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Neutrino bursts from gravitational stellar collapses with LVD

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Abstract. The main goal of the Large Volume Detector (LVD), in the INFN Gran Sasso National Laboratory (Italy), is the study of neutrino bursts from gravitational stellar collapses in our Galaxy or in the Magellanic Clouds. Both the detector and the data analysis procedure have been optimized for this purpose. The modularity of the apparatus allows to obtain a duty cycle that is very close to 100%, so that the experiment is continuously monitoring the Galaxy. Data analysis is performed online, with the selection of alarms for the Supernova Early Warning System (SNEWS), and offline. In both cases, LVD is sensitive to neutrino emission from core collapse Supernovae from the whole Galaxy.
No neutrino burst candidates were selected over 6013 days of observation. As a result, the 90% confidence level upper limit to the rate of gravitational stellar collapses in our Galaxy is 0.14 y^{-1}.

Key words. Gravitational stellar collapse – Neutrino burst – Neutrino detection

1. Introduction

Gravitational stellar collapses are astrophysical events of great interest. Because of the complexity of the problem, the modeling of the physical processes is still in evolution, but it is generally accepted that the role of neutrinos is critical to allow the supernova to form out of a collapse (Bethe & Wilson 1985). The detection of a neutrino burst in correlation with SN1987A in the Large Magellanic Cloud (Hirata et al. 1987; Bionta et al. 1987; Alekseev et al. 1987; Aglietta et al. 1987), in spite of some unresolved controversies, opened the way for a new method of investigation: neutrino astronomy. Starting from this milestone, a new generation of neutrino detectors, many of which are still operating, was set up. The neutrino burst from the next Galactic supernova will be clearly visible in various detectors spread around the world, and will allow us to study the core collapse in detail.

2. The detector

The *Large Volume Detector* (LVD) is a 1 *kton* liquid scintillator neutrino observatory located in the INFN Gran Sasso National Laboratory (Italy). The main goal of LVD is the detec-

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tion and detailed study of neutrino bursts from gravitational stellar collapses which happen in our Galaxy or in the Magellanic Clouds. The LVD detector is made up of 840 counters which are arranged in a compact and modular geometry (Aglietta et al. 1992). One single counter is a $1.5 \times 1.0 \times 1.0\,m^3$ stainless steel tank, filled with 1.2 *tons* liquid scintillator ($C_nH_{2n+2}, < n >= 9.6$). Each counter is viewed on the top by three photomultiplier tubes, whose coincidence above the threshold gives the trigger condition for the experiment. With the current configuration this corresponds to about 4 MeV energy release in the counter. Eight counters are packed together to give a module, and 105 modules are equally divided in three towers. The main neutrino interaction that is expected to occurr at the typical energies of supernova neutrinos, from 10 to 100 MeV, is the Inverse Beta Decay (IBD)

$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

followed by the monochromatic signal given by neutron capture

$$n + p \rightarrow d + \gamma_{2.2MeV} \tag{2}$$

with a mean delay that, in one LVD counter, is $\Delta t = 185\,\mu s$. This delayed signal provides us with a clear signature of the IBD interaction. To optimize the identification of IBD interactions, LVD has a dedicated double-threshold system. If a trigger occurs, the threshold is lowered down to less than 1 MeV for 1 ms in all counters of the module in which the counter giving the trigger is located. The system records all the low energy signals (LEP) occurring in this time window, associating each of them to the trigger. Beside this interaction, LVD is sensitive to both charged and neutral current neutrino interaction on electrons and Carbon nuclei. Moreover, due to the Iron present in the array, interactions on Iron nuclei can be also detected (Agafonova et al. 2007).
The modularity of LVD allows to obtain a very high duty cycle, and so to continuously monitor the Galaxy looking for neutrino bursts. This is possible because a failure involving one or more counters does not affect the whole experiment and LVD can be serviced during data taking. Moreover, thanks to a dedicated software, in case of electronic failure, the telescope automatically remove the not properly working region and reconfigures itself at lower mass. The effect is to minimize the dead time adjusting dynamically the LVD active mass. The LVD active mass, M_{act}, is another important parameter to be considered, as it must be as great as possible to collect a good number of neutrino events. In figure 1 duty cycle and active mass are shown together as a function of time starting from the very beginning of the experiment. In 2001 the detector was completed, and the active mass has been greater than 950 *tons* on average since then, while the duty cycle has been > 99%.

3. The expected signal

When a gravitational stellar collapse occurs, a total energy of around $E_b = 3 \cdot 10^{53} erg$ is liberated. The largest amount of it, around 99%, is taken away by neutrinos, and this explains why it is useful to study this phenomenon through neutrino detection. Neutrino emission lasts around 20 s, with the production of all flavours both for neutrino and antineutrino, for a total number of $\sim 10^{58}$. An energy equipartition among the various species of neutrino is often assumed in the description of the emission. The mean energy for ν_e is $< E_{\nu_e} >\sim 12\,MeV$, for $\bar{\nu}_e$ is $< E_{\bar{\nu}_e} >\sim 15\,MeV$ and for all other flavours (labelled as x) is $< E_{\nu_x} >\sim 20\,MeV$, see e.g. Totani et al. (1998). For a detailed calculation of the number of interactions in LVD we rely on the parameterization of neutrino emission by Pagliaroli et al. (2009). We take into account neutrino oscillations inside the star, given by the usual matter effect (Wolfenstein 1978; Mikheev & Smirnov 1985). We consider here a normal neutrino mass hierarchy and a non adiabatic transition in the interior of the star, for which the survival probability for ν_e is $P = 0.3$, and the survival probability for $\bar{\nu}_e$ is $Q = 0.7$.

Considering, as a reference, a distance of the gravitational stellar collapse of $D = 10\,kpc$, we obtain around 350 events are expected in LVD with various possible interaction channels. All of these events would concentrate in a time window of $\sim 20s$. It is easy

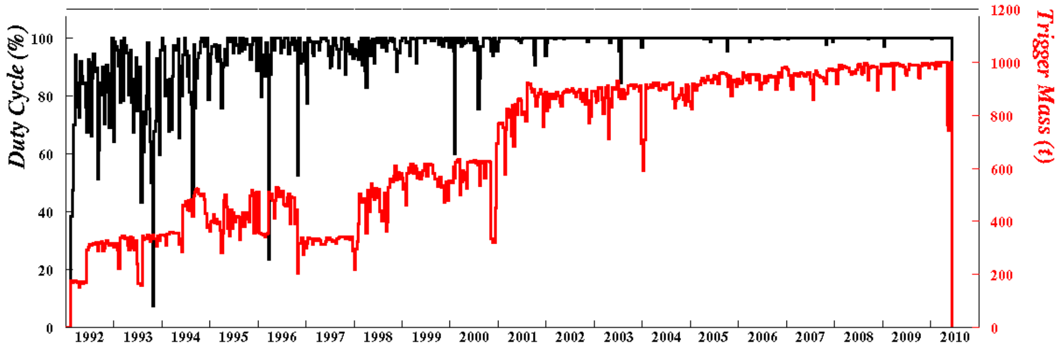

Fig. 1. Duty cycle (in black, top plot) and active mass (in red, bottom plot) as a function of time, updated to May 31st, 2010.

to obtain the number of expected events for different distances, considering that the neutrino flux scales as D^{-2}.

4. Search for neutrino bursts

The data set to search for neutrino bursts is given by all the triggers in the 7-100 MeV energy range. A cut on muon crossing at least two counters inside 250 ns is applied as well as basic cuts to avoid electronic problems affecting the data. A *cluster* is defined as a set of m events within a Δt time window. It is necessary that a neutrino burst producing events in LVD is disentangled from background even without an external trigger, like an optical counterpart from the supernova. For this purpose a selection of neutrino burst candidates has been set up on a statistical basis. Under the hypothesis that background behaviour can be described by Poisson statistic, it is possible to predict the number of clusters of a given multiplicity m, or multiplicity $k \geq m$, that lasts a certain time Δt. This theoretical prediction is compared with real data from the background. The result of this study, with durations up to 200 s and different multiplicities, is reported in figure 2.

As we are able to describe the background in LVD, we identify as *neutrino burst candidates* only those clusters which would be produced by background fluctuations less than $1/(100\,year)$. This kind of procedure can be applied both online and offline. The online analysis (Agafonova et al. 2008) was introduced in order to be connected to the *SuperNova Early Warning System* (SNEWS), whose main purpose is to provide the astronomical community with a prompt alert of the occurrence of a Galactic core collapse

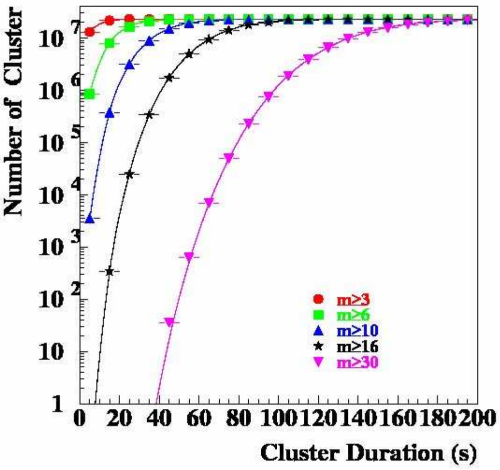

Fig. 2. Number of cluster of different multiplicities vs duration. The solid lines refer to theoretical predictions, while markers refer to data.

event (Antonioli et al. 2004). The offline analysis (Fulgione et al. 1996) introduces a second level of investigation in case of a positive selection of a neutrino burst candidate. In particular three features of the selected cluster are studied:

1. The topology of the event, that is how the events in the cluster are distributed in the detector. Thank to its modularity, LVD can identify the counter where an event occurred. We expect that a neutrino burst would distribute uniformly in the detector, while events from the background favour external counters over the internal, more shielded, ones.
2. The energy spectrum. Events from a supernova neutrino burst peak at around 20 MeV, while the events from the background reach their maximum just at the energy threshold (7 MeV).
3. The temporal distribution of neutron capture candidate signals. A real neutrino burst would mainly interact through IBD, so we expect the temporal distribution of LEP following the triggers to be exponential decaying with mean capture time $\tau = 185\,\mu s$.

Both the procedures reach full efficiency for the detection of neutrino bursts from gravitational stellar collapses up to a distance of $d = 30kpc$, so all our Galaxy ($d \leq 20kpc$) is kept under observation (Agafonova et al. 2008). The selection procedure has been applied to all the period of data taking of the experiment, starting from June 6^{th}, 1992 up to May 31^{st}, 2010. Taking into account the duty cycle during time, this data set corresponds to 6013 days of observation. No neutrino burst candidates have been found, the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy is 0.14 events/year.

5. Conclusions

LVD has been continuously monitoring the Galaxy since 1992 looking for neutrino bursts from gravitational stellar collapse. The telescope duty cycle, in the last nine years, was $> 99\%$. No burst candidate has been found over 6013 days of live-time, the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy is 0.14 events/year.

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