The 20th Anniversary of SN1987A

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ABSTRACT

Observation of a neutrino burst from the supernova, SN1987A opened a new window of observational astronomy by neutrinos. And the history showed that the SN1987A neutrino burst observation was the vanguard of successive discoveries of neutrino properties by Super-Kamiokande, SNO, K2K, KamLAND and so on. On the occasion of the SN1987A 20th anniversary, the backstage story up to the discovery of the SN1987A neutrino bursts is summarized, tracing the Kamiokande log-note and including the IMB, LSD and Baksan data.

1. Before February 1987

1.1. Kamiokande-II

Kamiokande is an imaging water Cherenkov detector with 3000 tons of pure water in the main detector tank located at a depth of 2700 m.w.e. in the Kamioka mine. The unique feature of this experiment is the use of 1000 20-inch diameter (the world-largest photosensitive aperture) photomultiplier tubes (PMT’s), which provide a large coverage of the photosensitive area over the inner detector surface. The original motivation which stimulated the construction of the Kamiokande detector was searches for nucleon decay. The experiment started on July 6, 1983. After running the detector for several months, the careful analysis on cosmic-ray muons which are stopped in the detector and are accompanied by $\mu \to e$ decay electrons, gave us hints to detect the $^8$B solar neutrinos. From Fig.1 one can see that the lower end of the energy spectrum reaches down to $\sim 15$ MeV. Below this energy, the number of background events rises up enormously. This figure implies the possibility to detect the $^8$B solar neutrinos with a maximum energy of 14 MeV, with the aid of reasonable reduction of background events. This was the motivation for upgrading the Kamiokande detector (Kamiokande-II, Fig.2).

The Kamiokande-II construction began in September 1984. In April 1985 the renewed water purification system turned on, although the detector water was insufficient in quality of radio impurity. The trigger rate under a 8.5 MeV detection threshold energy decreased rapidly with the same decay time as that of $^{222}$Rn as shown in Fig.3. However we often suffered from water leak troubles in the purification system. This obligated us to supply fresh water into the detector tank. Consequently a big jump-up of the trigger rate occurred due to much $^{222}$Rn resolving in the fresh
mine-water, shown also in Fig.3. Fortunately such troubles calmed down until the end of December 1986. Fig.4 is the trigger rate change in 1986 and 1987.

Figure 1: Energy spectrum of observed electrons from cosmic-ray $\mu \rightarrow e\nu\bar{\nu}$ decays. 110 photoelectrons correspond to $\sim$ 30 MeV.

Figure 2: Kamiokande-II detector.

Figure 3: Trigger rate in 1985.

Figure 4: Trigger rate in 1986 and 1987.

1.2. IMB-3

The IMB detector, designed to search for proton decay, is located in the Morton-Thiokol salt mine near Fairport, Ohio at a depth of 1570 m.w.e. It consists of a rectangular tank ($22.5 \times 17 \times 18$ m$^3$) filled with 8000 ton purified water. The six sides are instrumented with 2048 5-in. PMT’s arranged on an approximate 1-m grid. The
IMB detector started operation in July 1982. Since the early phases of the experiment (IMB-1 and IMB-2) did not have a sufficient performance to allow an efficient particle identification, the detector-upgrade by replacing 5-in. PMT’s by 8-in. PMT’s with a wave shifter plate (60cm × 60cm) shown in Fig.5 was proposed in September 1983. In September 1986, IMB-3 was ready, having 4 times the light collection of IMB-1. The inner view of the IMB-3 detector is shown in Fig.6.

Figure 5: Photosensor unit : 8-in. PMT with a wave length shifter plate.

Figure 6: IMB-3 detector (from J. van der Velde, Hawaii 2007).

1.3. LSD and Baksan

The Mont Blanc Neutrino Observatory is located in the Mt. Blanc tunnel at a vertical depth of 1930 m.w.e., is a 90 ton Liquid Scintillation Detector (LSD) (Fig.7) consisting of 72 counters (1.0 × 1.5 × 1.0 m³) in 3 layers, arranged in a parallelepiped shape with (6 × 7 m²) area and 4.5 m height. The low-energy local radioactivity background from the surrounding rock is reduced by shielding each counter and the whole detector with more than 200 tons of Fe slabs. The liquid scintillator is watched from the top of each counter by 3 PMT’s (15 cm diameter). LSD has been running since January 1985.

The Baksan scintillation telescope shown in Fig.8 is located at a depth of 850 m.w.e. at the North Caucasus. It consists of 3156 standard detectors arranged in eight planes forming a parallelepiped shape with two internal horizontal layers. Each of 3156 standard detectors is an aluminum box (0.7 × 0.7 × 0.3 m³) containing oil-based liquid scintillator that is viewed by one 15 cm PMT. The total target mass is 330 tons. The data taking has been continuing since June 1980.

1.4. Summary of this section

The detection efficiencies of the above 4 detectors at the beginning of 1987 are
summarized in Fig.9 as a function of event energy. The energies of 50% detection efficiency were 5.5 MeV for LSD, 7.5 MeV for Kamiokande-II, 10 MeV for Baksan and 36.5 MeV for IMB-3. Thus 4 detectors were ready for detecting supernova neutrinos.

2. On 23-25 February 1987

On February 23, 1987 bursts of light and neutrinos reached the earth from the brightest supernova (named SN1987A, Fig.10) in 383 years since the Kepler’s supernova. Light from the explosion, ~170,000 light-years away in the Large Magellanic Cloud (LMC), a satellite galaxy of our own, was visible only in the Southern Hemisphere. The light was discovered by I. Shelton at the Las Campanas Observatory in northern Chile\(^1\) on a photograph of LMC taken in February 24.23 UT, 1987. R. McNaught, however, later reported\(^2\) that SN1987A had already been there at magnitude 6.5 in a photograph taken on 23.443 UT. On February 25, the presence of hydrogen
was observed in the spectra of SN1987A. This feature indicates that SN1987A is a type-II supernova caused by the gravitational collapse of a massive star. By comparing the supernova’s position with older photographs of LMC, the progenitor star was identified to be a hot blue supergiant star, called Sanduleak -69 202. According to the supernova theory, this means the birth of a neutron star which is accompanied by the emission of \(\sim 99\%\) of the released gravitational energy in the form of neutrinos within a few seconds. Thus the neutrino burst signals the time of core collapse, which is earlier than the time of brightening by 1–10 hours, depending on the size of the progenitor.

Figure 10: Supernova SN1987A in LMC. The left shows the immediate neighborhood of the supernova before (1977) and the right after the explosion. (photographs from European Southern observatory’s 1-m Schmidt Telescope at La Silla in Chile)

3. On 25 February 1987

The curtain of SN1987A neutrino drama was raised by the fax of February 25 sent by Sidny Bludman (Univ. of Pennsylvania) to E. Beier (Univ. of Pennsylvania), one of the Kamiokande-II US collaborators. This fax says "SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLANIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4~5, WILL REACH MAXIMUM MAGNITUDE IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!" (see Fig.11) E. Beier and I were working inside the mine to construct the air-tight structure on the detector roof.
4. On 26 February 1987

The data-tapes taken in February 20-25 were sent to Tokyo by a door-to-door delivery service. The analysis team in Tokyo rushed into developing utility-software-programs for finding neutrino burst events, using previous data samples. The team found that $N_{\text{hit}} - \text{Time}$ plot for space-reconstructed events was useful for this purpose, where $N_{\text{hit}}$ is proportional to an event energy and Time stands for event-production-time.

5. On 27-28 February 1987

The data-tapes arrived at Univ. of Tokyo. Analysis of the data started from the evening of February 27. Normal event reduction procedures and a subsequent
supernova-burst-search were carried out all day long. The team could easily found out the event-burst around 7:35 UT in the $N_{\text{hit}} - \text{Time}$ plots. The team said it was an easy work to pick up a cluster of 11 events which lasted for about 10 sec. from 500 pages of print-outs. Fig.12 and Fig.13 show the scatter plot of $N_{\text{hit}}$ against event time. The neutrino burst at 7:35:35 UT is evident in this figure. The data over a period of 2.7 days from 21 February to 24 February was searched to determine the statistical significance of the burst at 7:35:35. This is indicated by the Poisson distribution shown in Fig.14 for events with $N_{\text{hit}} \geq 20$. It is seen that the probability of occurrence of a burst with 9 events per 10 sec., based on the observed distribution in Fig.14 is less than $5.7 \times 10^{-8}$. For events with $N_{\text{hit}} \geq 30$ the probability is less than $5.2 \times 10^{-11}$. The burst was so significant. Fig.15 is the scatter plot of the burst event time and the angular correlation between the burst event and LMC. It is seen that the first 2 events point back to LMC.

6. On 1-2 March 1987

The whole story of the supernova data analysis was informed to Prof. Koshiba by M. Nakahata. Nakahata expected Prof. Koshiba’s smile for the discovery of historical event. On the contrary Prof. Koshiba did not smile and ordered Nakahata to analyze more data back to January 1 in order to make the burst sure for more significant confirmation. We rushed again into data analysis. Meanwhile on 2 March,
the news of SN neutrino detection arrived from LSD. LSD reported the burst of 5 pulses at 2:52:36 UT on 23 February 1987. This burst time is 4.5 hours before that of Kamiokande. The probability of occurrence of a burst with 5 events per 7 seconds is found to be $\sim 4 \times 10^{-4}$ (see in Fig.16).

We searched the event rate around the LSD event-time, but did not find any significant signals as shown in Fig.17. The expected event number in Kamiokande is $27 \pm 12$, using the Kamiokande detection efficiencies for the LSD event energies, the fiducial mass difference and the difference of the number of free protons (see also Fig.18). More detailed analysis was carried out with an additional trigger system in Kamiokande called a low-level trigger. This trigger system has a 50% efficiency for 6.5 MeV energy deposit and is used to monitor a trigger rate precisely, particularly for a noise-event rate. Kamiokande observed 20 events at the LSD burst time during 7-second period. On the other hand 92 events are expected, based on the LSD data. Kamiokande did not confirm the neutrino-burst at the LSD time.

7. On 2-7 March 1987

Until 6 March the data analysis was completed and the preprint was prepared. We were ready for submitting the paper. The abstract in this paper$^3$ entitled "Observation of a Neutrino Burst from the Supernova SN1987A" says that "A neutrino burst was observed in the Kamiokande-II detector on 23 February 1987, 7:35:35 UT"
Figure 18: Quick calculation of the event rate at the LSD time, based on the Kamiokande data (from my note).

\[(\pm 1 \text{ min.}) \text{ during a time interval of 13 seconds. The signal consisted of electron events of energy 7 to 36 MeV, of which the first two point back to the Large Magellanic Cloud with angles } 18^\circ \pm 18^\circ \text{ and } 15^\circ \pm 27^\circ.\] Typical burst event-patterns are shown in Fig.19.

On 7 March 1987, the paper was posted for a submission to Phys. Rev. Lett. We thought all the analysis works were finished. We had a small party in a seminar room. Our satisfied time was blown off, once one of graduate-students came into this room. He told us that our definition of the coordinate system was wrong. Soon after this, we found he was correct. We were not familiar with the right ascension-declination coordinate. Although the analysis went back to the beginning, fortunately our mistake gave only a sign-change, and what’s more we took this mistake two times. Thus \((-1) \times (-1) = (+1)\) led a minimum modification on the results. In this workshop, I heard the similar trouble had happened in IMB.

8. On 8 March 1987

The burst-analysis report of IMB was faxed to us on 8 March 1987. The report starts from ”As everyone by now, we have good evidence for having seen the supernova in the Large Magellanic Clouds from the salty depths of Cleveland . . .” Then ”First of all we began by knowing the time that Kamiokande was reporting, namely that they had a neutrino burst on 2/23 at 7:35:35 UT. Fig.20 shows the results of a scan of our data from Tape 2601 with a sliding time window of 10 seconds over a period of 20 minutes around the Kamiokande time. Note that the only data cut was to take events with \(N_{\text{hit}} < 100\). One sees a nice peak of 6 events in 2 seconds at just about the trial time. . . . . , so that the probability of coincidence is something less than \(4 \times 10^{-3}\). . . . .”
Figure 19: Tree-dimensional reproduction and exploded view of the Kamiokande burst events.

The final result of IMB was summarized in the paper entitled "Observation of a Neutrino Burst in Coincidence with Supernova SN1987A in the Large Magellanic Cloud"\(^4\). The observed signals of IMB consist of 8 neutrino events with energies in the range of 20-40 MeV, spread over an interval of 6 seconds. The burst time is 23 February, 7:35:41.37 (±50 msec.) UT. The patterns of PMT-hits for the burst events are shown in Fig.21.

Figure 20: (Left) The number of events in sliding average over 10 seconds. (Right) Distribution of the number of occurrence for 10-second window. (from the IMB report of March 8 1987)
9. On 9 March and On 6 April 1987

Kamiokande and IMB submitted their papers to Phys. Rev. Lett. on 9 March 1987. Kamiokande had a press release at the Ministry of Education (see Fig. 22). Both papers of Kamiokande and IMB were published in the April 6 1987 issue of Phys. Rev. Lett.

![Figure 22: The Kamiokande results were opened to the public on 9 March 1987.](image)

10. Baksan Data and Data Summary

Afterwards we received the report on "Detection of the Neutrino Signal from SN1987A Using the INR Baksan Underground Scintillation Telescope". A signal of 5 events within 9.1 seconds was found in the fiducial mass of 200 tons at February 23, 7:36:11.8 (+2-54)sec. The random background probability was $1.5 \times 10^{-5}$. The time sequence of events detected by the Kamiokande-II, Baksan$^6$, IMB-3 and LSD$^5$...
Fig. 23: The time-sequence structures of burst events observed in Kamiokande-II, Baksan, IMB-3 and LSD. (from E.N. Alexeyev, Hawaii 2007)

at 7:35 UT is listed is shown in Figs. 23 and 24\textsuperscript{7}) where the earliest events of three groups (Kamiokande-II, Baksan and IMB-3) are assigned at \( t = 0 \).

![SN1987A neutrino events observed by Kamiokande, IMB and Baksan](image)

Fig. 24: SN1987A neutrino events observed by Kamiokande, IMB and Baksan showed that the neutrino burst lasted about 13 seconds. (see ref.7)

11. Lucky !?

Kamiokande observed a neutrino burst from the supernova SN1987A, escaping through several accidents and happenings. We learned much about the difficulty to continue data-taking under a good detector condition which is requisite for observa-
Fig. 25 shows the most serious accident in Kamiokande. The supernova burst arrived ~2 minutes after a data-taking blind period due to an electronics gain calibration. Gain calibration of the Kamiokande electronics, generating test pulses into all of the PMT channels, was repeated every 2 hours. It took about 3 minutes each. Based on this experience, the procedure of gain checks was modified by carrying out channel by channel instead of all channels simultaneously. Thus there has been no dead time for the gain check with a victim of one rest channel.

IMB also got out of one of attempts to thwart the supernova detection. On 23 February, 5:00:00.001 UT, ~2 hours before the neutrino burst, high-voltage power supplies tripped off, shutting down one-fourth of the detector’s 2048 PMT’s. This also caused the on-line data-filtering routines to stop functioning. Fortunately, the raw data could be recovered from the partially malfunctioning detector and suffered no serious biases due to the missing PMT’s.

With the above mentioned stories, people might say that Kamiokande and IMB would be so lucky. However according to the Japanese proverb, catching good luck is a kind of ability.

12. Conclusion; On 11 June 1988

On 11 June 1988, Prof. L. Okun had the summary talk of Neutrino’88 in Boston. He made comments on "To predict the year of explosion of a supernova is not harder than to predict the year of funding a big accelerator or a big detector. I expect that
the date of the next supernova is 2003 ± 15 years.” We have to be more serious to detect next supernovae. We say “Another SN soon - nearer, but not too near”.

13. References

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