PROCEEDINGS OF SCIENCE

The SN 1987a

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Abstract

Near twenty four years ago, on February 23, 1987, the explosion of the SN in the L.M.C. has been observed both optically and by underground detectors. The optical observations were done in Chile and Australian observatories while the neutrino burst had been detected by several underground experiments in the Northern Hemisphere, running at that time: Mt. Blanc in Italy, Kamioka in Japan, and Baksan in Russia and IMB in USA. For the first time in the history of the human existence, an astrophysical phenomenon has been observed in underground detectors. In this astrophysical event, the Mt. Blanc experiment detected five pulses on-line that were not at the same time, as detected by the other three detectors around five hrs later. It is not yet oblivious to astrophysicists to have detected two bursts at two different times and how a SN can generate two neutrino bursts. Few ideas have been put forward in order to explain this phenomena, but only almost 20 years a new model has proposed in order to explain for a double stage collapse in two different times, as recently suggested by V.S. Imshennik and O. Ryazhskaya. In this paper, a detailed occurrence of something strange that happened on February 23 is presented while most of the scientific information has been already exhibited in other several published papers.

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1. Introduction

The first suggestion by G. Gamow and Schoenberg[1] in 1941 about the role of neutrinos in astrophysical phenomena happened fifteen years before the real discovery of their existence by F. Reines in 1956.

After 24 year from Gamow and Shoenberg idea, the paper of G.V. Domogatsky and G.T. Zatsepin[2] shows that the dream of detection of neutrinos from SN explosion would be reality. According to their idea it should be possible to detect the neutrinos from SN through the emission of electrons in β processes induced by them in detectors consisting of many tons of target material.

Another 35 years have passed since the dream of Domogatsky and Zatsepin has become a reality. In fact, with the present SNEWS system (Super Nova Early Warning System[3]), we will be able to provide a robust early warning of a SN occurrence to the astronomical community using a coincidence of neutrino signals around the world.

After the idea of Domogatsky and Zatsepin on 1965, experiments to detect neutrinos from SN was started by the Soviet scientists by constructing a very large detectors at Baksan, in Caucaso[4] and at Artyomovsk in Ukraine[5]. Both experiments started running on 1977.

A different approach was attempted to detect neutrinos from SN by searching for coincidences between two intercontinental detectors was made in an Italian-USA collaboration[6].

The Liquid Scintillation Detector (LSD) constructed and running under the Italian-Russian collaboration between the Russian Academy of Science, the University of Torino and the Istituto of Cosmogeofisica in the Mt Blanc tunnel. It played an important role in the neutrinos detection from SN 1987A, a detailed reminiscence of the occurrence in the original form of the real facts is presented and discussed in this review.

2. The Mt. Blanc Neutrino Detector

A collaboration between Italy and Russia (at that time USSR) foresaw since the beginning, the construction of a Liquid Scintillation Detector (LSD) dedicated to the detection of neutrinos from collapsing stars. This experiment was at the Mt. Blanc tunnel at a depth of 5200 m w.e. located at about 150 km north from Torino. The cavity was 12x6x8 m^3. The detector we chose was liquid scintillation both as a target and as a detector in a 72 iron steel tanks.

In principle all the neutrino reactions of any flavour are possible to be detected in our scintillation counters, but due to the low mass of our detector of only 90 tons and because the cross section of neutrino reactions are very small, the most important reaction was the capture of antineutrino on protons in the liquid scintillation counter.

From the beginning we took extreme care of the low energy background and accurately studied its effects on LSD detector.

The LSD started running since January 1985. Before then the Neutrino Physics and Astrophysics Conference was held at Dormund, Germany in June 1984 where amongst the main characteristics of the forecasts of the LSD neutrino detector under construction in the Mt. Blanc Laboratory, I also pointed out that 1-2 neutrino events could be detected by LSD if the SN would happen in the LMC[7].

The experimental characteristics of the apparatus are well described elsewhere by Badino et al[8]. Briefly the detector consists of 90 tons of liquid scintillation ($C_{10}H_{22}$) contained in 72 stainless-steel tanks (1.0x1.0x1.5 m^3) placed on three layers as it is shown in fig.1 Three FEU49 Russian PMs (15 cm diameter) watched each counter.

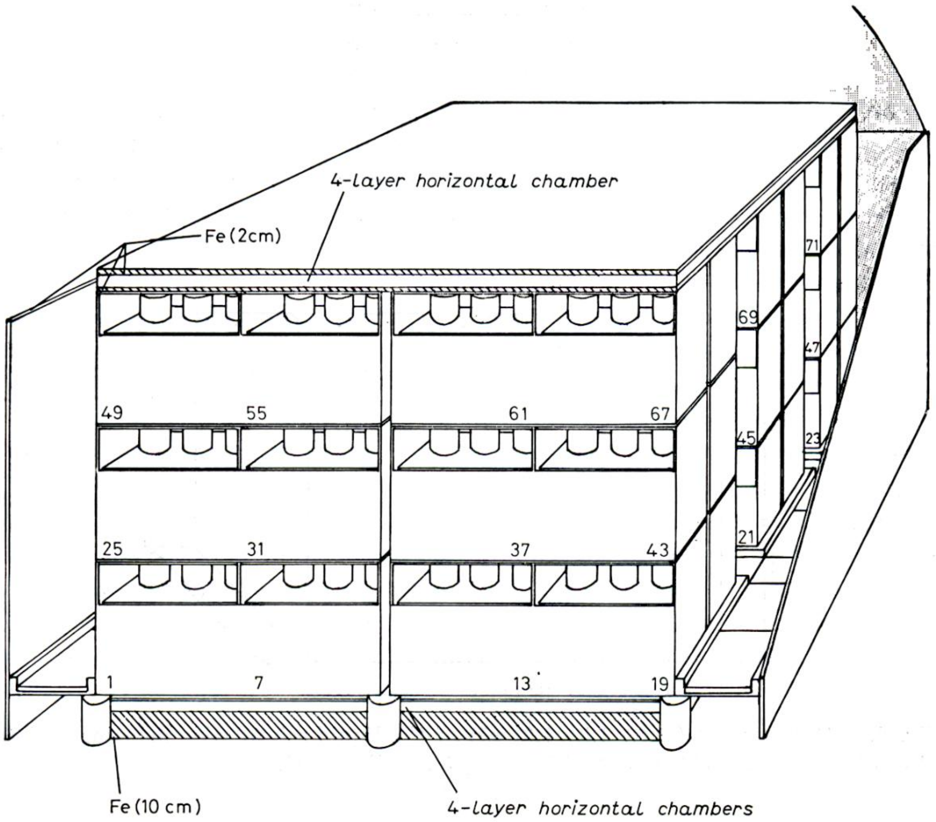

Figure 1.- The 90 ton Liquid Scintillation Detector (LSD) at Mt. Blanc laboratory. The total 200 tons shield of Fe is not shown in this figure.

Since the conception, the LSD experiment has been dedicated to the detection of antineutrinos burst from gravitational collapse of stars in our Galaxy, Saavedra et at.[7] through the antineutrino capture on the free protons from reaction (1) (energy threshold E_{th} = 1.8 MeV):

$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$\text{and} \quad n + p \rightarrow d + \gamma \qquad (1)$$

The reaccion (1) gives two signals in the time coincidence: the prompt positrons pulse with energy: $E_{el} = E_{\bar{\nu}_e} - 0.8$ MeV followed by a gamma pulse of energy $E_\gamma = 2.2$ MeV with an average delay of ~190 μs. This double pulses detection, proposed by Chudakov, Ryazhskaya and Zatsepin[9] gives a good signature for the reaction of neutrino capture in one of our detectors. The careful and systematic study of the low-energy radioactivity background spectrum was performed during several years and continuous monitoring.
In order to remove the low energy radioactivity from natural elements of the surrounding rocks of the cavity, which is the main background in the LSD, from the

beginning it was shielded by ~200 tons of Fe which was also considered as a target of heavy material for neutrino interactions.

The electronics were made with the idea of having a good signature for both reactions in (1). The prompt signal due the e^+, with energy > 5 MeV gives the trigger signal and opens a gate of 600 μsec for all the 72 tank counters. In the time duration of 600 μsec our electronic is able to lowering the threshold energy at 0.8 MeV where the n-gamma capture of 2.2. MeV is detectable. Both pulse high and time measurements are determined for any of the 72 counters.

The counter was divided according to their counting rate: those near the walls where the radioactivity was high and those internal tanks where the radioactivity was almost eliminated. A threshold of 7 MeV was set at the first class of tanks while a 5 MeV to the second one. In both cases the low energy threshold was the same: 0.8 MeV.

Every pulse was tagged by a time clock which has been given by the Italian Standard Time with an accuracy of 2ms. An electronic check to the whole detector was given every 7 min in order to have the entire detector under control at all the time.

Under the above threshold conditions the total rate was 0.012/sec while the muon counting rate was 3.5/hr.

In our LSD data acquisition system, on line software identifies on real time and prints on the computer output any burst candidate. The neutrino burst was recognized on the statistical on-line analysis by our computer on the basis of the actual frequency of events. With this system our computer was able to detect any burst of N pulses, recorded in any interval of time Δt between 1ms and 600s, this program computes the background imitation rate according to the standard distribution:

$$F_{imit} = f \sum_{n=N-1}^{\infty} P(n,\Delta t) = f \sum_{n=N-1}^{\infty} \frac{e^{-f\Delta t}(f\Delta t)^n}{n!}$$

Where f is the raw trigger rate.

In the on-line analysis if there is an abnormal burst of pulses, which is out of the computed Poisson statistics, our computer printed out the burst given the main information of the burst: the time duration of the burst, the tanks in the trigger and their pulse high, the low energy pulses if any and the imitation probability as well as the Italian time of occurrence. In off-line one is made in similar way, but including a more detailed analysis of the single pulse in the burst.

2.1 The event detected by LSD

On February 23, 1987, at 3:52 hr Italian time (2:52 UT) the LSD computer printed an alarm on-line burst of 5 pulses within 7 sec duration time. The burst has been analyzed on line by the computer given the probability of simulation by the background of $\sim 10^{-3}$ on the base of the actual frequency of the background rate of 0.012 event/sec. Such type of event was never presented before by our computer since the start of the experiment on January 1985.

Since such a burst occurred at the 3.52 in the early morning of Monday 23 February it was not observed by any operator on shift at the laboratory. It has been seen only in the morning of the same day at 8.30 by a member of our group on shift at the experiment and who called the headquarters in Torino and informed us about what our computer printed. The burst consisted of 5 pulses, distributed uniformly in the entire LSD detector. From the computer out put we can see that the tanks are 31,14,25,35 and 33. From the pulse high it appears that all pulses are low energy and in only one tank the prompt pulse is followed by a second one at 259 μs in the 500 μsec gate. The time duration of the burst is 7, 00 sec while the imitation probability is 1.7 10^{-3} per day, see Saavedra 2007[10] for more details. In Tab. 1 are shown the burst of 5 pulses detected on-line at LSD. On the same Table are shown also the two pulses detected at the IMB time.

TABLE I.- The burst of 5 pulses detected by LSD. It is included also the two pulses detected near IMB time.

Number of event	Time U.T. $\pm$ 2ms	Energy MeV
994	2 h 52 m 36.79 s	7-6.2
995	2 h 52 m 40.65 s	8-5.8
996	2 h 52 m 41.01 s	11-7.8
997	2 h 52 m 42.70 s	7-7.0
998	2 h 52 m 43.80 s	9-6.8
1285	7 h 36 m 00.54 s	8
1286	7 h 36 m 18.88 s	9

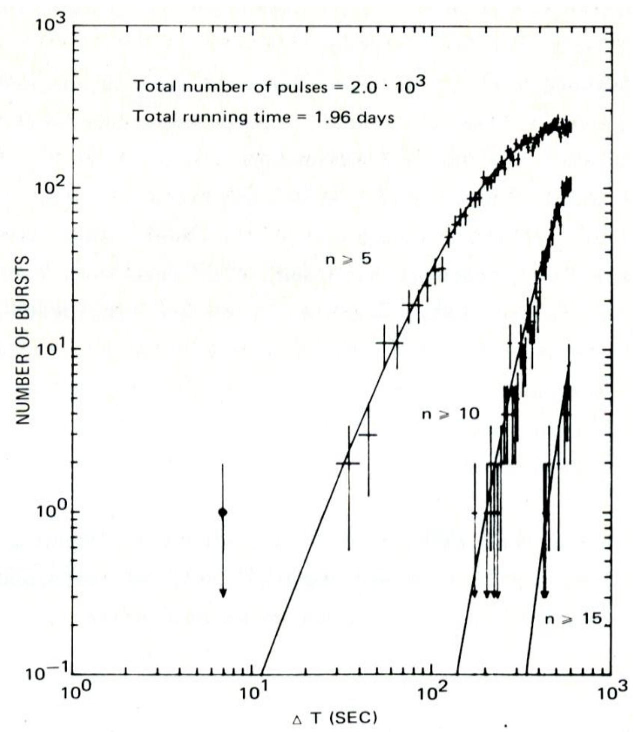

Figure 2.- Number of bursts detected at LSD as a function of time duration of the burst for 1.96 days running with multiplicity of pulses >5, >10 and >15. It is seen the burst of 5 and duration 7 s as a dot.

It was only on Wednesday 25 February that we have received the news that a SN has been optically observed in the Southern Hemisphere Observatories. Immediately we have brought the tape and analyzed our Mt. Blanc data in order to see whether or not the pulses detected in our experiment have something to do with the optically observed SN explosion in the LMC.
The analysis off-line of our data shows that everything was OK long before Feb. 23 and after the checks and discussions with our Italian-Russian colleagues, in particular checking the time of occurrence of SN explosion with the time of the probable start of the explosion by comparing with optical measurements, we decided to announce the detection of the Mt. Blanc event on Saturday February 28th on the circular No. 4323[11]

Fig. 2 shows the No of bursts as function of their duration and the multiplicity of pulses in the burst (>5, >10 and >15) in the period of 2 days. The burst of 5 pulses with 7s duration in the fig. is shown as a dot.

2.1.1 The Gravitational Antennas an LSD events

Soon after detection of the burst at LSD detector we informed the Gravitational wave antennas (thereafter called GWA) group of professor E. Amaldi at Roma where it was operating the Geograv antenna at room temperature.
Immediately after this information the Roma group found a signal in time coincidence with LSD burst. The first reports were given by LSD, Aglietta et al.[12] and by RGW, Amaldi et al.[13].
Roma group also learned that Weber antenna was operating at room temperature during the same time in Maryland (MGW). An exchange of data allowed a first comparison.
The data of RGW and MGW consists of two sequences of equally spaced, δt=1s, variations of the energy status of the GWAs.
From the beginning, the analysis of Roma and Maryland antennas in coincidence with LSD pulses shows that other than the 5 pulses burst from LSD, also other pulses in coincidence with GWA occurred during a period of few hours around the 2h 52min burst.

This was the reason why we decided to analyze a much longer period time and not limiting our attention only around Mt. Blanc burst time. In Aglietta et al.[14] is well described our analysis
In order to represent the correlations of our interest, the following quantity has been used:

$$C(\varphi) = \frac{1}{N}\sum_{i}^{1,N} x(t_i + \varphi) \qquad (2)$$

which is computed over a given period of time τ that can be the entire period under study or part of it. Here $x(t)$ indicates one of the four quantities representing the GWA data: $E_R(t), E_M(t), E_R(t) + E_M(t), E_R(t) \cdot E_M(t)$; N is number of pulses events occurring in the given period τ; t_i is the time of i-th pulse event; φ is the delay time between Mt. Blanc pulses and antennas events. It is remarkable that the quantity $C(\varphi)$ is the usual cross correlation function with time delay φ of the two time series of events of LSD and GWA. Aglietta et al.[15].
This data analysis has been applied to the interval of time from 13 hr of February 22 to 5 hr of February 23. In fig. 3 is shown the results of calculations by moving the two-hour period in steps of ½ hour for all the period under study where we can see the sum $E_R(t)+E_M(t)$ and for the product $E_R(t)$x$E_M(t)$. We notice that the correlation becomes very large around 1 to 3 hr of February 23. The calculations have been repeated excluding the 5 pulses from the burst detected

at LSD. The effect is still very clear, indicating that the contribution to it comes mainly from other LSD pulses.

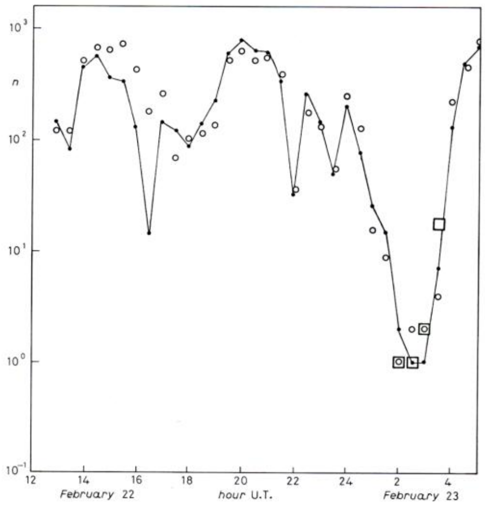

Figure 3.- The quantity n with N=1000 vs. time for the entire period under analysis calculated for two-hour periods that are moved by steps of ½ hr. The open circle are the sum and the dots the product of RGW and MGW respectively. The squares is calculated having excluded the 5 pulses of LSD burst. This fig. shows a strong correlation effect about the time of the Mt. Blanc event. See Aglietta et al. for more details [Aglietta et al., 1988].

These uncommonly coincidences occurred in about two hours encompassing the 2.52 hr of Mt. Blanc burst. We extracted the pulses in coincidence if we put a threshold on the GWA data $E(t)=E_R(t)+E_M(t) \geq 150$ K and in the window W=120 min centered at 2h 45 min during which we have N_{LSD}=96 and $N_{G.A.}$ = 172 events at LSD and at GWAs respectively. We found 13 events in coincidence. The expected number of uncorrelated events is: $\bar{n} = \frac{N_{LSD} \cdot N_{G.A.} \cdot 1s}{120\min} = 2.29$

For a Poisson distribution, the probability for 13 events to be accidental is $p(\geq 13)=9.410^{-7}$.

In fig. 4 is shown the distribution of coincidences.

From these coincidences it was very clear for us that it was of paramount importance to continue with our research of coincidence but taking into account also other underground neutrino detectors operating on February 23.

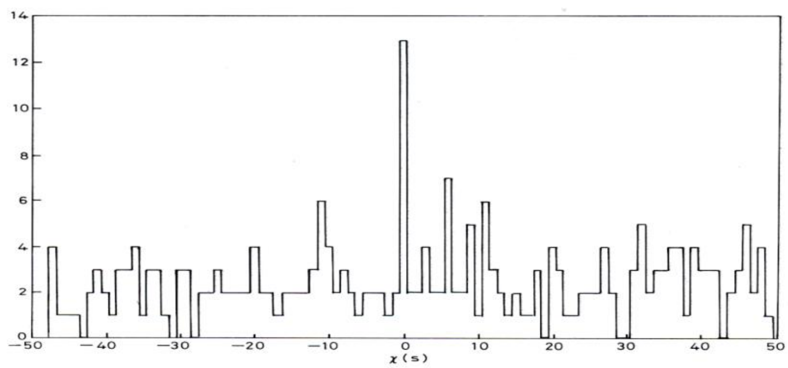

Figure 4.- The coincidences between 96 N_{LSD} and the 172 N_{GA} sum above 150 K. See Aglietta et al. for more details [Aglietta et al., 1988]

3.1 The Kamioka, Baksan and IMB events

On Monday 9th March the Japanese group announced in a press conference that the Kamiokande II experiment detected (thereafter call K2) 12 pulses but at ~5 hours after the event of Mt. Blanc time. Hirata et al.[16]. Almost at the same time, the IMB, Bionta et al.[17] and the Baksan[18] (thereafter call BST) groups gave their results in coincidence with K2 experiment.

As it is well known the K2 and IMB used water as detector while Mt. Blanc and Baksan used liquid scintillation detector. The reaction of neutrinos was the same on both types of detectors. What pulses were detected by Mt. Blanc experiment? A very quickly interpretation of these two bursts was given by De Rujula[19] as a manifestation of two bangs. The analysis of De Rujula was based on 2 events in the Kamioka data that are in coincidence with the Mt. Blanc data at the Mt. Blanc time. It seems very plausible even if the idea of two bangs was not well acceptable by the canonical standard theory of SN explosions. The events from the K2, IMB and Baksan detectors showed a number of "anomalies." For example the average $\bar{\nu}_e$ energies inferred from IMB and K2 observations are quite different. The large time gap of 7.3 s between the first 8 and the last 3 K2 events looks worrisome. The distribution of the final-state positrons from the $\bar{\nu}_e + p \rightarrow n + e^+$ capture reactions should be isotropic, but is found to be significantly peaked away from the direction of the SN, Dadykin and Ryahzskaya[20] In any case, in absence of other explanations, these features have been blamed on statistical fluctuations in the sparse data. We have analyzed accurately all our Mt. Blanc data not only during the two burst time but several days before and after these two times. It was clear that in both intervals the Mt. Blanc experiment was running properly and no cuts in statistics nor in the energy of events was necessary.

The unexpected results of the analysis of the coincidences pulses with the GWA in a period of about two hours encompassed the Mt. Blanc event, brought us to look for similar analysis also with other particle detectors. Therefore, after asking the data to the K2 group, they kindly forwarded us about 32 hours period data that included the Mt. Blanc and K2 events.

One of the things that struck at very much was that the K2 and Baksan detectors have had the errors in their clocks, $\pm$ 60 sec for K2 and + 2 minus -54 sec for Baksan, while the accuracy of IMB clock was 50 ms. Therefore, we have assumed that the time of IMB was the correct arrival time of the burst. The problem was how to conciliate the time of the pulses detected by the other two detectors.

We made an accurate analysis of the data and search for the coincidences with the same technique used among two sets of data as with the GWA, but in this case we have been forced to use a shift δt, (from 0.1 to 2.0 sec) for K2 data in the interval of ± 60 s for all the available data in our hand. The K2 times are reported with millisecond precision and an overall uncertainty of one minute. We can imagine therefore that the K2 time differences in the interval of time under consideration could be in error by no more than a fraction of a second during the time interval analyzed. The result of our analysis shows unexpected results. It shows clearly a coincidence peak only when we shift all the Kamioka data by + 7 sec. This means that all Kamioka data must be shifted by +7 sec for all the time under consideration. Assuming a coincidence window of $\Delta t = \pm 0.5$ s, as we did in the analysis with GWA data, the expected number of random coincidence is given by N= (91x191x2x0.5)/7200=2.41, where 91 and 191 are the counting rate of LSD and K2 respectively in the interval from 1:45 to 3:45 U.T. The most striking thing was the time shift for Kamioka events must be +7 sec in order to synchronize their burst with IMB one. Aglietta et al.[14].

Figure 5 shows the distribution of coincidences LSD-K2 events in the interval 1:45 to 3:45 as a function of the shift of K2 events and for a temporal window $\Delta\tau$=0.5 sec. The same analysis has been made over all the 17 intervals of two hours each from 11:45 U.T. of February 22 to 21:45 of February 23. In this period, 1462 and 2890 events have been recorded in LSD and K2 respectively; hence the number of expected random coincidences is 2.03 per interval. With the K2 time shifted by +6.9 to +7.0, the only period with significant excess of coincidences is in period previously considered, that is from 1:45 to 3:45 U.T. during which 9 coincidences have been found. In all the other 16 intervals the observed coincidences agree very well with the number expected from a Poisson distribution.

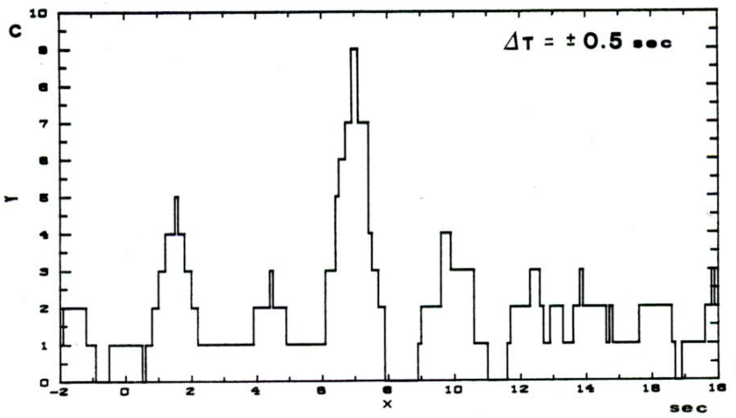

Figure 5.- Distribution of the number of coincidences between K2 and LSD in the period from 1:45 to 3:45 U.T. on 23 February 1987 a as function of the time shift in the K2 absolue time. The temporal window $\Delta\tau$ was taking to be 0.5sec.

In Figure 6 we can see a very clear peak of the distribution is in the two hrs interval from 1:45 to 3:45 of Feb 23 the distribution of the coincidence in 2 hours interval taking all available K2 data from 11:45 Feb 22 to 21:45 Feb 23 with two shifts values: 6.9 and 7.0 sec.

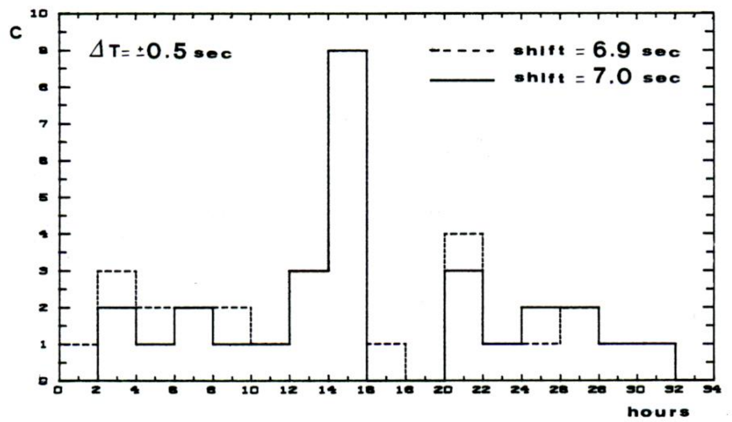

Figure 6.- Number of coincidences between Kamioka and LSD observed during 34 hours starting from 1:45 U.T. on 22 February binned in 17 time intervals of two hours each.

The analysis of GWA and K2, see Amaldi et al.[21] also gives exceptional results. The same are plotted in Fig. 7. It is clear that there is a peak in the correlations when K2 corrected the clock by ~ +7 sec. in order to be coincide with IMB clock. See Amaldi et al. [21] for more details. After these exciting results we decided to do the same analysis with Baksan data. In fact, after discussions with Prof. Chudakov we decided to exchange our data and make analysis of data quite independently. Our results are the same as those found by Chudakov[22] The results of analysis of Chudakov are given in fig. 8.

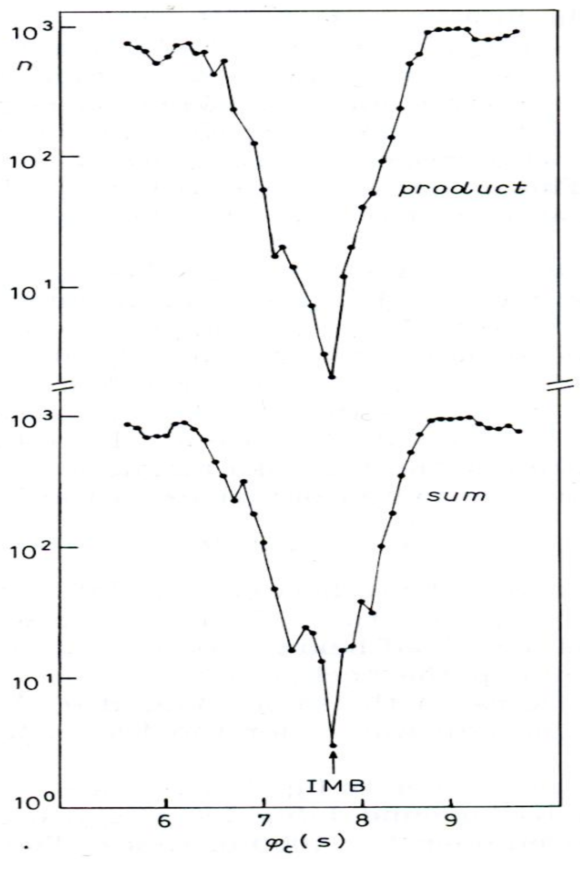

Figure 7.- Time correlation between Kamiokande data and GWA data for the period 2 hr to 3 hr of February 23. The upper curve is the product of the GWA signals while the lower is the sum of the GWA signals. It is clear the coincidence peak at ~ +7 sec.

After these exciting results we decided to do the same analysis with Baksan data.
In fact, after discussions with Prof. Chudakov we decided to exchange our data and make analysis of data quite independently. Our results are practically the same as those found by Chudakov[22] The results of analysis of Chudakov are given in fig. 8.
We can see a clear peak of coincidences when and only when the data of Baksan is sifted by -30 sec. This is fantastic because this time is exactly the time that Baksan data needs to be shifted in order to synchronize with IMB burst. Again, these positive coincidences are presented only in the two hours interval encompassing the Mt. Blanc burst at 2.52 between 1:45 to 3:45 exactly in the same time interval as the coincidences LSD-K2 occurs. The same analysis was done for the whole set of BST and LSD data by observing the coincidences per hour computed with several time shifts and coincidence windows $\Delta\tau$. The only period with a significant excess of coincidences is in the interval from 2:00 to 3:00 U.T.
We did not expected such positive result because of the fantastic nature of the phenomenon in question as mentioned by Chudakov[22].
We can see (in particular from fig. 8) that three independently analysis of data by the groups of Roma, Torino, and Baksan reach at the same conclusions: there are coincidences in a two hours interval encompassing the Mt. Blanc burst.

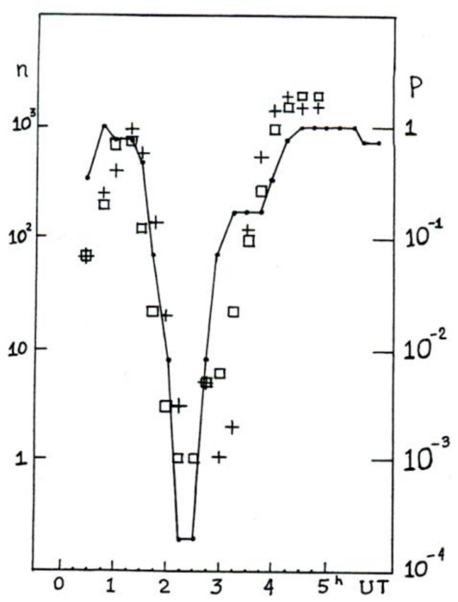

Figure 8.- The significance of observed correlations for both GWA-LSD (square and crosses and LSD-Baksan (dots and solid line) as a function of the position of the period T on the U.T. scale.

This result, together with the LSD-K2 was very rare and fantastic at the same time since the -30 sec and + 7 sec is just the time for adjust the clocks of Baksan and Kamioka with that of IMB clock. Having a look at the events it seems that there are nothing more than a background in the three underground detectors which are in coincidence.

One additional effect, that it is rather unusual, is also presented in this fatidic day of February 23: By analyzing the data from LSD from 10 February to 1 July 1987 and look for correlations among all pulses above 5 MeV we found an strange correlation of nine pairs of pulses, high energy pulses, (muons) and low-energy pulses within a time window $\Delta t = 2$ s in an interval between 5:42 U.T. and 10:43 U.T. of 23 February 1987. The frequency of such a random fluctuations of the background is ~1/(10yr). Dadykin et al[23]. 1992.
The question is if such result indicates a relationship between the temporal correlation of the pulses and the SN1987A?

4. Conclusions

In this paper I intended to limit to the chronological reminiscence of the facts occurred on February 23 1987, and to the presentation of the already published analysis data by the several groups involved in this problem. The crucial point in the analysis was the timing problem for the Kamioka and Baksan detectors. From our analysis come out that the Kamioka data we must be corrected by ~ +7 s while the Baksan data the correction is ~ -30 s. For GWA is not necessary any correction since they have an accuracy of absolute time of ± 0.1 s, see for example fig.4.
In this case the correlations would have been simulated by the background calculated from separate and independently groups are: for LSD-GWA: 10^{-5}; LSD-Baksan: $4x10^{-3}$; LSD-Kamioka: $8x10^{-4}$; GWA-Kamioka: $5x10^{-4}$ and GWA-Baksan $5x10^{-2}$. I think that it is undeniable to admit that the during SN 1987A some thing very usual occurs during few hours in the morning of February 23[25].
I would like to stress that the effects have been observed in independent, different and at intercontinental distance detectors during the SN 1987A. Furthermore, the time when the excess of coincidences is found, is centred at the time of the burst detected by LSD at Mt. Blanc. Even the double pulse correlations found by Dadykin et al. [Dadykin et al., 1992] occurs only in the morning of February 23 and it is not repeated in several months data analyzed. The question is if the probability for the double and triple coincidences is very small this effect can be aleatory? If it is not, then the problem is to give a scientific explanation that take into account for all effects of the SN gravitational explosions.
We can separate the two effects: the first one being the detection of the 5 pulses burst by LSD at 2:52. For this event there is now a the possibility that a collapsing supernova leads to two-stage collapse with a phase difference of ~ 5 hours due to the rotation of massive start. This idea was put forward by Imshennik and Ryazhskaya[24]. A very comprehensive and convinced about the analysis of the events of several detectors is given by Dadykin and Ryazhskaya.
About the second effect, coincidences pulses among several detectors in the word, there is no at the moment any plausible explanation.

Acknowledgements

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