

## Upper limits to low energy $\bar{\nu}_e$ flux from GRB 990705

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**Abstract.** The detection of Gamma Ray Burst GRB 990705 on 1999, July 5.66765 UT, pointing to the Large Magellanic Clouds, suggested the search for a possible neutrino counterpart, both in coincidence with and slightly before (or after) the photon burst. We exploited such a possibility by means of the LVD neutrino telescope (National Gran Sasso Laboratory, Italy), which has the capability to study low-energy cosmic neutrinos. No evidence for any neutrino signal, over a wide range of time durations, has been found, at the occurrence of GRB 990705. Due to the lack of information about both the source distance and its emission spectrum, the results of the search are expressed in terms of upper limits, at the Earth, to the  $\bar{\nu}_e$  flux · cross-section, integrated over different time durations,  $\int \int \Phi_{\bar{\nu}_e} \sigma dE dt$ . Moreover, assuming thermal  $\bar{\nu}_e$  spectra at the source, upper limits to the  $\bar{\nu}_e$  flux, integrated over time duration, for different spectral temperatures, are obtained. Based on these limits and on the expectations for  $\nu$  emission from collapsing astrophysical objects, the occurrence of a gravitational stellar collapse can be excluded up to a distance  $r \approx 50$  kpc, in the case of time coincidence with GRB 990705, and  $r \approx 20$  kpc, for the 24 hours preceding it.

**Key words.** stars: supernovae – gamma ray bursts

### 1. Introduction

Gamma Ray Burst GRB 990705 was detected on 1999, July 5.66765 UT, by the BeppoSAX Gamma-Ray Burst Monitor, and localized by the BeppoSAX Wide Field

Camera (Celidonio et al. 1999). It was promptly noted (Djorgovski et al. 1999) that its position, in projection, corresponded to the outskirts of the Large Magellanic Cloud (LMC), and it was suggested that, if the burst was indeed located in the LMC or its halo, a search for a neutrino signal, coincident with, or just prior to the GRB, would be quite interesting.

At the time of GRB 990705, the LVD neutrino observatory, located in the Gran Sasso underground Laboratory, Italy, was regularly taking data, with active scintillator mass  $M = 573$  tons. The main purpose of the telescope is the search for neutrinos from gravitational stellar collapses in the Galaxy.

On July 19th 1999, the result of a preliminary analysis of the LVD data recorded during 48 hours around the time of GRB 990705 was reported (Fulgione 1999), and the absence of a neutrino signal, that would be expected from a gravitational stellar collapse in our Galaxy, was established (no additional results from other neutrino observatories were reported).

The search for low-energy neutrinos possibly associated to GRBs is indeed of interest, especially in view of the recent observational evidence linking (some) GRBs and supernovae (see, e.g., Galama et al. 1998; Bloom et al. 1999; Reichart 1999). Many recent widely discussed models of the sources of GRBs involve the core collapse of massive stars (see, e.g., Woosley 1993; Paczynski 1998; MacFayden & Woosley 1999; Khokhlov et al. 1999; Wheeler et al. 2000): in this scenario the neutrino emission could be associated to the cooling phase of the collapsed object, the time separation between the neutrino and gamma signals depending on the time necessary to transfer energy from the central engine, which emits thermal  $\nu$ , to the outer region, emitting high energy photons.

It is clear that the possibility of detecting neutrinos correlated to GRBs depends on the distance of the associated source: even if it appears established that most of them lie at cosmological distances (Metzger et al. 1997), there is evidence, for at least one of the GRBs, to be related to a supernovae event in the local universe (Tinney et al. 1998). In particular, from the study of the afterglow of GRB 990705 (Masetti et al. 2000), although an extragalactic origin might be supported, the association with LMC cannot be ruled out.

Consequently, a more careful analysis of the LVD data in correspondence of GRB 990705 has been performed, to search for weaker neutrino signals, not only in coincidence with, but also preceding<sup>1</sup> and even shortly following it.

The paper is planned as follows: in Sect. 2 we briefly describe the LVD detector, and we explain the structure of the data. In Sect. 3 we present the results of the analysis: a search for a  $\bar{\nu}_e$  signal coincident in time with GRB 990705 has been performed. Moreover, a time interval spanning from 24 hrs preceding the burst up to 10 min later, has been scanned, searching for any non-statistical fluctuation of the background. For sake of completeness, a wider interval, since 10 days before to 1 day after the event, has been investigated. We conclude in Sect. 4, discussing the results in terms of upper limits to the  $\bar{\nu}_e$  flux possibly associated to the GRB, under the hypothesis of thermal

neutrino energy spectrum at the source, and comparing such limits with the expectations from existing models on  $\nu$  emission from collapsing objects.

## 2. The LVD experiment and the data

The Large Volume Detector (LVD) in the Gran Sasso Underground Laboratory, Italy, consists of an array of 840 scintillator counters,  $1.5 \text{ m}^3$  each, interleaved by streamer tubes, arranged in a compact and modular geometry (see Aglietta et al. 1992, for a more detailed description), with an active scintillator mass  $M = 1000$  tons. The experiment has been taking data, under different larger configurations, since 1991 (at the time of GRB 990705, the active mass was  $M = 573$  tons).

The main purpose of the telescope is the detection of neutrinos from gravitational stellar collapses in the Galaxy, mainly through the absorption interaction  $\bar{\nu}_e p$ ,  $e^+ n$ . This reaction is observed in LVD counters through two detectable signals: the prompt signal due to the  $e^+$  (detectable energy  $E_d \simeq E_{\bar{\nu}_e} - 1.8 \text{ MeV} + 2m_e c^2$ ), followed, with a mean delay  $\Delta t \simeq 200 \mu\text{s}$ , by the signal from the  $np$ ,  $d\gamma$  capture ( $E_\gamma = 2.2 \text{ MeV}$ ).

Counters can be considered as divided into two subsets: external, i.e. those directly exposed to the rock radioactivity, which operate at energy threshold  $E_{\text{th}} \simeq 7 \text{ MeV}$ , and inner (core), operating at  $E_{\text{th}} \simeq 4 \text{ MeV}$ .

In the search for antineutrino interactions ( $\bar{\nu}_e p$ ,  $e^+ n$ ), raw data are processed in order to reject muons, and filtered on the basis of the prompt pulse ( $e^+$ ) energy release and of the presence of delayed low energy signals ( $n$  capture).

We define three classes of data:

- class A: pulses with  $E_d \geq 7 \text{ MeV}$  ( $M = 573$  tons);
- class B: pulses with  $E_d \geq 7 \text{ MeV}$ , followed by a delayed ( $\Delta t \leq 600 \mu\text{s}$ ) low energy pulse in the same counter ( $M = 573$  tons);
- class C: pulses detected by core scintillators ( $E_d \geq 4 \text{ MeV}$ ), followed by a delayed low energy pulse in the same counter ( $M = 256$  tons).

The average efficiency for  $n$  detection is  $\bar{\epsilon}_n \simeq 60\%$  for the core and  $\bar{\epsilon}_n \simeq 50\%$  for the whole detector.

## 3. The analysis

As a first step, the detector performance has been checked, by studying the counting rate behavior during 48 hours around the time of GRB 990705. The number of events, detected every 15 min, is shown in Fig. 1, for the three classes of data defined in Sect. 2: the stability of the counting rate, always within statistical fluctuations, confirms the reliability of the detector.

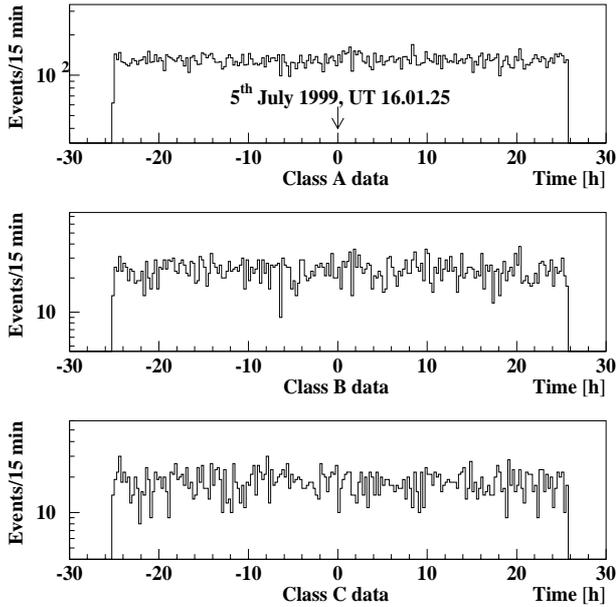
### 3.1. In coincidence with GRB 990705

The search for a signal in time coincidence with GRB 990705 has been performed by comparing the number of signals ( $N_d$ ), recorded during time windows having different duration  $\delta t$ , centered on the GRB time, with

<sup>1</sup> By analogy with SN explosions modelling, where few hours are required for the shock to reach the star envelope and give rise to the sudden increase of luminosity, a similar time gap can be assumed, between neutrinos and high-energy  $\gamma$ -rays.

**Table 1.** Number of events ( $N_d$ ) detected in coincidence with GRB 990705, for different duration of the time window ( $\delta t$ ), compared with the expectations from background

Number of events	$\delta t = 1$ s	$\delta t = 5$ s	$\delta t = 10$ s	$\delta t = 20$ s	$\delta t = 50$ s	$\delta t = 100$ s
Observed: class A	0	0	0	1	7	12
$\langle N_{\text{bk}} \rangle$	0.15	0.7	1.5	2.9	7.3	14.6
Observed: class B	0	0	0	0	0	0
$\langle N_{\text{bk}} \rangle$	0.03	0.1	0.3	0.5	1.3	2.6
Observed: class C	0	0	0	0	0	1
$\langle N_{\text{bk}} \rangle$	0.02	0.1	0.2	0.4	1.0	2.0

**Fig. 1.** Counting rates in the 48 hours time window centered on the GRB 990705

the average number of signals expected from background,  $\langle N_{\text{bk}} \rangle$ . The value of  $\langle N_{\text{bk}} \rangle$  has been evaluated by using the experimental rate in the 24 hours data after the GRB time (to avoid the contamination due to a possible signal): the resulting statistical error is in any case  $< 3\%$ .

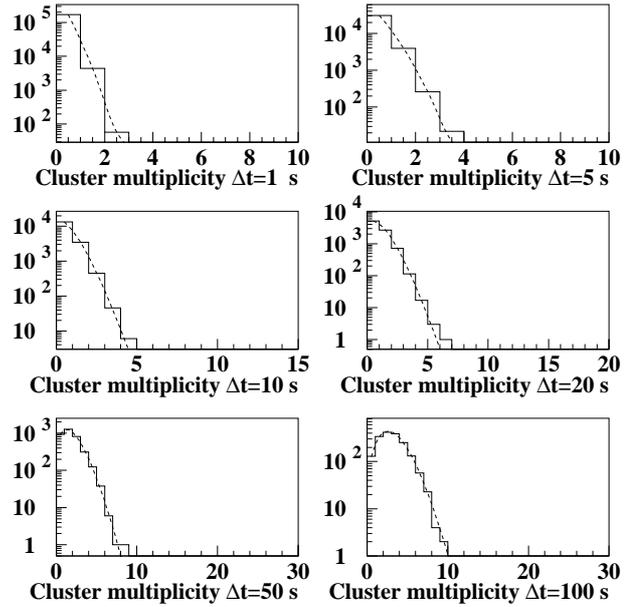
Results are summarized in Table 1, for  $\delta t = 1, 5, 10, 20, 50$  and  $100$  s. The differences between the number of detected pulses and expectations from background, for all event classes, are well within the statistical fluctuations.

No evidence for a  $\bar{\nu}_e$  signal coincident with GRB 990705 appears from this analysis.

### 3.2. Preceding (or following) GRB 990705

The search for a possible  $\nu$  burst has been extended to from 24 hours before GRB 990705 occurrence to 10 min after, for a total time  $T = 1450$  min.

The interval of interest has been divided into  $N_{\delta t} = 2 \cdot \frac{T}{\delta t}$  intervals of duration  $\delta t$ , each one starting at the middle of the previous one. The multiplicity distributions of clusters (number of events within each interval of duration  $\delta t$ ) have been studied for the three classes of data, defined in Sect. 2, and for  $\delta t = 1, 5, 10, 20, 50, 100$  s,

**Fig. 2.** Distributions of cluster multiplicity for events of class B detected during the 24 hours preceding GRB 990705. Dashed curves represent expectations from Poissonian background

and they have been compared with the expectations from Poissonian fluctuations of the background. In Fig. 2, we report, as an example, the result of the data analysis for class B events.

The agreement between data and expectations confirms the detector stability, allowing to state that there is no evidence for any detectable  $\nu$  signal during the considered period.

For sake of completeness, the same analysis has been applied to the data collected since 240 hours preceding the GRB, up to 24 hrs later. Also in this case, the data are in total agreement with the expectations from statistical fluctuations of the background.

## 4. Results and discussion

The number of expected  $\bar{\nu}_e$  interactions,  $N_{\text{ev}}$ , in a time interval  $\delta t$ , due to a pulsed  $\bar{\nu}_e$  emission, is defined as:

$$N_{\text{ev}} = M \cdot N_p \cdot \epsilon \int_0^{\delta t} dt \int_{E_{\text{min}}}^{\infty} \frac{d^2 \phi_{\bar{\nu}_e}}{dE_{\bar{\nu}_e} dt} \sigma(E_{\bar{\nu}_e}) dE_{\bar{\nu}_e}$$

**Table 2.** Upper limits (90% c.l.) to the  $\bar{\nu}_e$  flux · cross-section, at the Earth, integrated over different time intervals

$\delta t$ [s]	coincidence		24 hour preceding	
	$\int_0^{\delta t} dt \int_5^{\infty} \frac{d^2\phi_{\bar{\nu}_e}}{dE d\Omega} \sigma(E) dE$	$\int_0^{\delta t} dt \int_8^{\infty} \frac{d^2\phi_{\bar{\nu}_e}}{dE d\Omega} \sigma(E) dE$	$\int_0^{\delta t} dt \int_5^{\infty} \frac{d^2\phi_{\bar{\nu}_e}}{dE d\Omega} \sigma(E) dE$	$\int_0^{\delta t} dt \int_8^{\infty} \frac{d^2\phi_{\bar{\nu}_e}}{dE d\Omega} \sigma(E) dE$
1	$1.7 \cdot 10^{-31}$	$4.3 \cdot 10^{-32}$	$5.9 \cdot 10^{-31}$	$1.9 \cdot 10^{-31}$
5	$1.7 \cdot 10^{-31}$	$4.3 \cdot 10^{-32}$	$5.9 \cdot 10^{-31}$	$2.4 \cdot 10^{-31}$
10	$1.7 \cdot 10^{-31}$	$4.3 \cdot 10^{-32}$	$7.4 \cdot 10^{-31}$	$2.8 \cdot 10^{-31}$
20	$1.7 \cdot 10^{-31}$	$7.5 \cdot 10^{-32}$	$8.1 \cdot 10^{-31}$	$3.5 \cdot 10^{-31}$
50	$1.7 \cdot 10^{-31}$	$8.6 \cdot 10^{-32}$	$9.6 \cdot 10^{-31}$	$5.2 \cdot 10^{-31}$
100	$2.9 \cdot 10^{-31}$	$8.6 \cdot 10^{-32}$	$1.1 \cdot 10^{-30}$	$6.0 \cdot 10^{-31}$

where  $\epsilon$  is the detection efficiency,  $M$  [ton] is the active scintillator mass,  $N_p$  is the number of free protons per scintillator ton,  $\sigma(E_{\bar{\nu}_e})$  is the neutrino interaction cross section (Vogel 1984) and  $\frac{d^2\phi_{\bar{\nu}_e}}{dE d\Omega dt}$  is the differential neutrino flux at the Earth.

In the absence of any information on the source distance and its emission spectrum, we can express the results of the search in terms of upper limits to the flux · cross-section, integrated over the time duration, at the Earth:  $\int dt \int \frac{d^2\phi}{dE d\Omega} \sigma dE$ .

These limits, calculated at 90% c.l., are reported in Table 2, for various burst duration  $\delta t$ , and they are expressed in number of interactions per target proton.

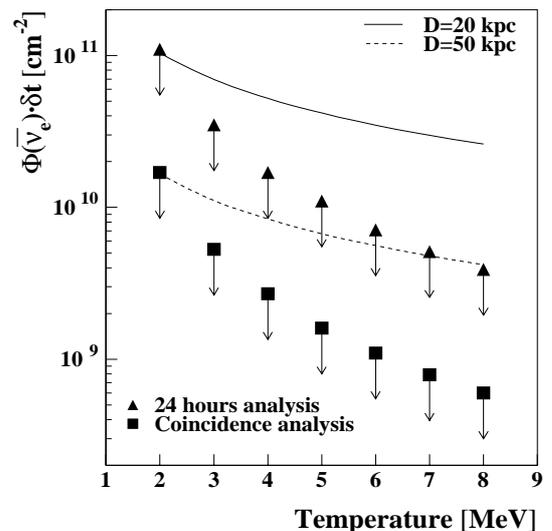
Any hypothesis on the  $\bar{\nu}_e$  source spectrum leads to a limit to the time integrated  $\bar{\nu}_e$  flux at the Earth. Assuming a thermal spectrum, constant during the emission interval  $\delta t$ , i.e.:

$$\frac{d\Phi_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} \propto \frac{\left(\frac{E_{\bar{\nu}_e}}{T_{\bar{\nu}_e}}\right)^2}{1 + \exp\left(-\frac{E_{\bar{\nu}_e}}{T_{\bar{\nu}_e}}\right)}$$

upper limits to the time integrated  $\bar{\nu}_e$  flux are obtained, as a function of the neutrinosphere emission temperature  $T_{\bar{\nu}_e}$  [MeV]. These results are shown in Fig. 3, for burst duration  $\delta t \leq 10$  s.

Most theoretical models on the  $\bar{\nu}_e$  emission from gravitational stellar collapses (Burrows 1992) predict that the neutron star binding energy,  $E_b \approx 3 \cdot 10^{53}$  erg, is emitted in neutrinos of every flavour (energy equipartition) with thermal energy spectra, during a time interval  $\delta t \approx 10$  s. The corresponding  $\bar{\nu}_e$  fluxes at the Earth, calculated, under the approximation of isotropical emission and pure Fermi-Dirac spectrum, for two different source distances: 50 kpc (i.e., corresponding to the LMC<sup>2</sup>) and 20 kpc (i.e., corresponding to the outskirts of our Galaxy), are

<sup>2</sup> One can compare these results with the neutrino flux observed from SN1987A, which was definitely located in the LMC. According to the combined analysis of the events detected by the KamiokandeII and IMB detectors (Jegerlehner et al. 1996), which yields a total emitted energy  $E_b = 3.4 \cdot 10^{53}$  erg and a  $\bar{\nu}_e$  spectral temperature  $T_{\bar{\nu}_e} = 3.6$  MeV, the resulting  $\bar{\nu}_e$  flux at the Earth, integrated over time, is  $\Phi(\bar{\nu}_e) \cdot \delta t \sim 9 \cdot 10^9 \text{ cm}^{-2}$ .

**Fig. 3.** Upper limits (90% c.l.) to the time integrated  $\bar{\nu}_e$  flux, at the Earth, for thermal  $\bar{\nu}_e$  spectra and  $\delta t \leq 10$  s, compared with expectations for different source distances

reported in Fig. 3 and are compared with the results of the burst search.

The occurrence of a gravitational stellar collapse, with  $\bar{\nu}_e$  emitted in the temperature range  $T_{\bar{\nu}_e} > 2$  MeV, can then be excluded within a region of radius  $r \approx 50$  kpc, in the case of time coincidence with the GRB 990705 event, and  $r \approx 20$  kpc, for the 24 hours preceding the GRB time<sup>3</sup>.

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<sup>3</sup> A possible effect of neutrino mixing on the signal from a gravitational stellar collapse would result in the merging of the energy spectra of neutrinos of different flavours. Because we are dealing with electron antineutrinos, which are characterized by a spectral temperature lower than the one of  $\bar{\nu}_\mu$  and  $\bar{\nu}_\tau$ , neutrino oscillation effects would lead to a hardening of the  $\bar{\nu}_e$  spectrum and, after all, to an increase of the  $\bar{\nu}_e$  detection probability. Therefore, excluding oscillations into sterile neutrinos, the limits obtained in this work would remain valid even in the case of neutrino mixing.

**References**

- Aglietta, M., Alpat, B., Alyea, E. D., et al. 1992, *Il Nuovo Cimento*, A105, 1793
- Bloom, J. S., Kulkarni, S. R., Djorgovski, S. G., et al. 1999, *Nature*, 401, 453
- Burrows, A., Klein, D., & Gandhi, R. 1992, *Phys. Rev. D*, 45, 3361
- Celidonio, G., Tarei, G., Rebecchi, S., et al. 1999, *IAU Circ.*, 7218
- Djorgovski, S. G., Kulkarni, F. A., Harrison, F. A., et al. 1999, *GCN Circ.*, 368
- Fulgione, W. 1999, *GCN Circ.*, 390
- Galama, T. J., Vreeswijk, P. M., van Paradijs, J., et al. 1998, *Nature*, 395, 670
- Jegerlehner, B., Neubig, F., & Raffelt, G. 1996, *Phys. Rev. D*, 54, 1194
- Khokhlov, A. M., Hoflich, P. A., Oran, E. S., et al. 1999, *ApJ*, 524, L107
- MacFayden, A. I., & Woosley, S. E. 1999, *ApJ*, 524, 262
- Masetti, N., Palazzi, E., Pian, E., et al. 2000, *A&A*, 354, 473
- Metzger, M. R., Djorgovski, S. G., Kulkarni, S. R., et al. 1997, *Nature*, 387, 879
- Paczynski, B. 1998, *ApJ*, 494, L45
- Reichart, D. E. 1999, *ApJ*, 521, L111
- Tinney, C., Stathakis, R., Cannon, R., et al. 1998, *IAU Circ.*, 6896
- Vogel, P. 1984, *Phys. Rev. D*, 29, 1918
- Wheeler, J. C., Yi, I., Hoflich, P., & Wang, L. 2000, *ApJ*, 537, 810
- Woosley, S. E. 1993, *ApJ*, 405, 273