SN1987A REVISITED

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Abstract. The measurements made with neutrino and gravitational wave detectors during the supernova SN1987A are revisited. It is found that the Kamiokande data show a second burst at $7^{h}54^{min}22.2^{sec}$ U.T., in addition to the well known one at $7^{h}35^{min}33.7^{sec}$ U.T. This second burst, consisting of a cluster of seven pulses lasting a time of 6.2 seconds, well above background, supports the idea, hinted by the LSD observation at an earlier time, that the phenomenon lasted a time much longer than a few seconds. The correlations between the g.w. detectors with the neutrino detectors are also revisited. It is shown that the g.w. detectors (Rome and Maryland) have signals correlated both with the LSD and with the Kamiokande detectors with a correlation lasting for a time of one-two hours centered, in both cases, at the LSD time.
Finally, a brief summary of the search for coincidences with the g.w. detectors EXPLORER and NAUTILUS is given.

1. Introduction

Supernova 1987A was a unique event during our time, since has occurred in the Large Magellanic Cloud, close to the Earth, and when underground neutrino detectors were taking data: LSD in the Mont Blanc, Kamiokande in Japan, IMB in the United States and Baksan in Russia.

A first neutrino burst was observed in real time at 2:52 hours U.T. of 23 February 1987 by the detector LSD located inside the Mont Blanc laboratory [1]. This event was automatically detected some hours before the optical detection of Supernova 1987A by naked eye in the southern hemisphere and it was immediately discussed on March 2 at the Reencounters de Physique de la Val d'Aoste. The SN visual detection triggered the search of pulses in the other underground detectors. A second neutrino burst was found at 7:35 hour U.T. of the same day in the data of Kamiokande [2,3], IMB [4] and Baksan [5].

The occurrence of two separate neutrino bursts, differing in time about four and half hours, appeared surprising because it did not fit the most a la page theories, according to which a gravitational stellar collapse must occur in a very short time, i.e. of the order of a few seconds or even less.

New theories were proposed suggesting that, because of fragmentation of a fast rotating core, the phenomenon could have lasted for a few hours [6,7], thus allowing both the Kamiokande and the Mont Blanc neutrino events. More recently Imshennik and Ryazhskaya [8] have proposed the collapsar model, where a detailed mechanism is developed, based on the idea that the collapsing star breaks under rotation in various pieces. In this way emission of gravitational waves could occur for several hours, precisely about five hours according to while the light fragments spiral around the collapsed massive central body.

In spite of these attempts to explain the experimental results, a large part of the scientific community persisted in the idea that the phenomenon should have lasted only a few seconds and the LSD observation were considered to be casual.

Nevertheless the problem remains open for theoretical and experimental investigations: does the phenomenon occur within a few seconds or it lasts a few hours?

New data analysis support this second possibility: it has been shown recently [9] that the Kamiokande data reveal a possible second burst, in addition to the well known one at $7^{h}35^{min}33.7^{sec}$ U.T. This second burst, discussed in the next section, consists of a cluster of seven pulses, well above the energy threshold of the detector, observed during 6.2 seconds starting at $7^{h}54^{min}22.2^{sec}$ U.T, inline with the idea of a long duration of the phenomenon, as already hinted by the Mont Blanc observations and by the correlation with the g.w. detectors.

2. Neutrino signals observed in Kamiokande

The Kamiokande data consist in a list of times and N_{hit}, being N_{hit} the number of photomultipliers hitted in the trigger. The Kamiokande group has put a threshold at N_{hit} =20, corresponding roughly to a neutrino energy of 7.5 MeV.

Using the experimental data provided to us by the Kamiokande collaboration we searched for possible trigger clustering and we found two clusters, the first one being that described by the Kamiokande collaboration of 11 pulses during 12.4 s, with a very low imitation rate from the background. Unexpectedly we found a second cluster, about 20 minutes later starting at $7^{h}54^{min}22.2^{sec}$ U.T., 7 pulses in a time window of 6.2 s with energy ranging from 22 to 33 N_{hit} and an imitation rate from the background of 1 event in 669 years.

Since muons have been removed by the list of data we received from the Kamiokande collaboration, and since the possible effects of muons on the pulses constituting the first cluster have been studied very carefully by the Kamiokande group, we believe highly improbable that the second cluster of triggers (not discussed by the Kamiokande collaboration) be due to muons. We believe that this second cluster of signals escaped to the search of the Kamiokande team.

One can find an indication of this second cluster already in the fig.4 of ref.3, from which, however, one does not realize, by looking to the figure, that the cluster consists of seven pulses in just six seconds and well above background. In the Table 1 we give the list of the pulses constituting the second burst.

hour min sec	N_{hit}
7 54 22.26	33
7 54 24.11	29
7 54 25.33	28
7 54 25.34	27
7 54 27.13	22
7 54 28.37	22
7 54 28.46	22

Table 1: List of the seven pulses for the Kamiokande second burst with duration of 6.2 s. The background gives 0.024 pulses per second above N_{hit} = 20. The probability (*a posteriori*) to have such a cluster is once in 669 years.

As far as the coincidence with the IMB detector, which has energy threshold above 20 MeV, while IMB did observe clustered signals in coincidence with the first Kamiokande cluster made by several high energy signals, it could not have observed clustered signals in coincidence with the second Kamiokande cluster, where the higher energy was of the order of less than 15 MeV.

3. Correlation of LSD and Kamiokande with the gravitational wave detectors

At the time of the SN1987A the cryogenic resonant gravitational wave detectors were not ready yet, still in the construction phase. However in Rome the room-temperature resonant detector GEOGRAV, intended to detect signals correlated with the Earth movements, was in operation.

Carlo Castagnoli immediately informed the Rome group that the LSD neutrino detector had observed a cluster of five neutrino signals, with very low Poissonian probability to be accidental, at $2^{h}56^{min}36^{sec}$ U.T. of 23 February 1987. On the next day, since GEOGRAV was in operation in the best possible noise condition, although this detector was not sensitive enough for a possible g.w., according to classical estimation of the cross-section, we carefully studied the data and found a correlation with the five-neutrino burst, with the g.w. signal anticipating the neutrino signal by 1.4 seconds. This result [10]was presented at the La Thuile meeting on 3 March 1987.

On 7 March we learned about the Kamiokande observation of a large neutrino cluster occurring about four and half hours after the Mont Blanc neutrino burst. In spite of the difficulty due to the Kamiokande observation at a later time, coincident with observation made with the IMB experiment, we thought important to continue the study of the GEOGRAV data, since there was a great chance that no other visible Supernova would have occurred for the next hundred years or so. In addition, also Joe Weber had made observations with his room temperature detectors, and these appeared to have some degree of correlation with GEOGRAV.

The key idea for our analysis was to consider all the signals recorded by the neutrino detectors[1], that is including those usually discarded as noise when not grouped together. This allowed us to analyze all the available data, and not just those occurring near the time of the Mont Blanc burst at $2^{h}56^{min}36^{sec}$ U.T. We used the following correlation algorithm [11], proposed by Sergio Frasca, based on summing the energies of the two g.w. detectors (GEOGRAV and Maryland) at the occurrence times of the neutrino signals, taking into account a possible common time shift between g.w. and neutrinos. We calculate:

$$E(\phi) = \frac{1}{N}\sum [E_R(t_i + \phi) + E_M(t_i + \phi)] \qquad (1)$$

with the following meaning for symbols:

N is the number of considered neutrino signals in a given time period for the analysis (say, one hour),

t_i indicates the time of the i^{th} neutrino signal in that time period,

E_R and E_M, (expressed in Kelvin) are the measured energy innovations for the Rome and the Maryland g.w. detectors at the times $t_i \pm 0.5$ s.

□ is a time shift common to the two g.w. detectors.

The statistical meaning of any result obtained for each value of □ with the above algorithm is checked by comparing the value of E(□) with the M values E(random) obtained by adding random time shifts □1 and □2, separately, to the two g.w. data streams, representing therefore cases with no match between the times of the g.w. measurements and the times of the measured neutrino signals. If a correlation exists at a common time delay □, we expect the value E(□) be the largest, or one of the largest among the M random values E(random) used as reference background, where M can be made very large, thanks to the independent addition of the shifts □1 and □ 2 to the data of the two g.w. detectors.

We call RO-MA the data obtained by the sum of the GEOGRAV-Rome data with the Maryland data. We found a very strong correlation of RO-MA with the Mont Blanc neutrino detector, with a time shift of □ ~-1.2 s, the g.w. signals preceding the neutrino signals, and lasting for a period of about two hours centered at the Mont Blanc time. The time shift of □ ~-1.2 s obtained with 97 neutrino signals was only 0.2 seconds off from our result presented several months before, when we used only the five-neutrino burst. This result was presented at the La Thuile meeting in March 1988, and published on Il Nuovo Cimento [12].

In fig.1 we present these results for the two periods, one and half-hour and two hours. On the abscissa we have the quantity [illegible]s, thus the maximum correlation for the two-hour plot occurs at [illegible]that is[illegible]We have used 10^6 random determinations of the background, thus $2/10^6$ expresses the strength of the correlation.

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[1] In the following, for simplicity, we use the word neutrino to indicate a pulse from the neutrino detectors, being aware that, in almost all cases, these signals are due to background.

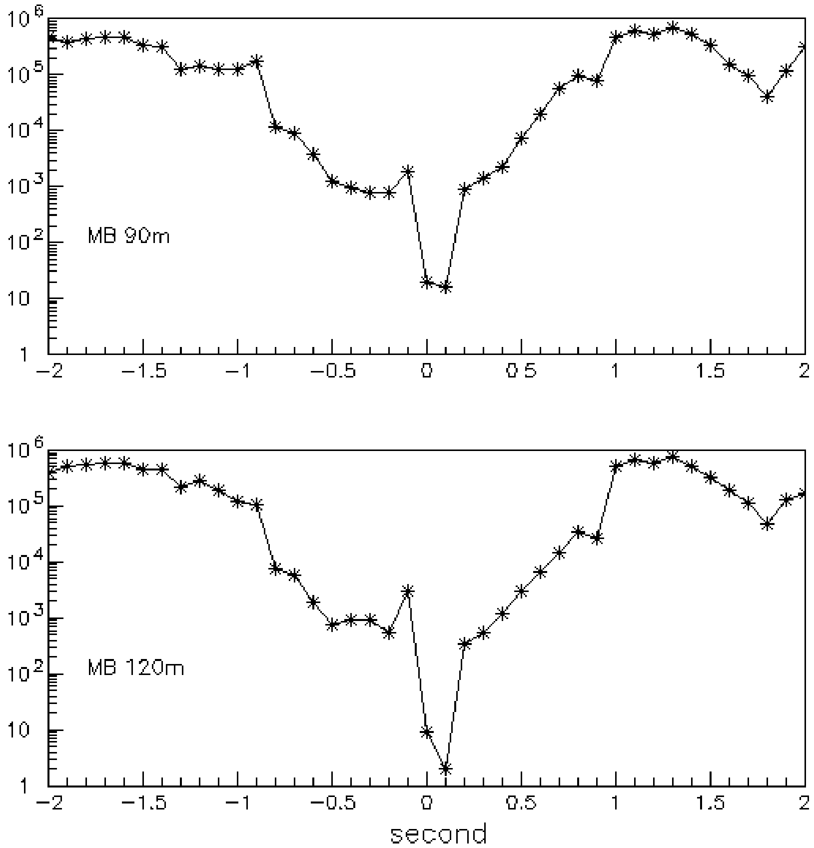

Figure 1: Correlation between the RO-MA gravitational wave detectors with the Mont Blanc neutrino detectors for two different time periods (90 minutes and 120 minutes) centered at the LSD time. On the ordinate scale we report the number of random trials (out of one million) giving $E(random) \geq E(\phi)$, versus the time delay ϕ+1.2 s.

At this point, we thought important to apply the same algorithm to the Kamiokande data. These data, recorded for an experiment aimed at the measurement of the proton lifetime, had a time uncertainty of ±1 minute but the time could be adjusted by imposing a coincidence with the IMB event at 7:35 hours. This correction was 7.8 s [13].
We obtained from Kamiokande a magnetic tape with the complete list of 31365 events (covering the day 23 February) and found a correlation with Kamiokande provided we added 7.8 s to the Kamiokande recorded time [14].

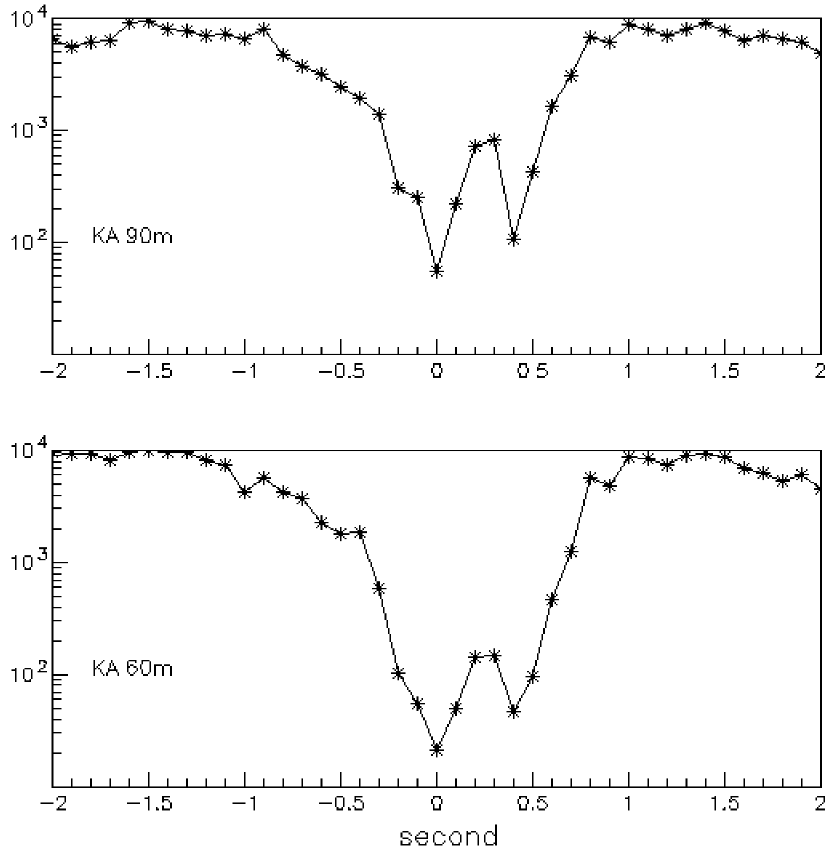

Figure 2: Correlation between the RO-MA gravitational wave detectors with the Kamiokande neutrino detector (with a time correction of +7.8 s) and for two different periods (60 minutes and 90 minutes) centered at the LSD time. Number of random trials (out of the thousand) giving $E(random) \geq E(\phi)$, versus the time delay ϕ (shifted by 1.2 s).

In fig.2 we present these results for the two periods, one and half-hour and one hour. On the abscissa we have the quantity □1□s, thus the maximum correlation for the one-hour plot occurs at □1□ □that is□ □1□sWe have used 10^4 random determinations of the background, thus $2/10^4$ expresses the strength of the correlation. We note that the correlation for Kamiokande is weaker than for LSD and extends on shorter time periods.

More recently we have studied the correlation in the entire period under study, from 0:00 UT hour and 8:00 UT hour. The correlation is calculated over one-hour time periods, running from 0.5 to 7.5 U.T. hours of February 23rd, 1987 in steps of 0.1 hour and shown in fig.3. The time of the Kamiokande experiment has been adjusted by 7.8 s.

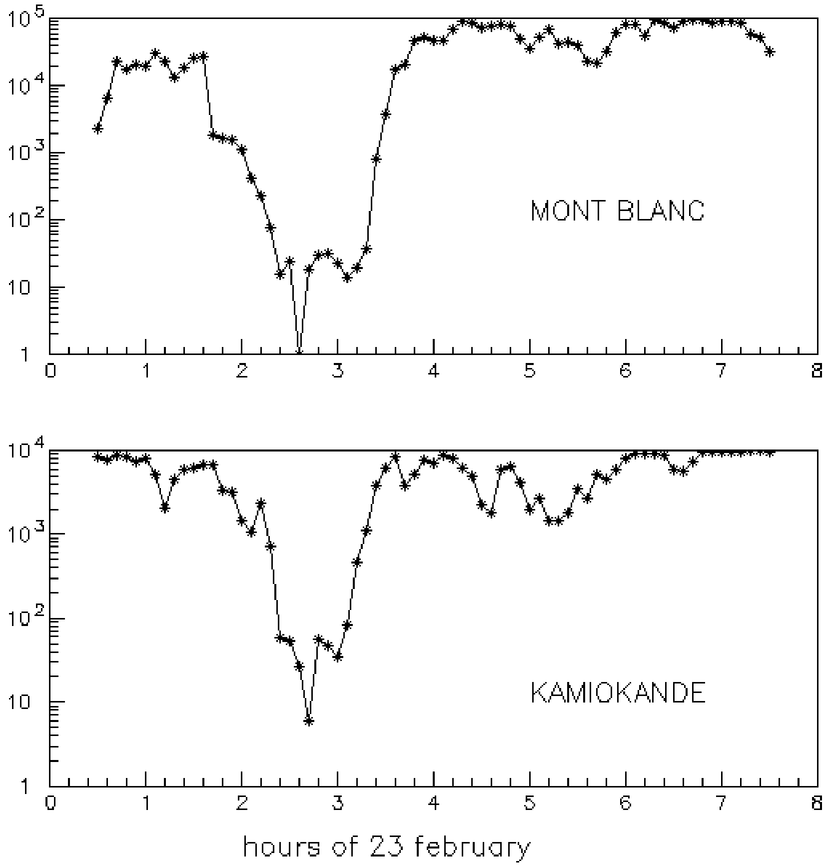

Figure 3: LSD and Kamiokande correlated with the g.w. detectors. As in Fig.1 and 2, for one-hour running time periods, from 0.5 to 7.5 UT hours, with the asterisk at the center of each time interval.
7.8 seconds have been added to the recorded Kamiokande time. The number of random times for the background evaluations are $M=10^5$ for LSD and $M=10^4$ for Kamiokande.

We notice that the data of both the two neutrino detectors are correlated with the data of the two g.w. detectors at the same time, with a striking similarity between them.

4. Discussion on the SN1987A

We have shown experimental evidence that the phenomenon connected with the supernova SN1987A had a duration of the order of a few hours. This statement is supported by the following facts:

a) the observation by LSD (threshold of 5 MeV) of neutrino signals about four and half hours before the occurrence of neutrino signals by Kamiokande (threshold of 7.5 MeV), IMB (threshold of 20 MeV) and Baksan (threshold of 10 MeV) detectors;

b) the observation of at least two signals by the Kamiokande apparatus at a time distance between them of about 20 minutes;

c) the correlation observed between the g.w. detectors and the neutrino detectors, both LSD and Kamiokande, with duration of one or two hours centered at the same LSD time ($2^h56^{min}36^{sec}$ U.).

The measurements by LSD at an early time can be explained by the lower threshold and by the use of iron in LSD (see discussion in ref. 8).

It remains the problem for the g.w. observation. The main problem with the g.w. detectors lies in the small cross-section, according to the classical theory. With this cross-section the signals observed with the g.w. detectors require a total conversion into g.w. of at least one thousand solar masses, which is impossible, provided we exclude that the g.w. have been produced in a beam and we were lucky to intercept it [15].

One cannot exclude, however, that the signals observed by the g.w. detectors are due to other causes than g.w. (exotic particles ?).

5. Coincidences between the g.w. detectors EXPLORER and NAUTILUS

In this section we give a brief summary of the search for coincident events made during the years 1998, 2001, 2003 and 2004 with the g.w. detectors EXPLORER and NAUTILUS, presented at the Eleventh Marcel Grossmann Meeting on General Relativity in Berlin (July 2006). During the above period EXPLORER and NAUTILUS were the only g.w. detectors in continuous operation.

We show in the Table 2 the main characteristics of the apparatuses.

Table 2. Main characteristics of the detectors for the coincidence search in the four years. *time* refer to the common time of operation. The coincidence window has been determined with the cosmic ray apparatuses when available.

year	detector	time	frequencies	bandwidth	window
1998	EXPLORER	94.5 days	904.7, 921.3 Hz	$\sim 0.4\ Hz$	$\pm 1\ s$
	NAUTILUS		907.0, 922.5 Hz	$\sim 0.4\ Hz$	
2001	EXPLORER	90 days	904.7, 921.3 Hz	$\sim 9\ Hz$	$3\sigma \sim 0.5\ s$
	NAUTILUS		907.0, 922.5 Hz	$\sim 0.4\ Hz$	
2003	EXPLORER	148.7 days	904.7, 921.3 Hz	$8.7\ Hz$	$\pm 30\ ms$
	NAUTILUS		926.3, 941.5 Hz	$9.6\ Hz$	
2004	EXPLORER	216.5 days	904.7, 921.3 Hz	$8.7\ Hz$	$\pm 30\ ms$
	NAUTILUS		926.3, 941.5 Hz	$9.6\ Hz$	

In the process of combining experimental data obtained in different situations, as in our case because of the continuous upgrades of the apparatuses, we are faced with the danger to make, perhaps unwilling, choices, which would affect the final statistical significance. Being aware of this, we have been careful to apply to the coincidence searches the same procedure whenever possible, in order to verify the initial result obtained in 1998. The results obtained for the coincidence search are shown in fig.4.

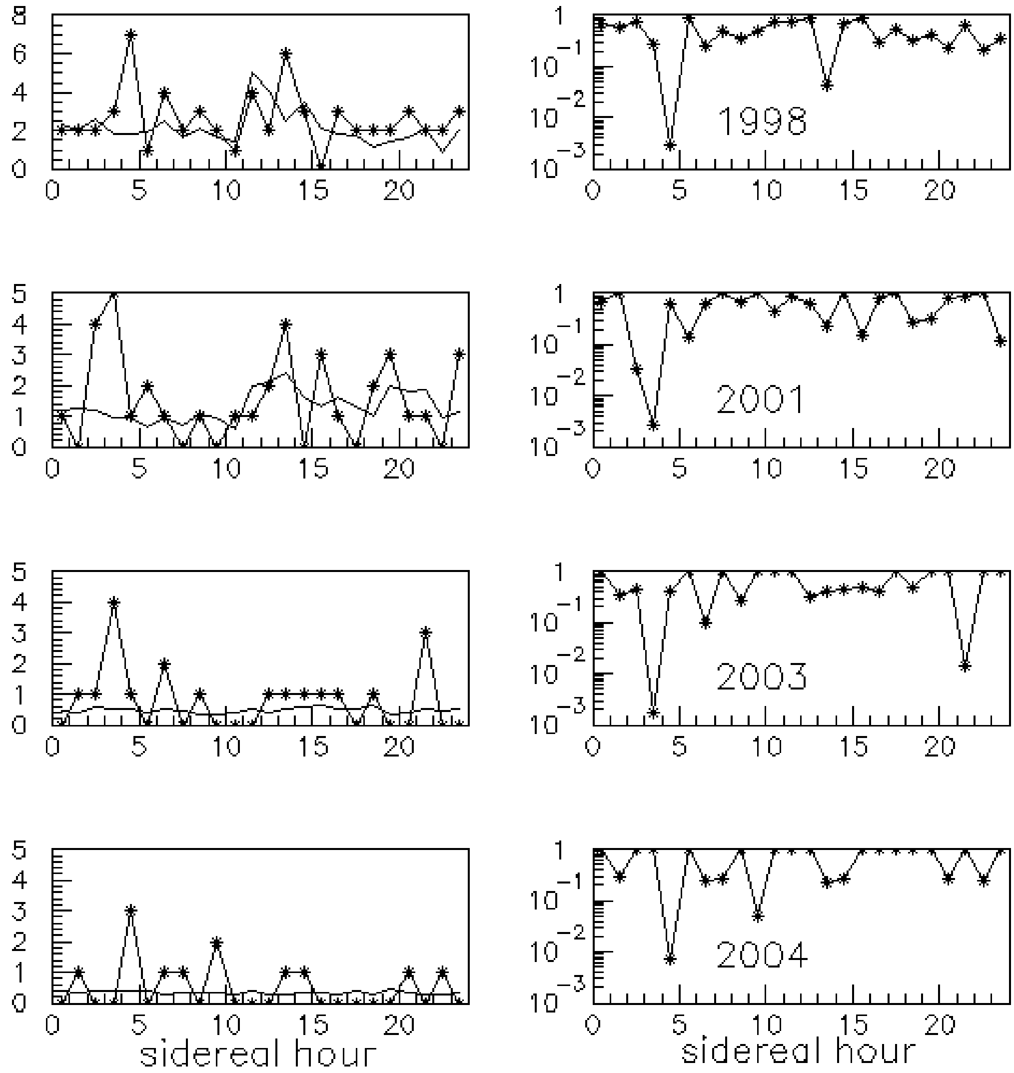

Fig.4. The left graphs show the hourly number of coincidences (data points) and the average number of accidentals (continuous line) versus the sidereal hour for each year. The right graphs show the corresponding Poisson probabilities.

In the Table 3 we give the number of coincidences and average number of accidentals for the four years. We also give the same information for the sidereal hour range when we expect signals due to sources in the galactic disk. This range, for a two-detector coincidence search, has been calculated in refs.18 and 19: 3.5 ± 1.5 sidereal hour.

Table 3: In the second column we give the threshold. In the third, fourth and fifth columns the total number n_c of coincidences, average accidentals $\bar{n}$ and the Poisson probability. In the remaining columns the number of coincidences in the sidereal hour range 2-5 and relative Poisson probability. In total we have 132 coincidences and 103.7 average accidental for a Poisson probability of 1.2 10^{-2}. In the 2-5 sidereal hour range we have 29 coincidences and 12.4 average accidental for a Poisson probability of 1.9 10^{-4}.

year	threshold	n_c	$\bar{n}$	poisson	n_c	$\bar{n}$	poisson
1998	4.3 10^{-18}	64	52.1	6.1 10^{-2}	12	6.26	2.7 10^{-2}
2001	1.6 10^{-18}	37	31.4	18 10^{-2}	8	3.06	1.3 10^{-2}
2003	1.9 10^{-18}	19	12.1	4.1 10^{-2}	6	1.60	6.0 10^{-3}
2004	1.2 10^{-18}	12	8.1	12 10^{-2}	3	1.23	13 10^{-2}

We now must attempt to combine all data in a single result. We do this by applying the following formula (see ref. 20)

$$P = P_1 P_2 P_3 P_4 \sum_{J=0}^{3} \frac{1}{J!} | P_1 P_2 P_3 P_4 |^J \qquad (2)$$

where Pi , i = 1, 2, 3, 4 are the Poisson probabilities obtained for the four years 1998, 2001, 2003 and 2004. The result is shown in the fig.5.

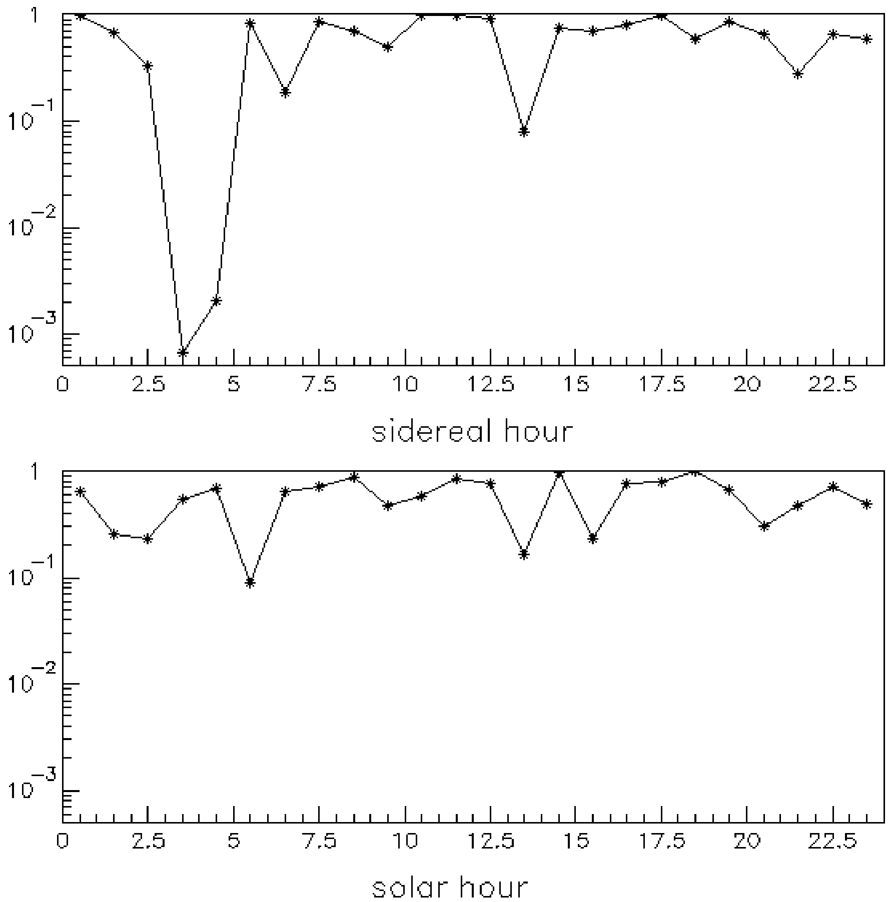

Fig.5. In the upper graph we show the combined probability, given by Eq. 2, versus the sidereal hour, in the lower graph the combined probability versus the solar hour.

We must conclude that in each year a small coincidence excess, a small excess during each year, is present at sidereal hours compatible with gravitational wave sources in the galactic disk.

The physical interpretation appears difficult with our present knowledge, also in consideration of the fact that the sensitivity of our apparatuses has changed during the years. Gravitational waves would require a cross-section larger by at least two orders of magnitude for producing the signals. But, one should not rule out, also, the possibility that dark matter be the cause of the observed coincidence excess.

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