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Neutrinos emission models with two temperatures for SN1987A

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Abstract. The neutrino burst (νs) from SN1987A that were detected in several experiments around the world in February 1987 and is now the subject of discussions and reanalyses. All the events that were detected (total $\sim$ 25) in the following experiments: Kamiokande II (KII) $\sim$ 12, Irvine-Michigan-Brookhaven (IMB) $\sim$ 8 and Baksan $\sim$ 5. The importance of the νs is that they have an importtant role in the cooling process of the renmant neutron star (NS), therefore, 99% of the energy of the collapse is lost in the first few seconds, and through the possibility of seeing the internal structure of the NS at the initial instants of its birth. This work proposes to analyze models with two temperatures, which presuppose two neutrino outbursts with time intervals of $\sim$ 5 s between them. The motivation of the proposal is to distribute the data in relation to the time of arrival, which explains the existence of a time gap between two distinct groups of νs, where the second group would come from a form center of Strange Quark Matter (SQM). This hypothesis was the motivation to use *Bayesian Information Criterion* (BIC) that was tested by different models with two temperatures.

Resumo. O surto de neutrinos (νs) da SN1987A que foram detectados num total de eventos detectados foi de aproximadamente 25 nos seguintes experimentos: Kamiokande II (KII) $\sim$ 12, Irvine-Michigan-Brookhaven (IMB) $\sim$ 8 e Baksan $\sim$ 5. A importância dos νs está no papel que eles desempenham no processo de resfriamento da Estrela de Nêutrons (EN) remanescente pois, 99% da energia do colapso é perdida na emissão de νs nos primeiros segundos, e através dos νs é possível "enxergar" a estrutura interna da EN nos instantes iniciais do seu nascimento. Este trabalho propõe analisar modelos com duas temperaturas, que pressupõe dois surtos de neutrinos com intervalo temporal de $\sim$ 5 s entre eles. A motivação da proposta passa pela distribuição dos dados em relação ao tempo de chegada, o que explicita a existência de um hiato temporal entre dois grupos distintos de νs, onde o segundo grupo seria proveniente de um cenário de formação de Strange Quark Matter (SQM). Em nosso trabalho anterior mostramos ser mais provável a existência de dois surtos e apresentaremos os resultados preliminares desses modelos de emissão com duas temperaturas.

Keywords. neutrinos — SN1987A — Astrostatistics

1. Introduction

The explosion of the Supernova 1987A (SN1987A) was perhaps the most extraordinary astronomical event ever observed by man. In addition to the optical observation that made evident the occurrence of the event, signature of the νs burst in large detectors around the world were clearly observed and correlated over time (Bionta et al., 1987; Hirata et al., 1987; Alekseev et al., 1987). In all, 25 events were observed distributed in the experiments of Kamiokande II (KII) — Japan, Irvine-Michigan-Brookhaven (IMB) — USA and Baksan — USSR. The compilation of events observed by these three experiments can be seen in Figure 1 which shows energy versus arrival time for each event. Valentim, Horvath & Rangel (2017) have shown that the strong evidence of two bursts of νs, this hypothesis was proposed by Benvenuto & Horvath (1989), is more likely than only one. The model proposed by us presupposes a temporal gap that according to likelihood function suggested by Loredo & Lamb (2002). These bursts would be of different physical nature: $t_1 \sim 2$ s via deleptonization mechanism in a *prompt* scenario and $t_2 \sim 3$ s after of temporal gap $\sim$ 5 s, in a deleptonization scenarios of the strange proto-star.

2. Statistical Methodology and Models

Statistical Methodology was adopted in this analysis derived likelihood function proposed by Loredo & Lamb (2002). The emission, propagation and detection of neutrinos on the KII, IMB and Baksan were modeled considering the parameters like efficiency curves and energy limits of detection. This approach allowed to estimate important parameters from compact object renmant: emission temperature and radii.

$$\mathcal{L}(\mathcal{P}) = \exp\left[-f\int_T dt \int d\boldsymbol{n} \int \bar{\eta}(\boldsymbol{n},\epsilon)R(\boldsymbol{n},\epsilon,t_i)\right] \times \prod_{i=1}^{Nd} e^{R_{\mathrm{eff}}(t_i)\tau}\left[B_i + \int d\boldsymbol{n}\int d\epsilon\mathcal{L}_i(\boldsymbol{n},\epsilon)R(\boldsymbol{n},\epsilon,t_i)\right]. \qquad (1)$$

Where f is the fraction time life of detector, τ is dead time, $\bar{\eta}(\boldsymbol{n},\epsilon)$ efficiency's curve of each detector, B_i is the noise's rate integrated on time, $\mathcal{L}(\boldsymbol{n},\epsilon)$ weight function and $R(\boldsymbol{n},\epsilon,t_i)$ is the rate of events measured.

2.1. Models

Now the models proposed by us with two temperatures are presented, these ideas were based on Benvenuto & Horvath (1989). Figure 1 shows clearly for us that the dataset has two different set of data (from the site `http://www.astrosurf.com`):

i. Two Constant Temperatures (TCT)

This model two constant temperatures were proposed, the temporal gap between them was $(tp + \tau_1)$ 3.10 s. The motivation is to propose a simple model with low parameters number.

ii.Two Exponential Temperatures (TET)

This model has a great physical motivation because the cooling process could have happened through exponential decays, one to each temperature T_1 e T_2) independently. The duration

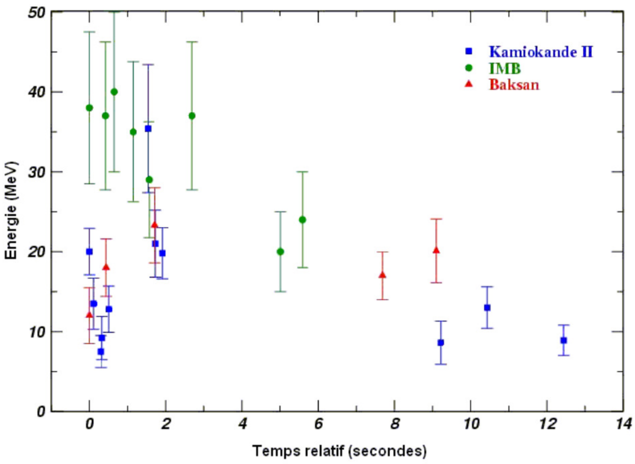

Figure 1. All events observed for different detectors: KII (~ 12), IMB (~ 8) and Baksan (~ 5). Each one has a distinct efficiency curve and observed events in different range of energy.

time for each burst in theses models are: τ_1 and τ_2 and the time interval (t_p) between them is ~ 5.00 s.

iii. Two Step Temperatures (TST)

The model proposes two steps temperatures T_1 and T_2. The bursts' times are: (T_1) first burst and T_2 for the second burst and are separated to t_p. The physical motivation that this model proposes that the cooling time is free.

3. Results

The results of the models calculated from the likelihood function (eq. 1) are shown in the table below. The parameter α is related to the radius of the neutrinosphere (km). At the temperature of t_1 is relative to the first neutrino burst, the TET model shows a higher temperature (~ 3.90 MeV) compared to the TCT model which provided ~ 3.30 MeV and TST with ~ 3.60 MeV. The temperature of second burst, for the TET (~ 3.12 MeV) model, is close value to theoretically proposed by Benvenuto & Horvath (1989), which was the values were for TST model with ~ 2.52 MeV which is a value within the predicted by the theoretical and TCT ~ 0.30 MeV which was a very low value, which suggests an imprecise description of the phenomenon. The relative time to the temporal gap, the TET model obtained ~ 5.00 s in relation to ~ 3.00 s for TCT models (which is the shortest time estimated) and ~ 4.50 s for TST that is close to the value suggested by the data (see figure 1). For the decay time of the first burst (τ_1), the TET model provided ~ 9.10 s which is a relatively long time since the burst has approximately 3 s. The TCT model provided a very short time (~ 0.10 s) and TST a very close time to the ~ 2.70 s from data. In relation to the time of the second burst (τ_2), the value of the TET model extends to ~ 28.00 s in relation to the longest time for TCT and the most reasonable time for TST to be ~ 8.00 s. These models had been tested by BIC for two models combinations: TET versus TCT with ~ 29 is the strong evidence in favor of the first model. TST versus TET outcomed with ~ 4 this is a weak evidence in favor TST. Finally, it was tested TST versus TCT with strong evidence in favor TST (~ 28).

4. Conclusions

Valentim, Horvath & Rangel (2017) suggested temperature's models for the existence of two neutrinos' bursts. This work tested the model two temperature exponential decay (TET), two step temperatures (TST) and two constant temperatures models. BIC test showed that two step temperatures model is the most probable among them. Our theoretical investigation proposed new and more complex models, it suggests better description of the neutrinos emission on the newborn proto-neutron star renmant from SN1987A. This work showed TET described better the values of temperature but this model is not the most probable. The extension of this work is to analyse database under *Support Vector Machine* point of view, this tool allows to separe two set of data from bursts.

Table 1. Models for the neutrino cooling temperature. These models have two componentes of temperature, neutrinosphere radius, time of temporal gap and time of cooling.

Parameters	TCT	TET	TST
α	1.50	2.90	1.50
Radius (km)	15.0	29.0	15.0
T_1 (MeV)	3.30	3.90	3.60
T_2 (MeV)	0.30	3.12	2.52
t_p (s)	3.00	5.00	4.50
τ_1 (s)	0.10	9.10	2.70
τ_2 (s)	28.00	20.10	8.00

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