SEARCH FOR STELLAR COLLAPSE WITH THE MACRO DETECTOR AT GRAN SASSO

The MACRO Collaboration
presented by
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The generally accepted modern view of stellar evolution[1] holds that stars in the range of 8 to 12 solar masses evolve gradually as increasingly heavier nuclei are produced and then consumed in a series of exothermic thermonuclear processes ultimately leading to the formation of a core composed almost entirely of nickel and iron. When the mass of this hot iron-nickel core reaches the critical value of approximately 1.4 solar masses, electron degeneracy pressure is no longer able to support the outer layers of the star and a collapse process begins. Since the core has exhausted its thermonuclear fuel, further stages of thermonuclear burning cannot prevent a runaway collapse.

As the density reaches 10^{10} gm/cm^3 at a temperature near 10^{10} K, most of the heavy nuclei are dissociated into free nucleons and electron capture on free protons leads to a decrease in the degeneracy pressure and further acceleration of the collapse process. This implosion of the stellar core takes place on a time scale only slightly longer than the free fall time (tens of ms) and leads to the formation of a neutron star or black hole and to the sudden release of a large fraction of the star's gravitational potential energy, much of which is ultimately emitted as a huge burst of neutrinos and antineutrinos of various species.

Although this general picture has received substantial confirmation over the past two decades with the discovery of radio pulsars (neutron stars), X-ray pulsars (accreting binary neutron stars) and Cyg X-1 (probably an accreting black hole), an actual neutrino burst has not yet been convincingly detected.

The **MACRO** detector[2] will employ 700 tons of liquid scintillator contained in 572 individual scintillation elements located in the favorable deep-underground, low-radioactivity environment of Hall B of the Gran Sasso Laboratory. The large mass and high sensitivity ($\lesssim$10 MeV visible energy threshold) of the detector will allow an extremely sensitive search for neutrino burst events.

The total energy released during a collapse event will be the gravitational binding energy of the residual neutron star, *viz.*

$$E = 3 \times 10^{53} (M/M_\odot)^2 (10 \text{ km}/R) \text{ ergs.}$$

Inserting typical values for neutron star masses and radii gives an energy release of about 3×10^{53} ergs. Since only a small fraction of this energy goes into the exploding envelope of the star, most of the energy is emitted in the form of neutrinos and (possibly) gravitational waves.[3]

Detailed computations of the time evolution of the collapse distinguish three phases:

a) **Neutronization**, lasting a few milliseconds, in which most of the protons in the core capture an electron to produce a neutron and a neutrino; only electron neutrinos are emitted in this phase.

b) **Deleptonization**, which can last up to 1 second, in which the remaining lepton (and hence proton) excess is radiated through the same process as above, although a sizeable antineutrino flux can also occur.

c) **Cooling**, lasting from 1 to 10 seconds. In this period, neutrinos of all flavors are emitted with a Fermi-Dirac thermal spectrum, modified by absorption in the source. The bulk of the neutrino radiation is in this phase; furthermore, the emission of electron antineutrinos, which are the most easily detected, is essentially limited to this phase.

We have performed Monte-Carlo calculations of the detection efficiency of the **MACRO** liquid scintillation detector to evaluate the sensitivity of a stellar collapse search with this instrument. The effective mass for neutrino burst detection is 600 tons of liquid scintillator with a chemical composition of C_nH_{2n}.

The main detection channel for antineutrinos is the charged current interaction with free protons; neutrino detection is mainly via elastic scattering on electrons. In the Monte-Carlo code we included the effects of module geometry and the appropriate neutrino cross sections and energy loss rates for electrons and positrons. The neutrino energy distribution for the burst was assumed to be a thermal Fermi-Dirac distribution, modified by absorption in the collapsing star[4]. We considered two sets of collapse parameters taken from the literature[5,6]. See Table I.

TABLE I. STELLAR COLLAPSE MODEL PARAMETERS

Parameters	Model I[4]	Model II[5]
Flux($\bar{\nu}_e$) at Earth	6×10^{11} cm^{-2}	1.7×10^{11} cm^{-2}
Flux(ν_e) at Earth	6×10^{11} cm^{-2}	2.4×10^{11} cm^{-2}
$<E_{\bar{\nu}_e}>$	12 MeV	10 MeV
$<E_{\nu_e}>$	10 MeV	10 MeV
Δt	20 s	10 s
E_{tot}	6×10^{53} ergs	2×10^{53} ergs
Number of Positrons:		
D = 1 kpc	3×10^4	4×10^3
D = 10 kpc	300	40

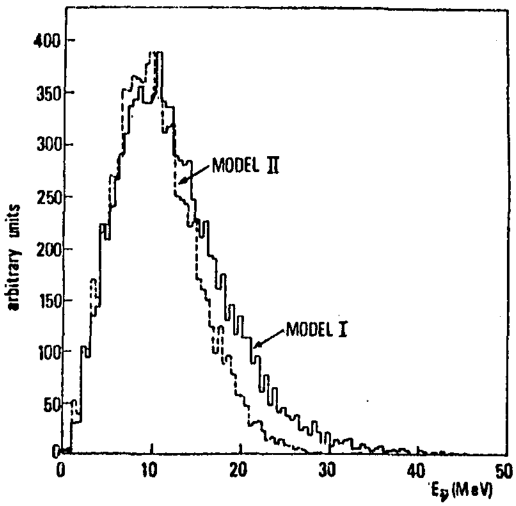

Fig. 1. Two theoretical models for the energy distribution of the neutrinos emitted during stellar collapse. Model I is from Ref. 5, while Model II is from Ref. 6.

Fig. 1 shows the neutrino energy distributions for the two models. Fig. 2 summarizes the results of our Monte Carlo calculations for the single module visible energy distributions of the positrons produced by electron antineutrinos. Note that, since the cross-section for antineutrino absorption increases as $E_{\bar{\nu}}^2$, the average positron energy of about 15 MeV is higher than that of the antineutrinos which produce them. Fig. 3 shows our result for the energy distribution of the electrons resulting from elastic scattering of electron neutrinos.

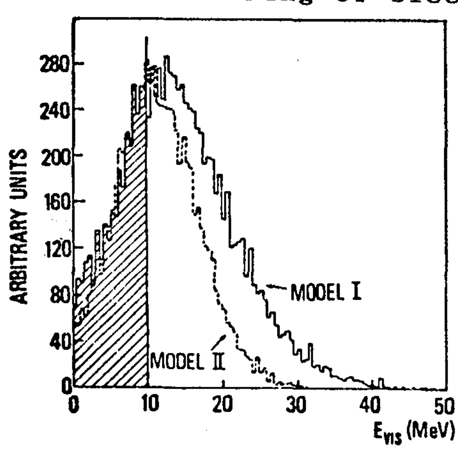

Fig. 2. Results of the Monte Carlo calculation for the energy distribution of positrons produced by electron antineutrinos.

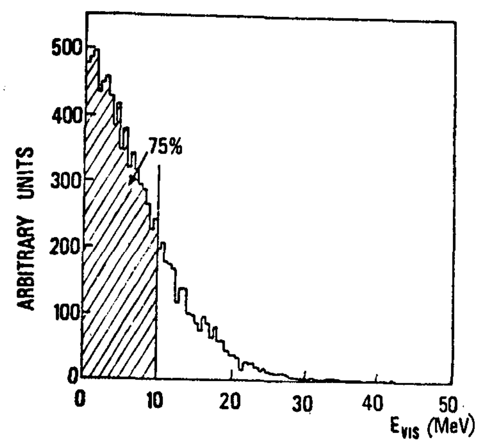

Fig. 3. Results of the Monte Carlo calculation for the energy distribution of electrons produced by electron neutrinos.

From Fig. 2 we conclude that, for the anticipated detection threshold of 10 MeV, positron detection efficiencies are 75% and 60%, respectively, for the two models. From Fig. 3, the electron detection efficiency is 25%, since the elastic scattering cross section grows only linearly with E_ν and the average electron energy is only $\sim .5\ E_\nu$.

The last two lines of Table I show the expected numbers of detected positrons for the two models, assuming a visible energy threshold of 10 MeV, for distances of 1 and 10 kpc. Even in the more pessimistic Model II, 40 counts are obtained for a collapse at the Galactic center.

Statistical fluctuation of the radioactive background counting rate in the detector can mimic a neutrino burst. For a 5 year run, 90% confidence level detection of a neutrino burst requires the frequency of spurious bursts to be kept below 1 per 12 years. Allowing this rate for spurious bursts, Fig. 4 shows the minimum detectable neutrino flux as a function of the background counting rate of the scintillator system for several values of the burst duration.

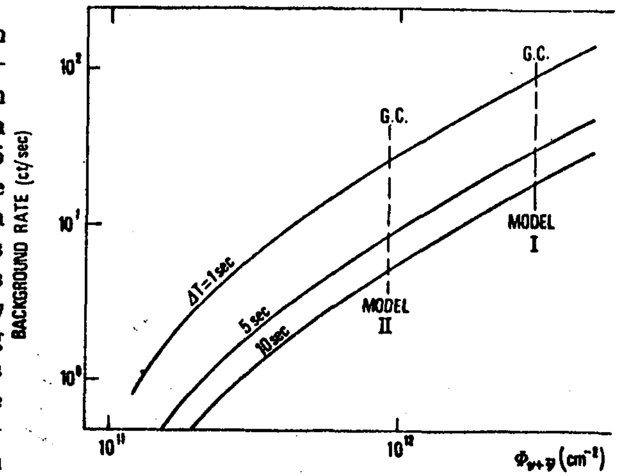

Fig. 4. Minimum detectable neutrino flux vs. detector background rate.

With an estimated maximum background rate of 1 Hz and a typical burst duration of 5 sec, the minimum detectable neutrino flux is $2 \times 10^{11}/cm^2$. Thus, in Model I, the maximum range for burst detection would be 40 kpc, while Model II predicts a maximum detection range of about 15 kpc. The **MACRO** detector therefore will be sensitive to stellar collapses occurring anywhere within the Galaxy.

REFERENCES

1. See, for example, J.M. Lattimer, *Ann. Rev. Nucl. Part. Sci.* 31, 337 (1983).

2. The **MACRO** collaboration, paper HE 6.1-4, these proceedings.

3. Only a small fraction of the total energy released by collapse can be radiated in gravitational waves. See S.L. Shapiro, *Ap. J.* 214, 566 (1977).

4. P.V. Korchagin, *et al.*, Proc. 17th Intl. Cosmic Ray Conf., Bangalore, 7, 110 (1981).

5. D.K. Nadyozhin and I.V. Otroshchenko, *Sov. Astron.* 24, 47 (1980).

6. A. Burrows and T.L. Mazurek, *Nature* 301, 315 (1983).