detectors. We have weighted the two detectors equally so that the height of an IMB detection is 12/8 the height of a Kamiokande detection (note we have included the count at .686 seconds rejected by the Kamiokande group as being too close to their threshold). If millions of counts had been seen, the CDF would be smooth and directly proportional to the number luminosity emitted by the supernova.

An estimate of the iron core mass before collapse is found as follows. We need 1.6 to 1.7 $M_\odot$ to explain the 12 second signal and a few tenths of a solar mass for the accretion phase luminosity. From a series of stellar evolution calculations of stars producing different iron core masses by Weaver and Woosley (private communication), we find that for models with iron core masses less than 1.5 $M_\odot$ the density exterior to the core falls so rapidly with radius that appreciable accretion could occur not in a few seconds. For high mass iron cores the density doesn't fall off

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rapidly with radius. We would get too large a final mass since the initial core mass would be augmented by a sizeable accretion mass. We thus arrive at 1.50 $M_\odot$ as our estimate for the initial iron core mass.

Convection will not drastically alter the results of our calculations. Smarr et al. (1981) found that with complete core overturn the luminosity increased at most by 30%. Mayle (1985) in a series of calculations with mixing length theory found about a 20% enhancement of the luminosity. Our models are unstable by the LeDoux and salt finger criteria but not the Schwartzschild criteria. Future calculations will include convection.

Our models produce luminosity and spectra that change smoothly with time, hence, we can put no limits on the neutrino mass below the present laboratory limets.

Since our calculations agree fairly well with the standard Weinberg-Salam neutrino theory we can put some limits on competing neutrino theories. We repeated the cooling calculation of the 1.64 $M_\odot$ soft EOS model with additional lepton families. We find the time after bounce at which the antineutrino luminosity had fallen to 10^{50} ergs/sec to be 11 seconds for 3 flavors, 7.4 seconds for 5 flavors, and 5.6 seconds for 7 flavors. Thus it appears that SN1987a will give an appreciable restriction on the number of neutrino types. Double beta decay experiments have indicated the possibility that neutrinos are majoran particles. We have put the Gelmini-Roncadelli neutrino model into our computer program. The result of calculations is that the majoran-neutrino coupling constant must be small or the antineutrino energies will be so low as to be inconsistant with observations. A calculation was done also with the inclusion of axion cooling. A limit on the axion coupling constant of 1×10^{12} GeV was found in order that axion cooling not remove the antineutrino signal. All these above particle models will be done in the near future with much more care. We only want to point out at this time the possibilities to be derived from SN1987a.

In conclusion, we mention the following statistically weak observational oddities; the 7 sec time gap in Kamiokande data, the lack of late time events in IMB, the occurrence of two possible electron scattering events very early in time, and the discrepancy of the Kamiokande and IMB average neutrino energies. The work on particle models is being pursued with G. Fuller, R. Mayle, K. Olive, D. Schramm.

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