NEUTRINOS: DETECTION AND INTERPRETATION

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ABSTRACT. Observations of the neutrino burst from Supernova 1987A by water Cherenkov detectors (KAMIOKANDE II, IMB) and liquid scintillator detectors (Baksan, Mont Blanc) are reviewed. It is shown that neutrino signal from SN 1987A was observed. There are 24 events in three detectors (KAMIOKANDE II, IMB, Baksan) recorded at 7:35 UT. The average properties of the signal (effective neutrino temperature, total energy of neutrino emission, burst duration) are consistent with the general theoretical description of supernova explosions. Special attention is concentrated on individual characteristics of the signals detected and the available discrepancies of the model estimates. Time profile of the neutrino burst, estimates of effective neutrino temperatures and total neutrino energies, angular distributions of the events are discussed. These properties point out, probably, a more compound picture of the phenomenon. The more detail analysis of the experimental data is needed and all possibilities must be at least considered. Based upon the Baksan observations, an upper limit of 0.35 core collapse in the Galaxy per year (90% C.L.) is shown.

1. THE DETECTORS

There is no doubt that the detection of the neutrino signal from SN 1987A is the remarkable corroboration of the theory of supernova explosions.

The idea of searching for neutrinos from collapsing stars suggested in 1965 by G.Zatsepin [1] led to the development of specific underground detectors with a high content of hydrogen in their targets. There were four groups looking for neutrino burst associated with this supernova: the IMB collaboration [2], the KAMIOKANDE II collaboration [3], the Baksan telescope [4], and the LSD detector of USSR-Italy collaboration [5].

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The first two detectors are water Cherenkov devices where Cherenkov light produced by relativistic charged particles measures by photomultiplier tubes. The other two detectors use liquid organic scintillator (C_9H_{20}) as a target of neutrino interactions. All of them are located underground at different depths. The main properties of the detectors and reported data are summarized in table 1.

Table 1. The detectors and reported candidates for the neutrino burst in association with SN 1987A.

Detector	Fiducial mass (t), target	Energy thresh (MeV)	Backgr rate (sec^{-1})	Number of events	Duration (sec)	Time (UT)
IMB	6800 (5000) H_2O	35	0.077	8	6.0	7:35
KAM II	2140 H_2O	8.5	0.022	11	12.5	7:35
Baksan	200 C_9H_{20}	10	0.034	5	9.1	7:35
Mont Blanc	90 C_9H_{20}	5.5	0.012	5	7.0	2:52

Arrival times of events with relative accuracy $\lesssim 1$ msec and energies with energy errors $\sim 20\%$ are defined by each detector.

The basic interaction which can be observed by both types of detectors is reaction of $\bar{\nu}_e$ absorption by freetarget protons, $\bar{\nu}_e + p \to n + e^+$. Angular distribution of positrons produced must be isotropic. It is possible to detect some additional reactions of $\nu(\bar{\nu})$ interactions in water and scintillator. The most importent of them is neutrino-electron elastic scattering, $\nu_e + e \to \nu_e + e$. A recoil electron approximately conserves a neutrino direction and angular distribution of recoil electrons will be sharply anisotropic one, showing the neutrino direction. Total contribution of other interactions $(\nu_e(\bar{\nu}_e) + {}^{16}O \to {}^{16}F({}^{16}N) + e^-(e^+)$ for Cherenkov detectors, $\nu_e(\bar{\nu}_e) + {}^{12}C \to {}^{12}N({}^{12}B) + e^-(e^+)$ for scintillation detectors) to the total number of observed events is estimated to be small [6,7].

The values of energy threshold at the level of 50% detection efficiency and background counting rates are also shown in Table 1. Evidently, the best detector is the KAMIOKANDE II (K II) due to its large mass, low energy threshold and low background rate.

2. THE DETECTION OF THE NEUTRINO SIGNAL

The details of the discovery of Supernova 1987A have been described elsewhere[8]. Three groups (table 1) reported the observations of $\bar{\nu}_e$ signals at 7:35 UT on February 23[2-4]. The Mont Blanc group observed signal of 5 events at 2:52 UT [5]. Firstly, we shall discuss the second burst detected at 7:35 UT and then we shall return to the first burst.

The overall uncertainty in time is ±1 min for the K II signal, is ±50 msec for the IMB one and is (-54 sec,+2 sec) for the Baksan one. Within errors these three signals can be supposed to be simultaneous. Figure 1 shows comparative trigger efficiencies of all detectors. The trigger efficiencies of the Mont Blanc, the K II and the Baksan are rather close each other but the IMB can detect only a high energy tail of neutrino spectrum.

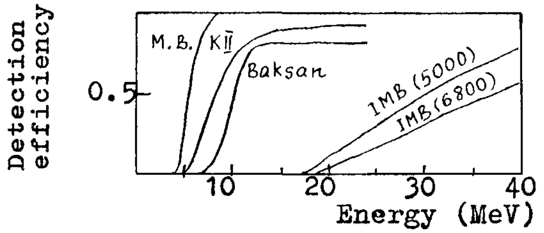

Figure 1. Comparative trigger efficiencies of all detectors.

Figure 2 shows the Poisson distributions for events within 10 sec interval detected in the period surrounding the time of Supernova. It is seen that background pulses of all detectors are well described by the Poisson law. There is usually no doubt that the KII signal and the IMB one were not originated by background. As regards the Baksan one, the chance probability of such signal to get into the one-minute interval respects to one occurrence per ~20 years. So, we can conclude that these detectors have sampled the same source of the observed events.

Figure 3 shows the observed neutrino event rate per second normalized to the individual number of the observed events versus time. Figure 4 depicts the intergrated number of neutrino events, normalized in the same way, versus time. It is remarkable that just such general evolution of the neutrino emission was predicted by different model calculations of stellar core collapse and subsequent cooling of a nascent neutron star[9,10] :

1) the evolution of the neutrino emission is approximately described as an exponentially decaying signal with characteristic time ~ 5 seconds;

2) the total duration of the neutrino signal is ~ 20 sec;

3) the detected energies of the events are consistent with thermal neutrino spectrum and the effective neutrino temperature of 3-5 MeV (if a single temperature spectrum is supposed);

4) the total energy of the neutrino emission is $\sim 3 \cdot 10^{53}$;

5) the residue of Supernova is most probably a neutron star with a mass of ~ 1.4 $M_\odot$.

The observation of the neutrino signal with the expected general characteristics is the great success of the theory and the experiment.

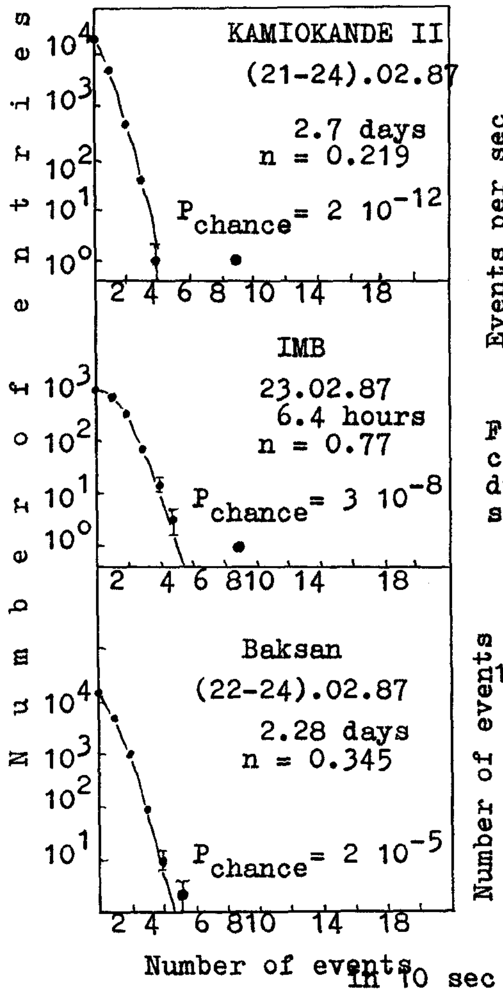

Figure 2. Poisson distributions for events within 10 sec intervals detected in the periods surrounding 7:35 UT on February 23.

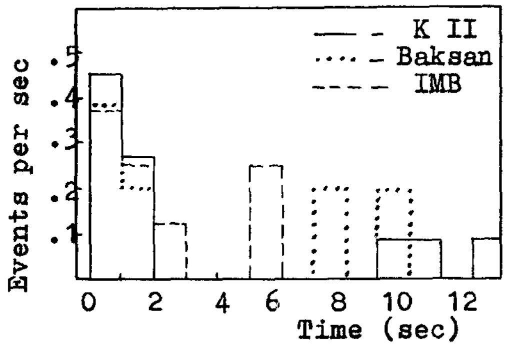

Figure 3. Event rate per second normalized to the individual total number of the observed events versus time.

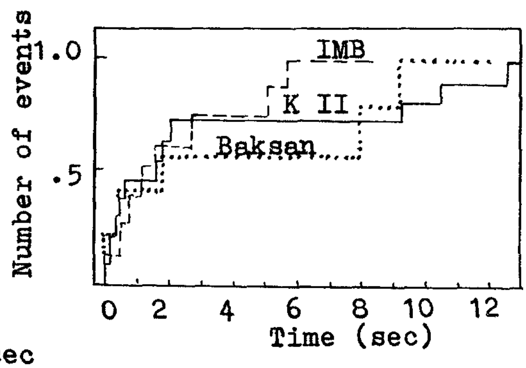

Figure 4. Integrated number of events normalized to the individual total number of the observed events versus time.

Now we shall discuss some facts most of which are ussually neglected with the reference to a "small-number statistic play". But we have the only supernova with the neutrino signal and the analysis of all, even small, facts is certainly desirable.

3. PROBLEMS

3.1. Time profile of the neutrino burst

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What is the true time profile of the observed neutrino signal? Due to the absolute time inaccuracies ,we do not know it. Figure 5a shows the ensemble of the KII and the Baksan data as a function of time, setting t=0.0 to be the time of the first events. The events of both detectors show a bunch structure in time. There are the gaps of more than 7 sec in the KII signal and of 6 sec in the Baksan one between the second and the third bunches. Based upon a constant rate of

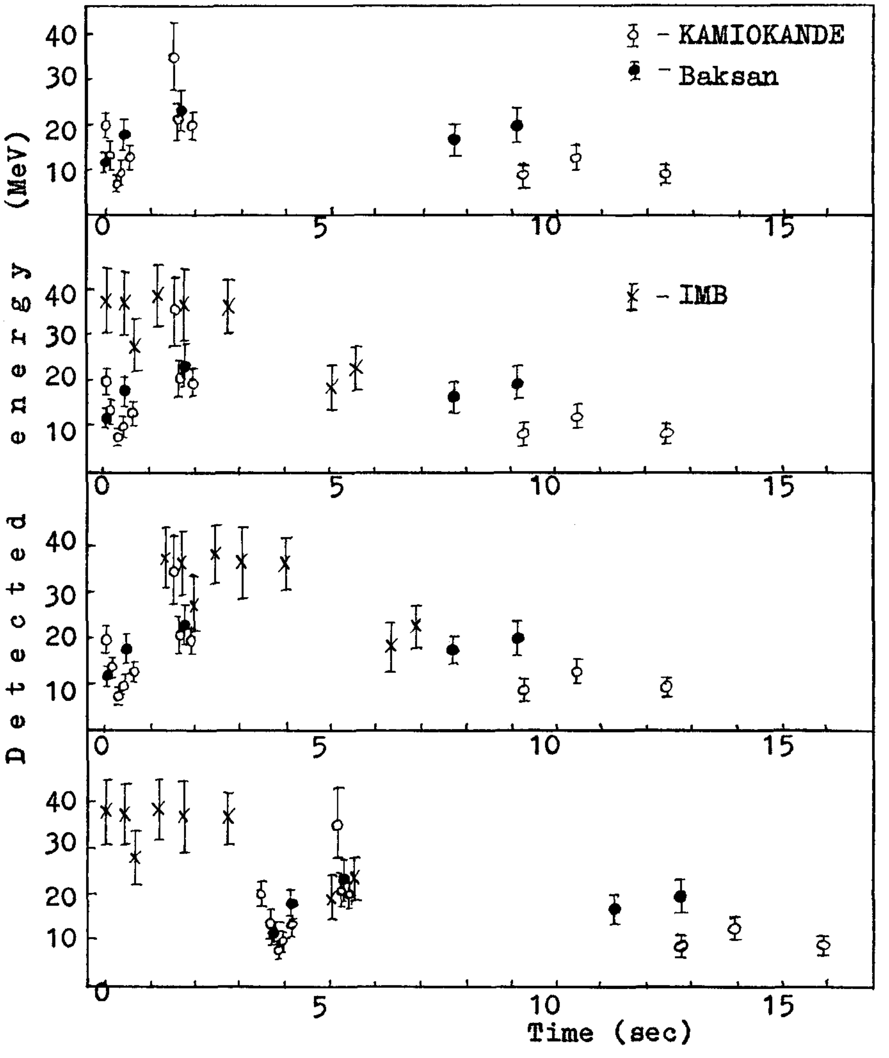

Figure 5. Time profiles of the events recorded by the KII and the Baksan (a) and by all three detectors (b), setting zero time to be the time of the first events. c) and d) depict possible time profiles of the observed signal.

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11 events in 12.4 sec, the probability that a 7 sec interval would have zero events is $2\cdot10^{-3}$ [11].The same probability of the Baksan 6 sec gap is $3.5\cdot10^{-2}$ .So, the joint probability is rather small. The first gap is statistically less significant. Thus, the appearance, at least, of 6-7 gap in both data is the question which needs to be answered.

The majority of authors superpose the IMB signal to the KII one in the way shown on fig.5b [10]. Are there serious reasons for such assumption? Due to the higher IMB energy threshold, it seems more naturally to suppose that the IMB sees the second bunch with higher energies of events (fig.5c). If this picture is true, that means that the second gap is indeed the result of small-number statistic play with low probability. But it is possible that the IMB signal passes ahead of the KII and the Baksan (fig. 5d). Outstripping can be about 3 sec. In this case the second bunch of the IMB would coincide with the second bunch of the KII-Baksan data, and the gap of 6-7 seconds remains indeed empty. Perhaps, this superposition reflects better the available data.Thus, the question on the time profile of the neutrino signal is open and all possibilities need to be considered.

3.2. Effective neutrino temperature

Derived temperatures for all data are summarized in table 2 [12].

TABLE 2. Derived effective neutrino temperatures and total energies of $\bar{\nu}_e$ emission

Detector	Average detected energy (MeV)	Neutrino temper.(MeV)	$E_{\bar{\nu}_e}^{*)}\cdot10^{52}$ (ergs)
KAMIOKANDE	16.7 ± 1.1	2.8 ± 0.3	5.8 ± 1.8
Baksan	19.4 ± 1.7	3.3 ± 0.4	18.6 ± 8.5
IMB (5000 t)	33.8 ± 2.9	4.5 ± 0.7	2.9 ± 1.1
IMB (6800 t)	33.2 ± 2.5	4.3 ± 0.6	3.2 ± 1.1

*) Distance to the star is adopted to be 50 Kpc

The estimates were obtained with the supposition of neutrino spectrum to be thermal single-temperature one. It is seen that the temperatures for the KII and the Baksan are much the same within errors, $\sim$ 3 MeV. The IMB data lead to a higher temperature, $kT_{IMB} \sim 1.5\, kT_{KII\text{-}Bak.}$.

There are at least two possibilities to reconcile data.
i) The detection of events in IMB is very sensitive to an inaccuracy of the energy threshold position.For example, inaccuracy of $\sim$20% in the energy range 20-25 MeV results in the substantial drop in the derived temperature, $\rightarrow$ 3.5 MeV.
ii) Another possibility is an assumption of neutrino spectrum in which high energy tail is considerably enhanced.

3.3. Total energy of neutrino emission

Table 2 shows also the derived total energies of $\bar{\nu}_e$ emission. The ratio of the values is (IMB:KII:Baksan) $\sim$ 0.5 : 1 : 3. Why is the Baksan estimate so large and is the IMB one so small? The Baksan signal consists of 5 events instead of 1.6 predicted by standard model [12]. The probability of such discrepancy to be the result of small-number statistic play is $\sim$ 8%. To reconcile the data we may have to assume a neutrino spectrum with enhanced high energy tail once more.

The IMB small value of $E_{\bar{\nu}_e}$ can be partly caused by the same inaccuracy in the energy threshold position which was discussed in session 3.2. Figure 6 shows the derived total energy of $\bar{\nu}_e$ emission versus $kT_{\bar{\nu}_e}$. Dashed line illustrates the IMB effect of imaginary 20% inaccuracy of the energy threshold position.

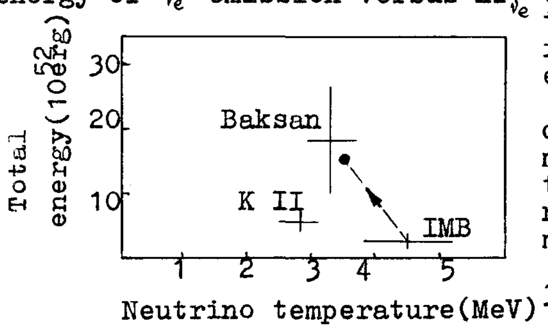

Figure 6. Derived total energy of $\bar{\nu}_e$ emission versus effective neutrino temperature.

Thus, the question on differences of the estimates of $kT_{\bar{\nu}_e}$ and $E_{\bar{\nu}_e}$, obtained for the detectors, needs to be considered in more detail.

3.4. Angular distributions of the events

Many authors have pointed out that the observed angular distributions, especially of the IMB events differ from the expected one and are quite puzzling [13]. The IMB group studied very careful all effects which could bias the expected distribution. They found the probability of the IMB distribution coming from a parent isotropic one to be only 5% [14].

3.5. The Mont Blanc signal

The Mont Blanc scintillation detector recorded a burst of 5 events within 7 seconds at 2:52 UT [5]. The chance background rate of such burst is $\sim$ 0.7 per year. During the SN period two room temperature gravitational wave antennas installed at the Universities of Maryland and Rome were in operation [15]. Analysis of the data recorded by the Mont Blanc detector and by the antennas in the period of 2 hours roughly centred on the 5 burst shows correlation between data [15]. 14 Mont Blanc events instead of 2 expected by chance coincide with antenna peaks within time interval 1.2±0.5 seconds. At present time the same analysis is performed using the data of the KAMIOKANDE II and the Baksan.

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4. SUPERNOVA RATE LIMIT

The Baksan telescope observes Galaxy since June 1980 [4]. The "live" observational time is 6.6 years. In accordance with the standard collapse model we can expect about 35-50 events if a distance to a star is 10 Kpc. We never see any pulse burst which could be definitely interpreted as a collapse neutrino signal. So, the upper limit on the collapse rate in our Galaxy is $\xi < 0.35$ per year (90% c.l.).

5. CONCLUSIONS

1)The neutrino signal from SN 1987A was observed. There are 24 events in three detectors,recorded at 7:35 UT on February 23.
2)The average derived characteristics of the burst are consistent with the general theoretical picture of supernova explosions.
3)Some individual characteristics of the observed signals (time profile of the burst, differences in model estimates of $kT_{\bar{\nu}_e}$ and $E_{\bar{\nu}_e}$, angular distribution of the events) point out, probably, more compound picture of the phenomenon.
4)The preliminary results of the joint analysis of the Mont Blanc data and two gravitational antennas show the correlation within two hours centred at 2:52 UT on February 23, which has a low level of chance probability.
5)Based upon the Baksan data obtaining during 6.6 years of "live" observational time, the upper limit on Galaxy collapse rate is $\xi < 0.35$ per year (90% c.l.).
6)The approaching observation of the SN residue will help us to understand the phenomenon in more detail.

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