Search for neutrino bursts with LVD at Gran Sasso

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***Abstract*. The Large Volume Detector (LVD[1]), in the INFN Gran Sasso National Laboratory (Italy), at the depth of 3600 $m\ w.e.$, is a 1 kt liquid scintillator detector whose major purpose is monitoring the Galaxy to study neutrino bursts from gravitational stellar collapses. The experiment has been taking data, under different larger configurations, since 1992, reaching in 2001 its present and final one. Its modularity, rock over-burden and trigger strategy, make this detector particularly suited to on-line disentangle a cluster of neutrino signals from the background.**

The search for neutrino bursts is performed on-line, within fixed-duration time windows (20 s), and off-line with variable time windows (from few ms to 200 s). In both cases, and during all the period, the detector sensitivity was sufficient to observe the entire Galaxy.

No candidates have been detected during seventeen years of observation: the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy is 0.15 events / year.

***Keywords*: Supernova Core Collapse; Neutrino detection; Burst Identification**

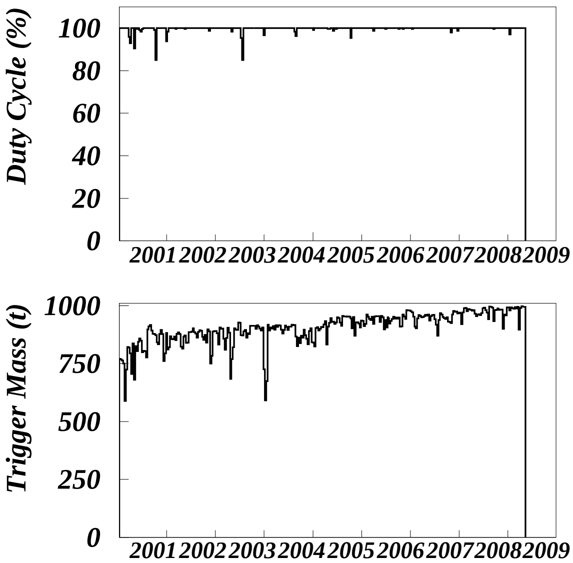

Fig. 1: LVD duty cycle (top) and trigger mass (bottom) during 2001-2009.

I. Introduction

LVD consists of an array of 840 scintillator counters, 1.5 m^3 each [1]. The whole array is divided in three identical "towers" with independent high voltage power supply, trigger and data acquisition. Each tower consists of 35 "modules" hosting a cluster of 8 counters. Each counter is viewed from the top by three 15 cm photomultiplier tubes (PMTs) FEU49b or FEU125. The charge of the summed PMTs signals is digitized by a 12 bit dynamic range ADC (conversion time = 1 μs) and the arrival time is measured with a relative accuracy of 12.5 ns and an absolute one of 100 ns. The modularity of the array allows high duty cycle performance ($\geq$ 99%) as shown in figure 1.

The main neutrino reaction in LVD is the inverse beta decay (IBD) $\bar{\nu}_{\rm e}{\rm p}, {\rm e}^{+}{\rm n}$, which gives two detectable signals: the prompt one due to the e$^+$ (visible energy $E_{\rm vis} = E_{\bar{\nu}_{\rm e}} - Q + m_{\rm e} = E_{\bar{\nu}_{\rm e}} - 0.789$ MeV) followed by the signal from the ${\rm np} \rightarrow {\rm d}\gamma$ capture ($E_\gamma = 2.23$ MeV). For the detection of both products of the reaction, each PMT of a single counter is discriminated at two different thresholds resulting in two possible levels of three-fold coincidence: H and L, corresponding to $\mathcal{E}_H \simeq 4$ MeV and $\mathcal{E}_L \simeq 0.5$ MeV. The H coincidence in any counter represents the trigger condition for the module. Once a trigger has been identified, the charge and time of the three summed PMTs signals are stored in a memory buffer. All the signals satisfying the L coincidences in the same module (8 counters) of the trigger counter are also stored, if they occur within 1 ms. The average neutron detection efficiency, $\epsilon_{\rm n}$, amounts to about 50% for neutrons detected in the same counter where the positron has been observed.

Besides interactions with free protons LVD is also sensitive to charged current interactions with carbon and iron nuclei through:

- $\nu_e\,^{12}{\rm C},^{12}{\rm N}\ e^-$, (physical threshold $E_{\nu_e} > 17.3\ MeV$) observed through two signals: the prompt one due to the e^- ($E_d \simeq E_{\nu_e} - 17.3$MeV) followed by the signal from the β^+ decay of ^{12}N (mean life $\tau = 15.9$ ms);
- $\bar{\nu}_e\,^{12}{\rm C},^{12}{\rm B}\ {\rm e}^+$, (physical threshold $E_{\bar{\nu}_e} > 14.4\ MeV$) observed through two signals: the prompt one due to the e^+ ($E_d \simeq E_{\bar{\nu}_e} - 14.4\,{\rm MeV} + 2m_ec^2$) followed by the signal from the β^- decay of ^{12}B (mean life $\tau = 29.4$ ms);
- $\nu_e\,^{56}{\rm Fe},^{56}{\rm Co}\ e^-$, where the mass difference between the nuclei is $\Delta_{m_n} = m_n^{\rm Co} - m_n^{\rm Fe} = 4.055$ MeV, and the first Co allowed state at 3.589 MeV (the efficiency for

[1]See the full LVD Collaboration List attached to the ICRC Proceedings

electron and gammas, also produced in the interaction, to reach the scintillator with energy higher than $\mathcal{E}_h$ has been simulated [2]; on average, the detectable electron energy is $E_d \simeq 0.45 \times E_\nu$).
- $\bar{\nu}_e\ ^{56}$Fe,^{56}Mn e^+.
And neutral current interactions through:
- $\overset{(-)}{\nu}_\ell$ ^{12}C, $\overset{(-)}{\nu}_\ell$ ^{12}C* ($\ell = e, \mu, \tau$), (physical threshold $E_\nu > 15.1\ MeV$), whose signature is the monochromatic photon from carbon de-excitation ($E_\gamma = 15.1$ MeV);
- $\overset{(-)}{\nu}_\ell$ ^{56}Fe, $\overset{(-)}{\nu}_\ell$ ^{56}Fe* ($\ell = e, \mu, \tau$), (physical threshold $E_\nu > 7.6\ MeV$);
and
- $\overset{(-)}{\nu}_\ell$ e^-, $\overset{(-)}{\nu}_\ell$ e^-, which yields a single signal due to the recoil electron.

II. Data taking

LVD has been taking data since June 1992 with increasing mass configurations (sensitive mass being always greater than 300 t), enough to monitor the whole Galaxy ($D < 20$ kpc) [3]. The LVD active mass since year 2001 up to April 30th 2009, is shown in figure 1. The results of the search for neutrino bursts in the period 1992-2007 have been reported in the previous editions of the ICRC (see [4] and references therein).
The results of the analysis of the last run, since May 31st 2007 to April 30 th 2009, for a total live-time of 699 days, are presented here.
The search for ν burst candidates is performed by studying the temporal sequence of H triggers and looking for clusters. The considered data set includes $\approx 12.6\ 10^6$ of such triggers. Preliminary cuts are applied to reject muons and events with an energy release lower than 7 MeV or higher than 100 MeV. The off-line neutrino burst candidate selection, widely discussed in [5], consists of the analysis of each cluster of triggers of duration up to 200 seconds. For each cluster, with multiplicity m and duration Δt, the imitation frequency F_{im} is calculated as a function of the background rate, f_{bk}, that, during the period under analysis was $\bar{f}_{bk} = 0.20$ Hz.
After this pure statistical selection a complete analysis of each detected cluster with $F_{im} \leq 1$ y^{-1} is performed, to test its consistency with a ν burst through the study of the topological distribution of pulses inside the detector. Additional information will come from the study of: *a)* the energy spectrum of the events in the cluster; *b)* the time distribution of the events in the cluster and *c)* the time distribution of delayed low energy pulses.
Only one event has been selected during the last run, with $F_{im} = 0.88$ y^{-1}. It has been analyzed in detail resulting fully compatible with background fluctuations.
The number of clusters, detected between 2007-2009, as a function of their duration (Δt), for different multiplicities (m) is shown in figure 2 compared to the expectations from Poisson statistics.

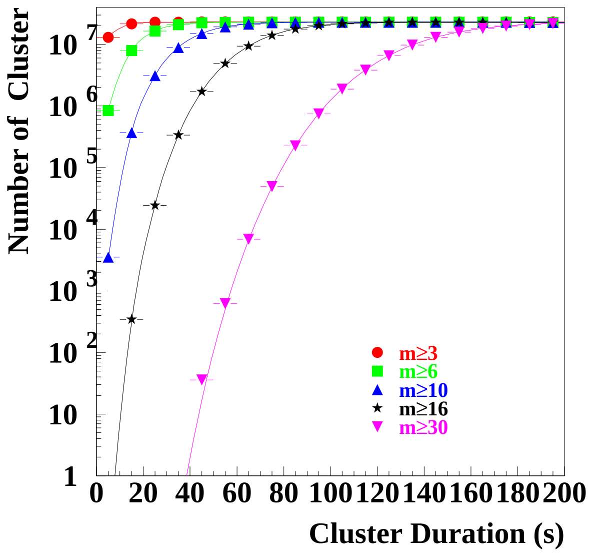

Fig. 2: Number of clusters detected during 2007-2009 as a function of their duration (Δt), for different multiplicity (m).

Each cluster of H triggers detected during this run is represented in figure 3 by a dot (Δt, m). The sensitivity of the telescope, at the level of 1 fake event every 100 years, corresponding to the LVD standalone sensitivity, is shown by a line.

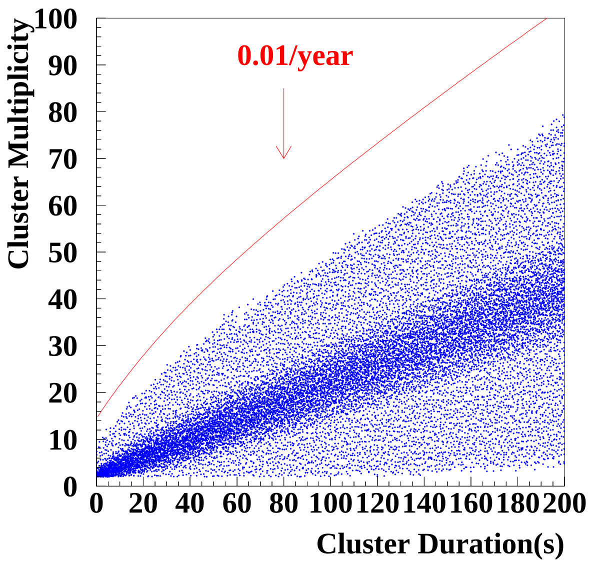

Fig. 3: Clusters ($\Delta t, m$) detected during 2007-2009. The line represents the LVD standalone alarm threshold ($F_{im} = 1 \cdot 10^{-2}$ y^{-1}).

No candidates have been found since 1992, see detail in table I, the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy is 0.15 events / year.

TABLE I: LVD data runs.

Run	Start	End	Time (days)	Uptime (%)	Mass (t)	Reference
1	Jun.6^{th} 1992	May 31^{st} 1993	285	60	310	23rd ICRC 1993
2	Aug.4^{th} 1993	Mar.11^{th} 1995	397	74	390	24th ICRC 1995
3	Mar.11^{th} 1995	Apr.30^{th} 1997	627	90	400	25th ICRC 1997
4	Apr.30^{th} 1997	Mar.15^{th} 1999	685	94	415	26th ICRC 1999
5	Mar.16^{th} 1999	Dec.11^{th} 2000	592	95	580	27th ICRC 2001
6	Dec.12^{th} 2000	Mar.24^{th} 2003	821	98	842	28th ICRC 2003
7	Mar.25^{th} 2003	Feb.4^{th} 2005	666	> 99	881	29th ICRC 2005
8	Feb.4^{th} 2005	May 31^{st} 2007	846	> 99	936	30th ICRC 2007
9	May 31^{st} 2007	Apr. 30^{th} 2009	699	> 99	967	this conference
Σ	Jun. 6^{th} 1992	Apr. 30^{th} 2009	5618	94		

TABLE II: LVD Burst Sensitivity

		F_{im} = 1 month^{-1}		F_{im} = 0.01 year^{-1}	
$E_{cut} = 7$ MeV	M_{act} (tons)	m_{min}	$S_{E_{cut}}$	m_{min}	$S_{E_{cut}}$
	1000	18	1.6 10^{-31}	22	2.1 10^{-31}
	330	10	3.0 10^{-31}	14	4.5 10^{-31}
$E_{cut} = 10$ MeV	M_{act} (tons)	m_{min}	$S_{E_{cut}}$	m_{min}	$S_{E_{cut}}$
	1000	8	8.3 10^{-32}	10	1.1 10^{-31}
	330	5	1.6 10^{-31}	8	2.6 10^{-31}

III. The Supernova On-line Monitor

Since 2001 a fast and reliable on-line ν-burst monitor has been implemented; the algorithm is based on the search for clusters of H triggers within a fixed time window, $\Delta t = 20$ s. The candidate is simply characterized by its multiplicity m, i.e., the number of pulses detected in Δt. All the other characteristics of the cluster, e.g., detailed time structure, energy spectra, ν flavor content and topological distribution of signals inside the detector are left to a subsequent independent analysis. In detail, the time sequence of total duration T, is scanned through a "sliding window" of duration $\Delta t = 20$ s, that is, it is divided into $N = 2 \cdot \frac{T}{\Delta t} - 1$ intervals, each one starting in the middle of the previous one (in this way the maximum unbiased time window is 10 s).

The frequency of clusters of duration 20 s and multiplicity $\geq m$, due to background, is:

$$F_{im}(m, f_{bk}) = N \cdot \sum_{\mathrm{k} \geq \mathrm{m}}^{\infty} P(k; \frac{20 \cdot f_{bk}}{s^{-1}}) \text{ ev} \cdot \text{day}^{-1} \quad (1)$$

where f_{bk} is the background counting rate of the detector for $E \geq E_{\mathrm{cut}}$, $P(k, f_{bk}\Delta t)$ is the Poisson probability to have clusters of multiplicity k if $(f_{bk}\Delta t)$ is the average background multiplicity, and N is the number of trials per day.

The search for burst candidates is performed, on-line, simultaneously for two values of the energy cut: E_{cut} = 7 MeV (f_{bk} = 0.2 Hz) and E_{cut} = 10 MeV (f_{bk} = 0.03 Hz). The chosen imitation frequencies, F_{im}, below which the detected cluster will be an on-line candidate supernova event, is 1 per 100 year working stand-alone while it is relaxed to 1 per month working in coincidence with other detectors, as in the SNEWS project [6] (and 1 per day for monitoring).

IV. On line sensitivity

The on line selection method defines a candidate as any cluster of $m \geq m_{min}$ signals within a window of $\Delta t = 20s$. For a known background rate, $m_{min} - f_{bk}\Delta t$ represents the minimum number of neutrino interactions required to produce a supernova alarm. It must be noted that in the algorithm described so far we have neglected the time distribution of signals inside the cluster and the capability of LVD to detect both products of the IBD reaction. This makes the selection algorithms

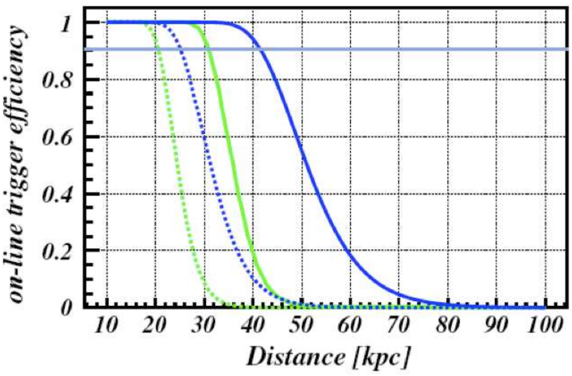

Fig. 4: On-line trigger efficiency versus distance (lower scale) and percentage of SN1987A signal at 10 kpc (upper scale) for E_{cut} = 7-10 MeV (light green and dark blue lines, respectively) and M = 330 t (dotted) and 1000 t (continuous) for LVD stand alone.

independent from the model of supernova emission and sensitive to all neutrino interactions.

If we consider only inverse beta decay (IBD) reactions, the dominant ones in LVD in the standard supernova model, and simply approximate the detector response to $E_{vis} = E_{\bar{\nu}_e} - 0.8$ MeV, we can write (see [3]):

$$m_{min} = f_{bk}\Delta t + M\ N_p\ \epsilon(E_{cut}) \int_0^{10s} dt \int_{E_{cut}+0.8MeV}^{100MeV} \Phi\cdot\sigma(E_{\bar{\nu}_e}) d(E_{\bar{\nu}_e}) \qquad (2)$$

where: M is the active mass, N_p = 9.34 10^{28} is the number of free protons in a scintillator ton, $\epsilon(E_{cut})$ is the trigger efficiency approximated as constant ($\epsilon = 0.9$ for $E_{cut} = 7$ MeV and $\epsilon = 0.95$ for $E_{cut} = 10$ MeV), $\sigma(E_{\bar{\nu}_e})$ the IBD cross section and $\Phi = \Phi(E_{\bar{\nu}_e}, t)$ the differential $\bar{\nu}_e$ intensity at the detector. The upper limit in the time integral (10 s) corresponds to the maximum unbiased cluster duration. Hence the integral on the right side of equation 2 is the detector burst sensitivity, S, in terms of minimum neutrino flux times cross section integrated over Δt and ΔE, expressed as number of neutrino interactions per proton target:

$$S_{E_{cut}} = (m_{min} - f_{bk}\Delta t)/(M \cdot N_p \cdot \epsilon) \qquad (3)$$

The values of S are shown in table II, for the two LVD thresholds of the imitation frequency, i.e., F_{im}= 1 per 100 years and F_{im} = 1 per month, two different masses, M = 1000 t and 330 t, and two values of E_{cut}. As it can be seen an important improvement is obtained by increasing the energy cut from 7 to 10 MeV.

Assuming a model for the neutrino emission and propagation, the detector sensitivity can be expressed in terms of source distance or emitted neutrino flux. In particular we adopt the following conservative values for the astrophysical parameters of SN1987A [7], [8]: average $\bar{\nu}_e$ energy $< E_{\bar{\nu}_e} >$=14 MeV; total radiated energy E_b = 2.4·10^{53} erg, assuming energy equipartition; distance D=52 kpc and average non-electron neutrino energy 10% higher than $\bar{\nu}_e$ [9], and concerning neutrino oscillations (see [2] for a discussion), we consider normal mass hierarchy. We calculate the number of inverse beta decay signals expected from a SN1987A-like event occurring at different distances, for $E_{\rm cut} = 7$ and $E_{\rm cut} = 10$ MeV. Taking into account Poisson fluctuations in the cluster multiplicity, we derive the on-line trigger efficiency as a function of the distance shown in figure 4 (lower scale) for LVD working stand-alone (the trigger efficiency, as a function of neutrino luminosity in terms of percentage of SN1987A one is shown in the upper scale).

V. CONCLUSIONS

LVD has been continuously monitoring the Galaxy since 1992 in the search for neutrino bursts from GSC. Its active mass has been progressively increased from $\sim$ 300 t in 1992 to the final 1000 t in 2001, always guaranteeing a sensitivity to GSC up to distances $D \leq 20$ kpc. The telescope duty cycle, in the last eight years, was $> 99\%$ (see tab.I).

No burst candidate has been found over 5618 days of live-time, the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy ($D \leq 20$ kpc) is 0.15 events / year.

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