Analysis of Neutrino Signals from SN1987A

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Summary. We study SN1987A neutrino events through a likelihood analysis with one-component (cooling) and two-component (accretion and cooling) emission model. We show that there is a 3.2\(\sigma\) hint for the initial accretion phase.

1 Introduction

On 23\textsuperscript{rd} February 1987 four neutrino detectors collected a burst of events from supernova (SN) explosion. The signal was detected by Kamiokande-II (KII) in Japan (11, +5 below threshold, events) \cite{1}; IMB in Michigan (8 events) \cite{2} and Baksan in Russia (5 events) \cite{3}, for an amount of 29 neutrino events in a window of \(T = 30\) sec. Four hours before 5 other events in a time window of 7 sec were detected by the LSD experiment \cite{4}. To the best of our knowledge, the first phase of the neutrino emission, revealed by LSD, cannot be explained inside the standard description of a core-collapse SN \cite{5}, whereas the second main phase of the neutrino emission can be described using the standard scenario that we adopt in the present work.

We investigate the neutrino events detected by KII, IMB and Baksan, in order to obtain maximal information through a detailed statistical analysis. We reconstruct the likelihood function for all events and maximize this probability varying some theoretical parameters related to the emission models that we take into account. In our analysis, we consider the time-energy distribution of the signal, the directional information of the data, the detectors properties (e.g. the efficiency functions). Furthermore we include a detailed description of the background, following and improving the seminal work of Loredo and Lamb \cite{6, 7}. 
To grasp the emission models used in our data analysis, now we briefly describe the main phases of the so-called standard model for a core-collapse SN [8]. At the end of its life, a massive star consists of a sequence of concentric shells corresponding to the relics of different burning phases and its inner core is formed by iron, which is the final stage of nuclear fusions. The iron core grows due to silicon shell burning and, when it reaches a mass of about 1.44\( M_\odot \) (the Chandrasekhar limit mass), the electron degeneracy pressure can not support the structure’s weight and then the core collapses. At the densities and temperatures involved, the processes of electron capture, \( \beta \) decay and partial photodisintegration of iron-group nuclei to alpha particles occur and cause the acceleration of the collapse and the neutrino trapping in the core. This collapse proceeds until nuclear densities of about 10^{14} g/cm^{3} are reached. At this density the nuclear matter is nearly incompressible and the outer iron core rebounds driving a shock wave that propagates outwards, whereas the external region falls inwards at supersonic speed. The explosion mechanism is still uncertain but, in ‘delayed scenario’ [9], the shock seems to loose its energy because of the dissociation of heavy nuclei into nucleons and because of the neutrino emission, that grows when the shock crosses the neutrinosphere. The weakened shock stagnates and transforms into a standing accretion shock, whereas the outside matter falls inward and joins the nascent compact remnant. We call this phase accretion (suffix \( a \)) phase and we suppose that, in this phase, \( \nu_e \) and \( \bar{\nu}_e \) are produced in similar amount by the \( ep \rightarrow n\nu_e \) and \( e^+ n \rightarrow p\bar{\nu}_e \) processes. The accretion phase occurs within the first second of \( \bar{\nu}_e \) emission, and for this non-thermal phase [10] we assume the following parameterized neutrino flux

\[
\Phi_{\text{acc}}^0(t, E_\nu) = \frac{1}{4\pi D^2 (hc)^3} \left[ \frac{8}{\pi c} Y_n M_a m_n g(E_\nu, T_a) \sigma_{e^+n}(E_\nu) \right],
\]

where \( Y_n = 0.6, M_a \) is the accreting mass exposed to the positrons thermal flux, \( g(E, T) = E^2 / [1 + \exp (E/T)] \), a Fermi-Dirac distribution with temperature \( T_a \), \( \sigma_{e^+n}(E_\nu) \) is the cross section of positron interactions increasing quadratically with \( E_\nu \). The time scale of accretion process (namely \( \tau_a \)) appears in the following function \( \varepsilon(t) = \exp\left[-(t/\tau_a)^{10}\right]/[1 + t/(0.5 \text{ s})] \). Taking into account the neutrino oscillations and the accretion assumptions (i.e. \( \Phi_{\text{acc},\bar{\nu}_e}^0 = 0 \)), the \( \bar{\nu}_e \) accretion flux is reduced by the factor \( P_{ee} = \cos^2 \theta_{12} \) (the survival probability function [11, 12]), hence the total flux becomes

\[
\Phi_{\text{acc}}(t, E_\nu) = P_{ee} \cdot \Phi_{\text{acc},\bar{\nu}_e}^0(t, E_\nu).
\]

The nascent proto-neutron star evolves in a neutron star (with radius \( R_{NS} \)) and this process is characterized by an intense flux of all the species of (anti)neutrinos. We call this phase cooling phase (suffix \( c \)), a thermal phase with a longer time scale, and we suppose that an equal amount of energy goes
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3 Data analysis

Let us construct the likelihood function for the data set. We assume that the detected $\bar{\nu}_e$ interact for Inverse Beta Decay (IBD), $\bar{\nu}_e p \rightarrow n e^+$. The signal rate (triply differential in time, in the positron energy $E_e$, in the cosine of the angle $\theta$ between the antineutrino and the positron directions) is given by

$$S(t, E_e, \cos \theta) = N_p \frac{d\sigma}{d\cos \theta}(E_\nu, \cos \theta) \eta_d(E_e) \xi_d(\cos \theta) \Phi_{\bar{\nu}_e}(t, E_\nu) \frac{dE_\nu}{dE_e},$$

where $N_p$ is the number of targets (free protons) in the detectors, $\sigma$ is the IBD cross section [13], $\eta_d$ is the detector dependent–average detection efficiency, $\xi_d$ is the angular bias ($\xi_d = 1$ for Kamiokande-II and Baksan whereas $\xi_d(\cos \theta) = 1 + 0.1 \cos \theta$ for IMB [14]) and, finally, $\Phi_{\bar{\nu}_e}$ is the total flux of $\bar{\nu}_e$, sum of the two terms $\Phi_{\text{acc}}$ and $\Phi_{\text{cool}}$ shown respectively in Eqs. (2) and (4). The theoretical parameters, that we have to deduce by fitting the data, are included in this last term and are 6 parameters (3 for each phase): $M_a$, $T_a$ and $\tau_a$ for accretion; $R_c$, $T_c$ and $\tau_c$ for cooling. The likelihood function is

$$L = \prod_{d=k,i,b} \mathcal{L}_d,$$

where the suffix $d$ ranges over the detectors. Using the Poisson statistic, the likelihood function for each detector is

$$\mathcal{L}_d = e^{\int_{-T_d}^{T_d} S(t + t_d) dt} \prod_{i=1}^{N_d} e^{S(t_i + t_d) \tau_d} \left[ \frac{B_i}{2} + \int S(t_i + t_d, E_{e_i}) G_i(E_e) dE_e \right],$$

where $N_d$ is the number of events for each detector and the suffix $i$ refers to the $i$-th event $(i = 1...N_d)$. The time $t_d$, called "offset time", is the temporal gap between the arrival of the first neutrino to the Earth and the detection of...
first neutrino event in the detector. As consequence, we add 3 new parameters $t_d$ to find out by our data analysis. The term $f_d$ is the detector live fraction ($f_d = 1$ for KII and Baksan, whereas $f_d = 0.9055$ for IMB), $\tau_d$ is the detector dead time ($\tau_d = 0$ for KII and IMB, whereas $\tau_d = 0.035$ for IMB). Using the well known background distribution, we calculate the probability that each event is a background signal, $B_i = B(E_i)$, and the gaussian function $G_i$ including the energy error $\delta E_i$ arising by the energy smearing. During the cooling phase, we assume that the muon and tau antineutrinos temperatures ($T(\bar{\nu}_\mu)$ and $T(\bar{\nu}_\tau)$ respectively) are proportional with the electron antineutrino temperature ($T(\bar{\nu}_e)$), i.e. $T(\bar{\nu}_e) / T(\bar{\nu}_e) = T(\bar{\nu}_e) = 1.2$ [15].

At first neglecting the accretion phase, we solely consider the neutrino flux of cooling phase. We study the probability function $L$ and we find a maximum when the model parameters reach the best-fit values shown in Table 1. We remark that the best-fit value for $R_c$ is larger than the theoretically expected one (namely $R_c \simeq R_{NS} \simeq 10Km$ [16]). We calculate the total energy carried by neutrinos during this phase corresponding to the gravitational binding energy of neutron star $\mathcal{E}_b$. Using the equipartition hypothesis the relations $\mathcal{E}_b = 6 \cdot \mathcal{E}_c(\bar{\nu}_e) = 3.39 \cdot 10^{-4} R_c^2 T_c^4 \tau_c = 3.87 \cdot 10^5$ erg hold, where the mean values of antineutrino energy are $\langle E_{\bar{\nu}_e} \rangle = 10 MeV$ and $\langle E_{\bar{\nu}_\mu} \rangle = 12$ MeV, a bit lower than expected [15, 17].

Motivated by the experimental fact that about 40% of the SN1987A events have been recorded in the first second, we consider the accretion phase completing the emission model. We set $M_a = 0.5 M_\odot$ that is a reasonable value of the outer core mass, therefore we maximize the likelihood as a function of the other parameters. We find the best-fit values shown in Table 2. Note that $T_c$, $R_c$ and $\tau_a$ are very close to theoretical values expected [16]. The binding energy is the sum of two terms, the energy of neutrino emitted in the cooling phase, $\mathcal{E}_c = 1.76 \cdot 10^5$ erg, and the energy $\mathcal{E}_a = 2 \cdot \mathcal{E}_a(\bar{\nu}_e) = 4.14 M_a T_\odot^2 \tau_a \varphi = 6.3 \cdot 10^5$ erg carried by $\nu_e$ and $\bar{\nu}_e$ in

### Table 1. Results for one-component (cooling) model with $2\sigma$ errors

| $T_c$ (MeV) | $\tau_c$ (sec) | $R_c$ (Km) | $f_{KII}$ (sec) | $f_{IMB}$ (sec) | $f_{Bak}$ (sec) |
|-------------|----------------|------------|----------------|----------------|----------------|
| 4.3$^{+1.5}_{-0.8}$ | 3.7$^{+2.4}_{-1.4}$ | 31$^{+32}_{-16}$ | 0$^{+0.9}$ | 0$^{+0.4}$ | 0$^{+1.5}$ |

### Table 2. Results for two-components (accretion and cooling) model with $2\sigma$ errors

| $T_c$ (MeV) | $\tau_c$ (sec) | $R_c$ (Km) | $f_{KII}$ (MeV) | $f_{IMB}$ (sec) | $f_{Bak}$ (sec) |
|-------------|----------------|------------|----------------|----------------|----------------|
| 5.1$^{+2.1}_{-1.4}$ | 4.4$^{+3.6}_{-1.5}$ | 13$^{+18}_{-8}$ | 2.1$^{+0.2}_{-1.4}$ | 0$^{+1.3}_{-0.8}$ | 0$^{+0.8}$ | 0$^{+0.7}$ | 0$^{+0.6}$ |
Fig. 1. The luminosity (a) and the mean energy (b) of $\bar{\nu}_e$ and $\bar{\nu}_x$ (dashed line and solid line, respectively) obtained from the emission model (accretion and cooling) exploiting the best fit values of Table 2.

Fig. 2. Time integrated energy spectra of neutrino for accretion (dashed line) and cooling (solid line) emission phase.

the accretion phase, where $\varphi \equiv \int_{0}^{\infty} dx \exp(-x^{10})/(1 + x^{\tau_a/0.5})$. Hence we obtain $E_b = 2.4 \cdot 10^{53}$ erg, $\langle E_{\bar{\nu}_e} \rangle_a = 10.3\, \text{MeV}$, $\langle E_{\bar{\nu}_e} \rangle_c = 12.6\, \text{MeV}$ and $\langle E_{\bar{\nu}_x} \rangle = 15\, \text{MeV}$. We report the neutrino luminosities, the neutrino energies mean values (as a function of time) in Fig. 1 (a) and (b), respectively. Moreover, we plot the neutrino energy spectra in Fig.2.

4 The evidence for the phase of accretion

In the analysis with accretion and cooling phases, we find that the absolute value of the likelihood function (in the best-fit point) is about 1000 times larger than the corresponding value in case of no accretion phase, giving a significant hint for an accretion phase. In fact, let us assume as null hypothesis
the case where the accretion is absent and compare it with the alternative hypothesis $H_1$ with an accretion phase described by two additional parameters $T_a$ and $\tau_a$. When we add $\nu = 2$ degrees of freedom, we expect that the $\chi^2$ will decrease by a certain amount $\Delta \chi^2$. In order to determine the rejection interval for the hypothesis $H_0$, we perform a likelihood ratio test; then the required probability distribution function is the regularized gamma function $Q(\nu/2, \Delta \chi^2/2)$. When we go from $M_a = 0$ (no accretion) to $M_a = 0.5 \, M_\odot$ (our reference point) the $\chi^2$ diminishes by $\Delta \chi^2 = 13.4$. As consequence, we reject the null hypothesis in favor of the hypothesis that accretion occurred with a significance of $\alpha = \exp(-\Delta \chi^2/2) = 1.2 \times 10^{-3}$. In Gaussian language, this amounts to $3.2\sigma$.

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