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NEUTRINO OBSERVATIONS FROM SUPERNOVA 1987A

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ABSTRACT

We discuss here the characteristics of the event detected in the Mont Blanc Underground Neutrino Observatory on February 23, 1987, consisting of 5 interactions recorded during 7 sec. The measured energies of the 5 pulses, the duration of the burst, and the advance of the detection time in comparison with the first optical observation give evidence that the event can be explained in terms of detection of neutrinos emitted during the stellar collapse originating supernova 1987A in the Large Magellanic Cloud. A second event, detected in Kamiokande II 4.72 hours after the Mont Blanc detection, is not contradictory from the experimental point of view, and can be explained within reasonable theoretical expectations.

1. Introduction

An Underground Neutrino Observatory (UNO) has been built[1] by our two Institutes with the main aim to search for bursts of low-energy neutrinos from stellar collapses. The UNO has been running[2] since October 1984 in the Mont Blanc Laboratory, at a depth of 5200 hg/cm^2 of standard rock underground. The very large coverage of rock and an additional shielding allow us to operate the UNO at a very low energy threshold.

An event, considered as a candidate for a neutrino burst, was detected[3] on February 23.12, 1987, ($2^h52^m36^s$ UT). Shelton in Las Campanas Observatory (Chile) reported observation[4] made on February 24.23 of an optical supernova (SN Shelton 1987) in the Large Magellanic Cloud (LMC), 52 kpc faraway. Optical data indicate that no star brighter than magnitude 12 was present at February 23.08, and that the supernova was of magnitude 6.1 at February 23.44. About a week later the Kamiokande II collaboration reported[5] similar evidence for a second burst detected 4.72 hours after the first one observed in the UNO.

The characteristics of the event which we observed in UNO are described here. In addition, since the detection techniques in the Mont Blanc and Kamioka experiments are different, namely liquid scintillator in the first and water Cerenkov in the second, we discuss here also both signals from the experimental point of view. This comparison shows that the 2 bursts are not in contradiction. Hence we can conclude that they are an indication of a double neutrino emission from supernova 1987A.

2. The Mont Blanc Underground Neutrino Observatory.

The neutrino telescope (see fig.1) is a 90 ton Liquid Scintillation Detector (LSD) consisting of 72 counters (1.0x1.5x1.0 m^3 each) in 3 layers, arranged in a parallelepiped shape with 6x7 m^2 area and 4.5 m height. The low-energy local radioactivity background, discussed in detail elsewhere[6], from the surrounding rock is reduced by shielding each counter and the whole detector with more than 200 tons of Fe slabs. The cosmic ray muons background is very low at the depth of the Mont Blanc Laboratory: after several months of running time we measured on the average 3.5 muons per hour in the whole LSD detector.

The liquid scintillator is watched from the top of each counter by 3 photomultipliers (15 cm diameter), and the total signal of the photomultipliers is recorded if they are in 3-fold coincidence within 150 ns. Our calibrations[1], both from muons and with a ^{252}Cf source, show that a 1 MeV energy loss yields on the average 15 photoelectrons in 1 scintillation counter.

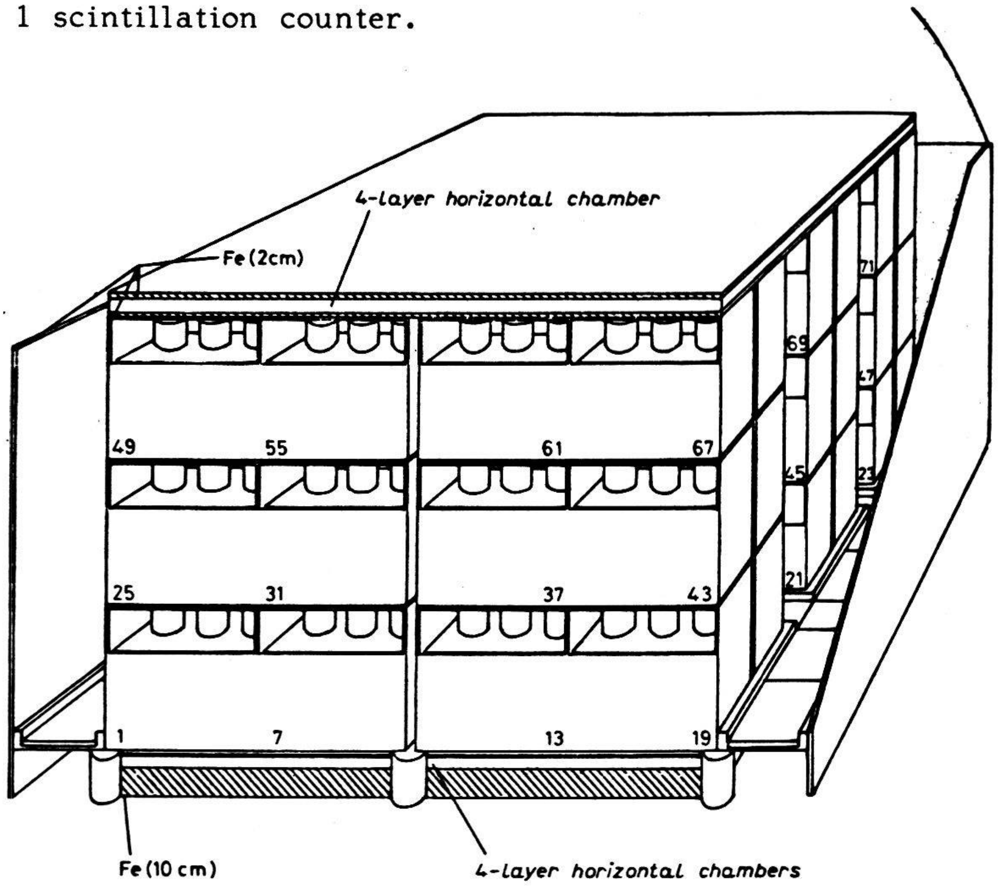

Fig. 1. – **The 90 ton liquid scintillation detector in the Mont Blanc Laboratory (dimensions (7×8×5) m³).**

The electronic system consists of 2 levels of discriminators for each scintillation counter. A high-level discriminator for pulses above the energy threshold ~ 6-7 MeV for the 56 surface counters, and ~ 5 MeV for the 16 internal ones, with a total trigger rate 0.012 Hz. A low-level discriminator for pulses above the energy threshold 0.8 MeV, active only during a 500 μs wide gate, opened for all the 72 counters by the main high-level trigger. The average counting rate of the low-level discriminator is 0.05 per gate for the internal counters, and 0.57 per gate for the external ones.

Two ADCs per counter measure the energy deposition in the scintillator in 2 overlapping energy ranges: from 4 to 800 MeV sensitive to high energy pulses, and from 0.8 to 50 MeV sensitive to the low energy ones. A TDC, automatically tested every 7 min, gives the time with a resolution of 100 ns. Three memory buffers, 16 words deep, for the 2 ADCs and the TDC of each scintillation counter, allow us to record all pulses without dead time. On-line software prints any burst of pulses satisfying our operational definition of a neutrino burst, namely a cluster of pulses above a given multiplicity in a given time.

This recording system allows us to detect both products of $\tilde{\nu}_e$

interactions with protons (namely positrons with energy above the high-level discriminator, and gammas, with energy above the low-level one, in a delayed coincidence within 500 μs), and of electrons from elastic scattering of neutrinos of other species with the electrons of the scintillator. For positron detection the pulse amplitude is given by the sum of the positron kinetic energy and the annihilation energy ($\sim$ 1 MeV) of gammas. The efficiency to detect γ's from the (np,dγ) capture reaction, in the same counter where the neutron was produced, measured by using a ^{252}Cf source as a neutron source, is $\gtrsim$ 60% when the Cf source is inserted in the central position of a scintillation counter, and $\sim$ 40% on the average.
The absolute time in LSD is recorded by using the signal broadcasted by the Italian Standard Time Service (IEN). The accuracy on the absolute time is better than 2 msec. The expected[(2)] neutrino burst, from a standard stellar collapse at the distance of the Large Magellanic Cloud, is made of 2-3 interactions during the burst duration in the LSD experiment.

3. The neutrino burst detected in UNO on Feb. 23.12

Since January 1, 1986, the LSD experiment has been running with an average efficiency of 90% (and almost 99% since October 1986). Recently, the detector shielding has been partly increased (for test purposes) with paraffin and lead in order to further decrease the low energy background from the surrounding rock.
Trigger pulses are analysed in order to have a long term statistics and to search for bursts. The experimental distributions of these pulses, grouped in bursts above a given multiplicity, are plotted in fig.2 as a function of their duration Δt. The distributions of fig.2 refer to a data taking period of 143.6 days (from September 28, 1986, to March 4, 1987). The smooth behaviour as well as the agreement with the predicted Poisson distributions (represented by the continous curves) show that the trigger counting rate is stable and the detector is properly working during this period. The detector counting rate is also checked on-line every 100 triggers. The analysis of the data taken several days before and after the event connected with the supernova 1987A shows that the apparatus was running properly throughout the entire period.
On February 23.12, 1987 ($2^h52^m36^s$ UT), an event, consisting of a burst of 5 pulses and printed in real time at the occurence, was recorded in 5 different counters (3 of them internal) during 7 seconds. Table I gives the event number, the absolute universal time (with an accuracy better than 2 msec) and the preliminary estimate values (with an accuracy better than 20%) of the visible energy of the detected pulses. A new calibration of the 72 scintillation counters at different energies is in progress. The more accurate values of the visible energies of the detected pulses seem to be lower ($\sim$10%), and

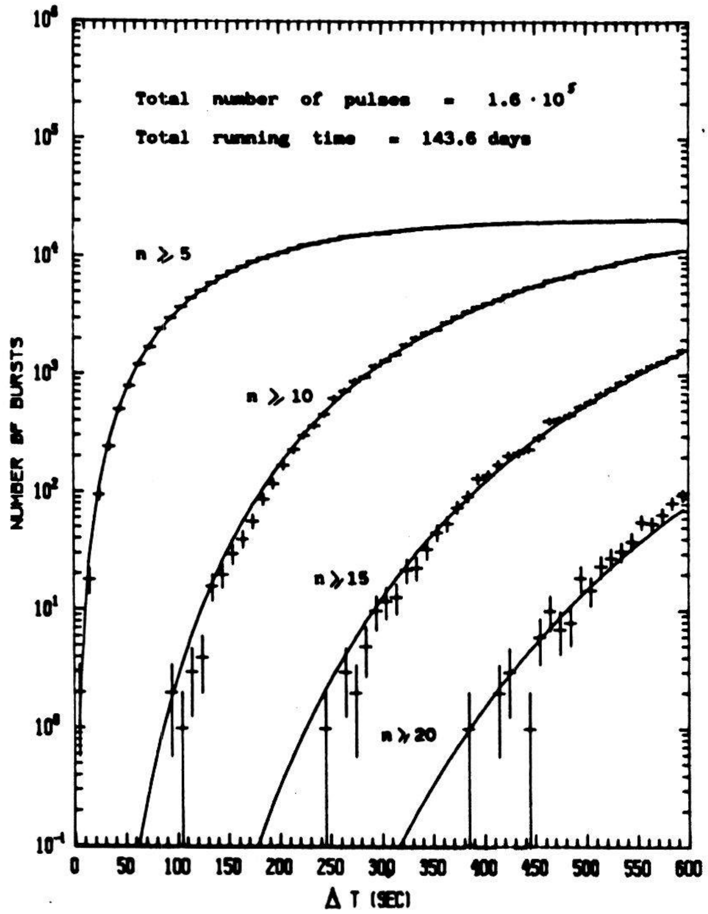

Fig.2 - Experimental distributions of bursts of pulses with multiplicity n⩾5, n⩾10, n⩾15, and n⩾20, as a function of their duration Δt (in sec), with a binning of 10 sec, measured during 143.6 days (from Sept.28, 1986, to Mar.4, 1987). The full lines are the corresponding expected distributions, assuming randomness (Poisson distribution) of the background.

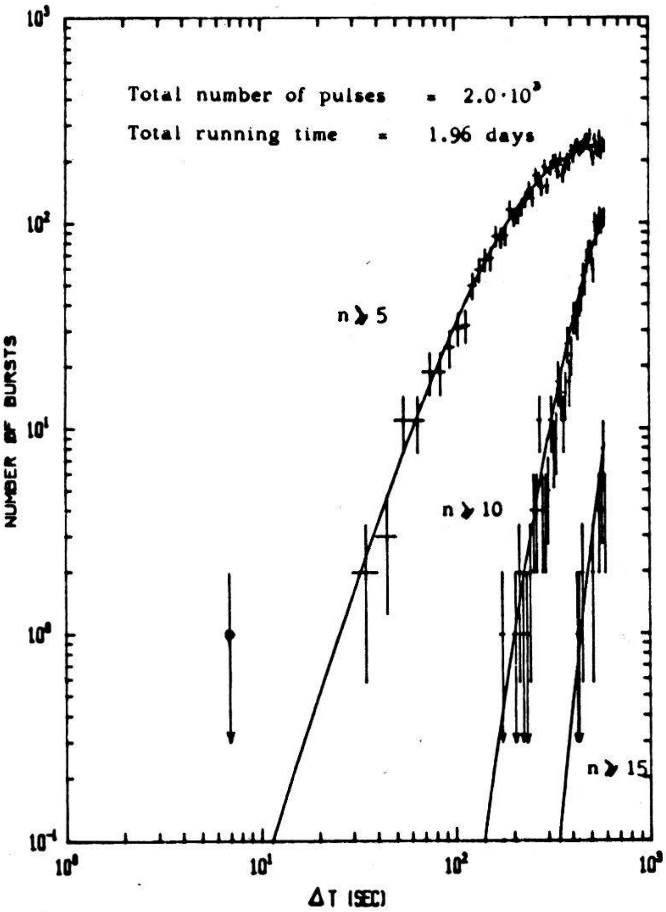

Fig. 3 - The same as for Fig.2 but for 1.96 days of data taking encompassing the event of Feb. 23.12, 1987, shown by a large dot.

Table I

event n°	time (UT)	E_v (MeV)
994	$2^h 52^m 36^s.79$	7
995	40.65	8
996	41.01	11
997	42.70	7
998	43.80	9

Table I - Event number, time (UT), and preliminary visible energy (MeV) of the pulses in the burst detected in UNO on Feb.23.12, 1987.

will be reported in a forthcoming paper.

A low energy pulse, with E = 1.2 MeV, accompanying the 3rd interaction, was detected 278 μs after the main pulse in the same scintillation counter. From the quoted efficiency to detect γ's from neutron capture, we expect on the average 2 such pulses in the 5 counters involved in the burst. We evaluate that $\sim$ 40% of neutrons can escape from the counter where they are produced, and could possibly be detected in the surrounding counters.

Figure 3 shows the distribution of the number of bursts with multiplicity $n \geqslant 5$, $n \geqslant 10$, and $n \geqslant 15$, relative to 1.96 days of data taking encompassing the event. The full lines are computed according to a Poisson distribution of the trigger counting rate, with a binning of 10 sec and mean value given by our average trigger rate, which has the value of 0.012 Hz during this run.

Excellent agreement between the expected and measured distributions is found, except for the point at t = 7 sec, which has been added just to show the event considered here. The imitation rate from the background is 0.7 per year for this burst, or $\sim 4\ 10^{-4}$ in the time interval corresponding to the uncertainty of the instant of collapse ($\sim$5 hours), as suggested by the first optical observation [4].

If we regard these low energy pulses as due to $\tilde{\nu}_e$ interactions in UNO, the emission spectrum from the neutrinosphere has to be rather soft, i.e. at a temperature of T $\lesssim$ 2 MeV, in agreement with some theoretical models [7] of collapsing stellar cores. The neutrino energy spectrum can be approximated [8] by a distribution similar to a Fermi-Dirac one, namely:

$$\Phi\left(\tilde{\nu}_e/\text{sec}\cdot\text{MeV}\right) \propto \frac{\varepsilon^2\, e^{-\alpha\varepsilon^2}}{1+e^{\varepsilon}} \qquad (1)$$

where $\varepsilon = E_\nu/KT$, with E_ν the $\tilde{\nu}_e$ energy (in MeV). The correction factor $e^{-\alpha\varepsilon^2}$ takes into account neutrino absorption in the stellar envelope above the neutrinosphere. The value $\alpha \gtrsim 0.15$ is suggested by the total mass of the supernova, $M \gtrsim 15\ M_\odot$, needed to explain the growing of the optical light curve for several weeks after the outburst.

Finally, a close coincidence in time was observed[9] between our event and data from the gravitational waves antenna operating in Rome. The detection time in the LSD is delayed of 1.4 sec in comparison with the data of the gravitational detector, within a time uncertainty of $\pm$ 0.5 sec from the antenna data. If our event is due to $\tilde{\nu}_e$'s, and assuming that the antenna signal is due to gravitational waves, from the previous arrival time values one would obtain a neutrino rest mass $m_\nu c^2 = 7.2 \pm 1.3$ eV assuming simultaneous emission of the two bursts of particles.

4. The neutrino burst detected in Kamiokande II on Feb. 23.32

The event detected in Kamiokande II on Feb. 23.32 ($7^h35^m35^s$ UT) is made of 11 pulses, with visible energies ranging from 7.5 to 35 MeV, recorded during a time of 12.4 sec. Some additional information has been obtained in other experiments: IMB[10] reported an event, consisting of 8 pulses with visible energies from 20 to 40 MeV, recorded at $7^h35^m41^s$ ($\pm$ 5 msec) during 5.6 sec.; Baxan[11] reported 3 pulses, above the energy threshold 12.5 MeV, recorded at $7^h36^m06^s$ ($\pm$ 3 sec) within 5.7 sec.

Since the IMB and Baxan observations are not in coincidence, and the time accuracy in Kamiokande is $\pm$ 60 seconds, we searched for a burst in our data near the time suggested by Kamiokande $\pm$ 1 minute. If there would have been a burst, it should have been printed on-line by our computer during its occurence, provided it is statistically significant; and, this was not the case. However, from the off-line data analysis, 2 pulses have been found, recorded with times $7^h36^m00.5^s$ and $7^h36^m18.9^s$ and visible energies 10 MeV and 9 MeV respectively. These 2 pulses may indicate a signal only if they are closely correlated in time with observations from other detectors.

5. Comparison between the two neutrino detections

As regards the neutrino burst detected at $2^h52^m36^s$ in the Mont Blanc UNO, from the temperature and α values of the neutrino spectrum quoted above, one obtains that the number of detected interactions in Kamiokande II should be $\lesssim 2.4$ times the value of the Mont Blanc UNO.

In order to estimate the number of neutrino interactions in Kamiokande II from the Mont Blanc data, it is necessary to take into account the detection peculiarities[12] of water Cerenkov in comparison with scintillation detectors. In our scintillator, the number of

free protons per unit mass is 1.39 times higher than in water, because the composition of the scintillator is C_nH_{2n+2}, with $\bar{n} = 10$. The main difference between the two techniques is given by the detection efficiency as a function of the energy. The energy threshold in UNO is lower than in Kamiokande II both for e^- and e^+. The positrons from the $(\tilde{\nu}_e p, ne^+)$ capture reaction give a visible energy in scintillator 1 MeV larger than in water Cerenkov detectors, because of the 2 gammas from e^+e^- annihilation, undetectable in Cerenkov light. In addition, the average visible energy in UNO is higher[13], about (10-15)% because of direct light collection in our scintillation counters, while about the same factor is lost in water Cerenkov detectors because of e^+ annihilation in flight. Hence, at low energy, in water (but not in scintillator) the efficiency curve for e^+ detection is appreciably smaller than for e^- of the same energy.
All these effects make a very important difference between scintillation and water Cerenkov detectors at the low energies of the $\tilde{\nu}_e$ from stellar collapses, which produce the main signal in underground detectors. Considering these detection differences, from the UNO signal with the present preliminary energies of the detected pulses, the expected signal in Kamiokane II, above the energy threshold $E_{th} \sim 6.5$ MeV for e^+ detection, should be $\lesssim (12 \pm 8)$ interactions. In effect, by looking at the data[14] of Kamiokande II close to our detection time, one sees 4 events (2 pulses with energies ~ 12 and ~ 8 Mev respectively, and 2 pulses that, within a 1 σ error, may have energies above E_{th}) spread in a time of 10 seconds. From this discussion one can conclude that the data from Kamiokande II do not contradict the burst detected at 2^h52^m in the Mont Blanc UNO. The same conclusion has been reached[15] through a systematic analysis of the 2 events detected in UNO and in Kamiokande II.
As regards the second neutrino burst at $7^h35^m35^s$, on the basis of the signal detected in Kamiokande II, we estimate that (25/17) = 1.5 would be the number of neutrino interactions in UNO, 25 being the total number of interactions expected in Kamiokande after correction for the detector's efficiency at the different energies, and 17 is the ratio of free protons in Kamiokande to free protons in UNO. Therefore, we can conclude that also in this case there is no contradiction between the two experiments.

6. Conclusions

From the above discussion, we can conclude that a reasonable, physical event can explain the two neutrino pulses. Indeed, low energy thermal neutrinos from the stellar collapse may have been detected in the Mont Blanc UNO, in time coincidence with the data of the gravitational waves antenna in Rome. This conclusion is strongly supported by the first optical detection of the supernova (at Feb.23.44) and by its subsequent luminosity and spectral evolution,

as shown by Wampler et al.[16], which agree with the start-time of the collapse as given by the Mont Blanc event time. Neutrinos detected in Kamiokande II may have been emitted in a delayed pulse from the neutron star already existing.
As already suggested[15,17,18], this interpretation seems to be a natural explanation of the two neutrino pulses, due to the formation of a neutron star and subsequently (2-9 hours later) to its collapse into a black hole. The two transitions could have originated the two pulses with the observed delay of 4.72 hours, which, because of the different energy spectra, have given different information in detectors of different type.

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