ON THE NEUTRINOS FROM SN 1987a

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ABSTRACT

The reported neutrino events from the Supernova SN 1987a have been critically analysed for their implications on the Supernova parameters and neutrino masses.

THE sighting of a Supernova[1], named 1987a, in the large Magellanic cloud, and reports of detection of neutrinos from it, have led to great excitement among the scientific community. The Mont-Blanc detector[2] has reported to have observed 5 pulses over an interval of 7 sec on 23 February at 0.124 UT (2:52:00 UT) above a 7-MeV threshold; the Kamioka detector[3], has reported a total of 12 pulses over an interval of 13 sec on 23 February at 7:35:35 (±1 min.) UT above a 7.5 MeV threshold; the IMB detector[4] has reported 8 events in a duration of 6 sec at the same time as the Japanese detector (23 February 1987 at 7:35:41.45 UT).

The detection of neutrinos from supernovae is important from many diverse points of view. From the astrophysical side it provides valuable information about the supernova phenomenon. In contrast to optical, radio, infrared measurements etc neutrinos provide a more direct glimpse of the core. Their detection is almost as close as one can get to directly observing gravitational collapse. Detection of neutrinos from suprnovae could in principle also throw light on such issues as neutrino masses, mixing, their interaction with matter, etc.

In this paper we analyse the observed events for their implication on such issues. Ideally such an analysis should be performed independent of the theoretical perceptions one may have of supernovae. But the inadequacies of observations which are inherent when data sample is small may tend to distort the actual picture. An analysis of Kamioka events with equal weightage yields a spectrum with an essentially constant average energy of 10 MeV over 12 sec, yet with bins well separated in time. This is hard to reconcile with a hot core (~ 20 MeV) which is cooling by neutrino emission. We have therefore opted to base our analysis in the framework of theoretical supernovae models studied widely in the literature, with the hope that both observation and theory will benefit in the process. Specifically, we have relied on the models of supernovae due to Wilson *et al*[5] and a recent work of Burrows and Lattimer[6] that models in detail the first 20 sec in the life of a neutron star. Much of the uncertainty in the present models concerns the details of shock formation, core bounce and ejection of the outer mantle[7]. Neutrino emission, on the other hand, appears to be better understood[5,6].

The bulk of the neutrinos with which we shall be concerned are emitted when the lepton-rich hot core settles down to a neutron star. The core mass has been found to be insensitive to the initial mass of the star; it varies in the range 1.3–2.0 $M_\odot$ as the star mass varies from 10–15 $M_\odot$[5,8]. This core finally settles down to a neutron star by losing about 10% of its mass as thermal emission of neutrinos with energy 10 ~ 20 MeV (for cores in the 1–1.6 $M_\odot$ range), or to a black hole if the core mass is 1.8–2 $M_\odot$ This amounts to an energy of nearly 3×10^{53} ergs. In contrast, the energy that resides in the shock wave which is supposed to blow off the outer mantle is expected to be only 5×10^{51} ergs[5,7]. During the core formation ν_e' s are emitted copiously (hereafter called 'burst' ν_e) as a result of electron capture. The average energy of these is 15 ~ 20 MeV and the total energy emitted ~ 10^{53} ergs[9]. The burst neutrinos leave the core only after several hundred dynamical times (10^{-3} sec) due to neutrino trapping[5,10].

Wilson *et al*[5] treat the first second after collapse very accurately. They find that 2×10^{52} ergs are emitted in $\bar{\nu}_e$ with an average energy 13 MeV (12 MeV for ν_e) during this phase. The total energy in $\bar{\nu}_e$ found by extrapolating this to the entire thermal phase is 6×10^{52} ergs. The BL model[6], which is not as reliable as Wilson's for the first 0.5 sec, predicts 9×10^{51} ergs to be emitted in $\bar{\nu}_e$ in the first second of which 6.5×10^{51} is emitted during the first 0.5 sec. The BL estimates for the averages energies during this phase are also significantly lower i.e. 8.75 MeV for $\bar{\nu}_e$ and 8.5 for ν_e. BL themselves stress that their origin of time could be different from others and that some of their assumptions may distort $\bar{\nu}_e$ emission in the early phase. We have, therefore, combined the reliable features of both models into one where during the first 0.5 sec, the average $\bar{\nu}_e$ energy falls from 18 to 13 (while radiating 1.35×10^{52} ergs), and from 13 to 10 MeV during the second 0.5 sec (while radiating 0.65×10^{52} ergs). All variations have been assumed to be linear (this has also been seen in the BL model). We have accounted for the proportionality between the rate of change of the average energy and the rate at which the energy is radiated. Our extrapolated model thus coincides with BL for $t\geqslant0.5$ sec, and reproduces the flux and spectrum of the Wilson model for the first second.

The neutrinos are detected by their interaction with atomic electrons ($\nu_e e\rightarrow\nu_e e$) as well as on nucleons,

$$\bar{\nu}_e+p\rightarrow e^+ +n, \tag{1}$$
$$\nu_e+(A,Z)\rightarrow e^- +(A.Z+1), \tag{2}$$
$$\bar{\nu}_e+(A,Z)\rightarrow e^+ +(A,Z-1). \tag{3}$$

According to the standard model, the cross-sections for these processes are ($\bar{E}_\nu$ in MeV units),

$$\sigma(\nu_e e^-\rightarrow\nu_e e^-)=8.9\times10^{-45}\ \bar{E}_\nu \mathrm{cm}^2, \tag{4}$$
$$\sigma(\bar{\nu}_e e^-\rightarrow\bar{\nu}_e e^-)=3.7\times10^{-45}\ \bar{E}_\nu \mathrm{cm}^2, \tag{5}$$
$$\sigma(\nu_\mu e^-\rightarrow\nu_\mu e^-)=1.45\times10^{-45}\ \bar{E}_\nu \mathrm{cm}^2, \tag{6}$$
$$\sigma(\bar{\nu}_\mu e^-\rightarrow\bar{\nu}_\mu e^-)=1.24\times10^{-45}\ \bar{E}_\nu \mathrm{cm}^2, \tag{7}$$
$$\sigma(\bar{\nu}_e p\rightarrow e^+ n)=8.18\times10^{-44}\ \bar{E}_\nu^2 \mathrm{cm}^2. \tag{8}$$

In principle, one should use thermal averages $\langle E_\nu\rangle$ and $\langle E_\nu^2\rangle$ in (4) to (8); but because of the expected paucity of high energy components these formulae are quite accurate[5,7] The total number of events is given by,

$$N=\sigma\times\phi_\nu\times n_T, \tag{9}$$

where n_T denotes the number of target particles and ϕ_ν the neutrino flux on earth. By virtue of the linear dependence on energy of the cross-sections (4) to (7), the number of events corresponding to these processes depends only on the total neutrino energy emitted and not on the average energy of the neutrinos, while the number of events produced through (1) has an additional, linear dependence on the neutrino energy.

The cross-sections for the reactions (2) and (3) depend on the nuclear physics details; this however is relevant only for a detector like the Frejus tunnel[11]

The super Kamioka detector[3] consists of 3000 tons of water of which 2140 tons comprise the inner fiducial volume while for the IMB detector[4] these numbers are 5000 tons and 3300 tons respectively. Thus whatever numbers we present for Kamioka will be scaled by a factor of 2.34 if the whole volume is used and 1.54 if the inner fiducial volume is used for the IMB detector (apart from differences arising from detector efficiencies).

The number of target particles are given by

$$\begin{aligned}&(\text{electrons})\,n_e=0.71\times10^{33}\\&(\text{free protons})\,n_p=1.42\times10^{32},\end{aligned} \tag{10}$$

for the Kamioka detector.

A burst energy of 10^{53} ergs in ν_e from SN 1987a (distance from earth $D=5.5$) corresponds to the flux

$$\phi_{\nu_e}(\text{burst})=2.02\times10^{11}/(E_{\nu_e}\text{MeV})/\text{cm}^2, \tag{11}$$

and we find the number of events due to the burst to be 1.3 for every 10^{53} ergs. When the neutrino energies are much greater than the electron mass, the electrons are emitted practically in the same direction as the incoming neutrinos carrying almost the same energy. On astrophysical grounds these electrons are expected to be in the range of 15–20 MeV for which the detector efficiency is 100% in the Kamioka facility.

From our earlier discussion the expected total energy in $\bar{\nu}_e$ emitted in the first second is around 2×10^{52} ergs giving a flux

$$\phi_{\bar{\nu}_e}=4\times10^{10}/(E_{\bar{\nu}_e}\text{ in MeV})/\text{cm}^2 \tag{12}$$

The average energy of $\bar{\nu}_e$ emitted after the first second may be well below the detector threshold for e^+ detection produced via (1). The detector efficiency is about 90% for 14 MeV electrons while it is only 50% for 8.5 MeV electrons. Since the nucleon recoil can be neglected the e^+ energies are approximately the same as $\bar{\nu}_e$ energies apart from a difference of 1.3 MeV due to neutron-proton mass difference. An important difference here is the completely isotropic angular distribution of emitted positrons. Combining these features with the flux and spectrum of our extrapolated model we get 8 events (if the detector efficiency is folded with the spectrum, we obtain 7 events) of which one is a burst ν_e event and the rest are isotropically distributed $\bar{\nu}_e$ events. These are given in table 1.

Table 1 also includes a detailed break-up of other events in the cooling phase due to ν_e, ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$. The expected number of events even in the absence of any cuts is only 0.3 from these processes.

These numbers are not likely to change very much if the neutrino oscillation phenomenon augmented by the MSW[12] mechanism is taken into account, if that is the explanation for the solar neutrino

Table 1 *Event break-up for various processes (4)–(8) for Kamioka detector. The fluxes are calculated on the assumption that the total burst energy is 10^{53} ergs, cooling $\bar{\nu}_e$ and ν_e energies are 2×10^{52} and 1.25×10^{52} and 0.5×10^{53} in other types for a duration of 1 sec. The distance to the supernova is assumed to be 55 KPC*

Time	$\nu_e e^- \to \nu_e e^-$	$\bar{\nu}_e e^- \to \bar{\nu}_e e^-$	$\nu_e \to \nu_e^*$	$\bar{\nu}_e p \to e^+ n$
Burst	1.3	–	–	–
0–1 sec	0.2	0.16	0.14	7

*Includes the contribution from all neutrino types.

problem. This is because, if ν_e's oscillate into ν_μ's by MSW mechanism, $\bar{\nu}_e$'s cannot oscillate into ν_μ's and vice versa. The oscillation of (ν_μ, ν_τ) from thermal emission into ν_e's, even if it takes place maximally, will contribute at most one extra ν_e induced event (if it is assumed that the energy radiated in ν_μ, ν_τ is 10^{53} ergs), that too if ν_e's do not oscillate into ν_μ's at all (unlikely prospect).

Thus comparing the prediction based on this analysis with the observations of the Kamioka collaboration, given in table 2, the following picture emerges: Event # 1 is most likely to be a burst event. The justification for this identification is that the burst events precede the 'cooling' events and will be directionally correlated with the supernova to a high degree. At this stage it is possible to identify event # 2 also with the burst. The fact that the event # 2 is also highly correlated in the direction with

Table 2 *Events observed by Kamioka group. Note that the events # 2, 4, 5, 10, 11, 12 are isotropically distributed*

Event	Time	Energy	Angle
1	0	20.0±2.9	18±18
2	0.107	13.5±3.2	15±27
3	0.303	7.5±2.0*	108±32
4	0.324	9.2±2.7	70±30
5	0.507	12.8±2.9	135±23
6	0.686	6.3±1.7*	68±77
7	1.541	35.1±8.0**	32±16
8	1.728	21.0±4.2**	30±18
9	1.915	19.8±3.2**	38±22
10	9.219	8.6±2.7	122±30
11	10.433	13.0±2.6	49±26
12	12.139	8.9±1.9	91±30

*The energy is too low; **These are unlikely to be thermal $\bar{\nu}_e$ events (see text).

SN 1987a would favour this. Then the energy emitted in ν_e by the supernova should be at least 1.5×10^{53} ergs. Of course, part of this flux can be accounted for by the oscillation mechanism alluded to before. But in such a case the second ν_e event should be expected much later (5 sec) as the integrated ν_e flux due to oscillation reaches 10^{53} ergs only then. The average energy being much lower it becomes questionable whether the detector could have seen it. On the other hand, one can argue that this is likely to be a $\bar{\nu}_e$ event since this interpretation leads to a completely isotropic distribution of observed events (except for # 7, 8, 9, see later). Events # 3 and 6 should be disregarded as their average energy is below the 8 MeV threshold. We also argue that events # 7, 8, 9 should not be identified with the (anti) neutrino from either the burst or the cooling phase. Thus we are left with # 2, 4, 5, 10, 11, 12 as events due to thermal $\bar{\nu}_e$.

The exclusion of # 7, 8, 9, gets support from several directions. The fact that these events are highly angular-correlated makes it unlikely that they are $\bar{\nu}_e$-induced, in which case they would have been distributed isotropically. If we ascribe these to the supernova ν_e's, the total flux in ν_e at the source will have to be $\sim 3.5\times10^{53}$ ergs which appears too large. But the difference in angle between # 1 and this cluster is about 15° which is one standard deviation for the electron angle of # 1, which means that with 70% confidence one can say that # 1 and the cluster are not due to the burst ν_e's. It is also very difficult to explain the observed high energy of the events # 7, 8, 9, if they are thermal in origin. But for these three events, the angular distribution of the remaining events becomes remarkably isotropic except for the burst event.

The average energy of $\bar{\nu}_e$'s as observed in Kamioka, when all events are weighted equally is 14.1±1.10 MeV. If event # 6 is excluded, this average goes up to 15±1.2 MeV, while excluding # 7, 8, 9 in addition leads to an average energy of 10.6±1.04 MeV. The total energy flux in $\bar{\nu}_e$'s when all events are weighted with appropriate detector efficiencies, is 7.8×10^{52} ergs. But this estimate becomes 4.4×10^{52} ergs if only events # 2, 4, 5, 10, 11, 12 are taken to be $\bar{\nu}_e$ events (without detector efficiency this is 2.5×10^{52} ergs). This number is higher than our input of 2×10^{52} ergs essentially because the observed events are systematically lower in energy. The total energy output in all neutrinos would be atleast six times the energy if there are three flavours[6,8].

Since according to our analysis the neutrinos detected at Kamioka should have been emitted at the supernova in just one second, an explanation has to be offered for the fact that the signal at Kamioka lasted 12.4 sec. There are essentially three possibilities: (i) The emission at the star itself is such that the average $\bar{\nu}_e$ energy is maintained at > 10 MeV for approximately 12 sec and total energy radiated in this period such that at least 3 events (if detector efficiency is taken into account, this is more like 5) are produced in the last few seconds. Then models like that of BL and Wilson have to be drastically modified and an expl··nation has to be found for the long gap of 8 sec where no events have been seen.

(ii) If the above possibility is rejected and if the last three events are genuine thermal $\bar{\nu}_e$-induced events, the following conclusions are hard to avoid; the neutrino mass is nonvanishing and of the order of ~ 25 eV. A histogram of expected events in such a case is displayed in figure 1, where we have also shown the histogram for $m_{\bar{\nu}_e} = 9$ eV for comparison. We have tried many variants of our extrapolated model, like upward scaling of the average energies etc but the qualitative features remain the same. Even if the model is stretched so far that the average energy is $\sim$ 10 MeV till as late as 4.5 sec after the burst ν_e's have left the core, the $\bar{\nu}_e$ mass still has to be around 18 eV. But the sequence of early events predicted by the model when the neutrino mass is in excess of 10 eV is not very good. Even if one assumes that low energy $\bar{\nu}_e$ leave the core before high energy ones contrary to currently accepted models, the above conclusions cannot be evaded if the last three events are taken seriously. From the point view of their energies, these events are not different from events # 2, 3, 4, 5.

(iii) The last three events are not genuine thermal-induced events: The data then strongly point to a nearly vanishing neutrino mass. The Wilson model then predicts five equally spaced events within 0.5 sec, a feature remarkably close to the observed pattern of events. One will then have to find a proper explanation for the last three events. Any such explanation (e.g. accretion) has to account for the fact that nearly $1\text{–}2 \times 10^{52}$ ergs of energy are emitted in these three events alone.

Thus we see that while the Wilson-BL model provides a qualitatively acceptable picture of the Kamioka events, satisfactory explanation of all facets of observed events is indeed very difficult. We have tended not to take the actual values of the observed energies very seriously as they do not seem to fall into any obvious pattern. Nevertheless, the model that we have used to base our analysis nearly reproduces, on the average, the observed energies (when events # 7, 8, 9 are not considered).

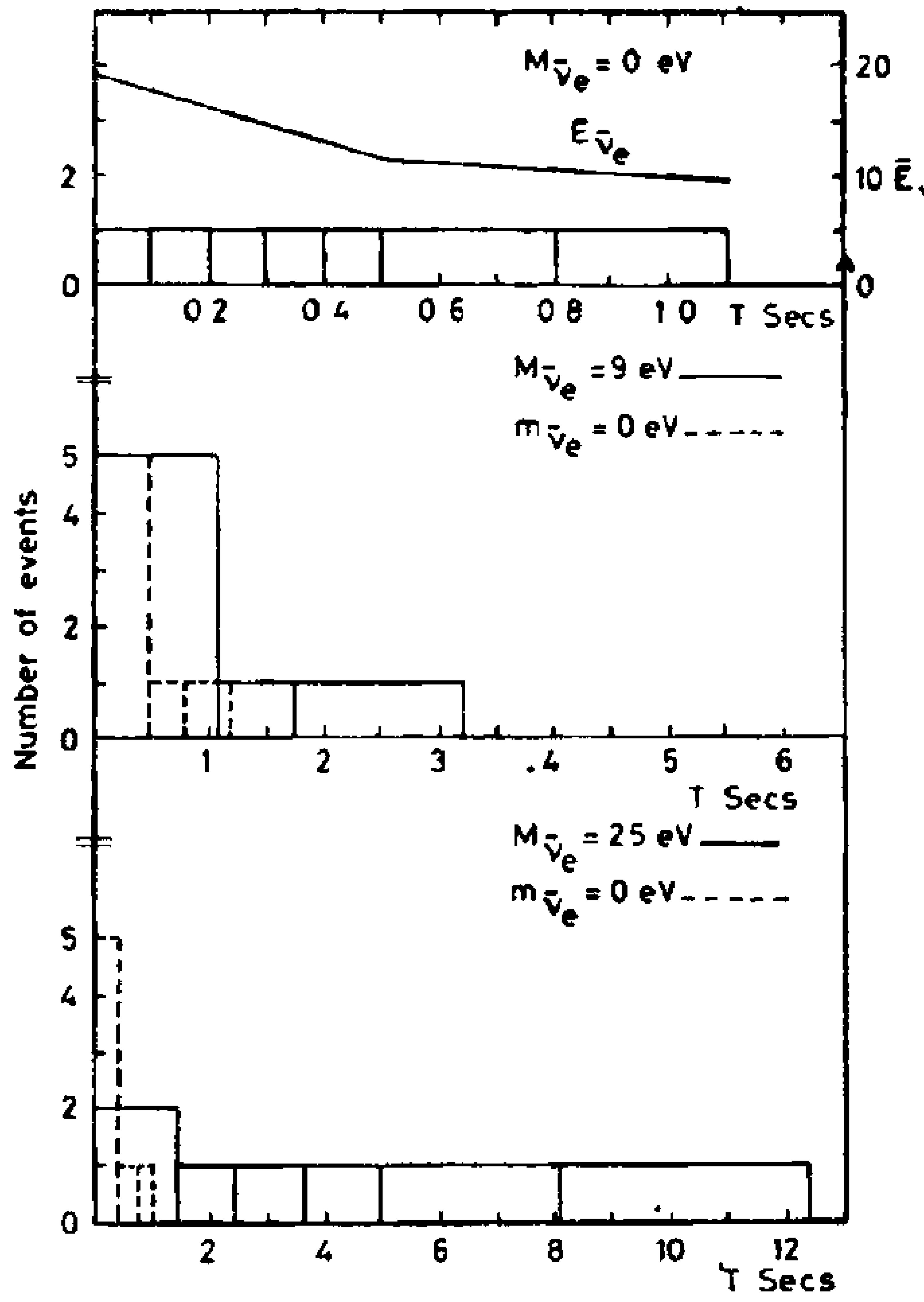

Figure 1. Histogram of the number of $\bar{\nu}_e$ events as a function of time is shown for $m_{\bar{\nu}_e} = 0$, 9 and 25 eV. Also shown is the variation of the average $\bar{\nu}_e$ energy, $\bar{E}_{\bar{\nu}_e}$ at the source from 0 to 1.1 sec. The distance to the supernova is assumed to be 55 KPC.

The data from IMB[4] consist of 8 pulses, 6 of which occur in the first 2.7 sec, and the remaining two occur in the last 0.6 sec. The whole pulse lasted for 6 sec. The average energy in the first bin is 36 ± 9 MeV, while that of the last bin is 22 ± 5.5 MeV. Both the pulse structure and the average energy are not in conformity with what has been seen at Kamioka.

An estimate of the energy flux when appropriate detector efficiencies are taken into account is as follows: 1.52×10^{52} ergs if all events are interpreted to be due to $\bar{\nu}_e$, and 7×10^{53} ergs if the events are attributed to ν_e's.

There are problems in attributing these events to either ν_e or $\bar{\nu}_e$ coming from the supernova. In the former case one would have expected the charged particle angular distribution to be highly peaked in the direction of SN 1987a, and in the latter case they would have been expected to be essentially isotropic. The observed distribution is anything but isotropic, 6 events being in the range $0.4 < \cos\theta < 0.8$ and 2 in other bins. But despite their directional correlation, none of the six are strongly correlated with the supernova itself ($\cos\theta = 1$).

The trigger efficiency of the IMB detector, for charged particle energies 20 MeV is very low, being only 0.14. Thus, we venture to suggest that IMB has not seen any events reported by Kamioka except for the events # 7, 8, 9 which we have argued are anomalous. There are several indicators which point to this. If one scales 3 events of Kamioka by a factor of 2.54 due to detector volume one gets 7.5 and this when folded with IMB detector efficiency of 0.76 for 40 MeV would yield 5.7 events as against the observed 6 events at IMB (in the bin under consideration). The average energy of these events at Kamioka is 25 ± 3.2 MeV, while in IMB it is 36 ± 9 MeV. Thus, within error bars these figures match. Further, the energy flux in these events as seen by Kamioka and IMB is 0.53×10^{52} and 0.4×10^{52} ergs if interpreted as $\bar{\nu}_e$ events and 2.34×10^{53} and 2.74×10^{53} ergs if interpreted as ν_e events. The angular distribution of these events both at Kamioka and IMB is also remarkably similar: highly peaked but not quite in the direction of SN 1987a. Despite these similarities, differences also exist. The 'anomalous' events of Kamioka occurred at a rate of one every 0.2 sec while those at IMB occurred at a rate of one every 0.26 sec (when the detector efficiencies are taken into account). It is conceivable that these differences are due to characteristics of Poisson distributions with a small number of events. This needs to be investigated further. In the light of our analysis, we urge that the events be reanalysed by both Kamioka and IMB. In the case of the former, special attention should be paid to the events # 7, 8, 9 as well as # 10, 11, 12, while in both cases the observed energies should be carefully reanalysed. The astrophysical models should also be reconsidered to see if the anomalous events as well as the last tnree events of Kamioka can be understood better.

We conclude with a few remarks on other detectors. The model we have used would only predict about 0.5 events in the Mont-Blanc detector[2]. If the reported number of events is genuine, the neutrino (not antineutrino) fluxes from supernova have to be 25 times as large as what is expected conventionally. In any case whatever is seen at Mont-Blanc must also be seen at Kamioka and IMB detectors (but not conversely). We are therefore reluctant to attribute the Mont-blanc events to the supernova 1987a. The reported difference in arrival times is also not easy to explain. We have also estimated the expected number of events at the Frejus tunnel detector[11] and find it to be about 1 event if the threshold can be lowered to detect electron energies > 8 MeV. It should however be emphasized that both Mont-Blanc and Frejus detectors are capable of detecting neutrinos from supernovae if they occur in our own galaxy (distance < 10 KPC) as the expected number of events will then be about 25. In view of the expectation that on the average there would be one supernova explosion in our galaxy every 15 years, the possibility of using these should be considered seriously. For all the detectors considered here such galactic supernova explosions offer the exciting possibility of measuring ν_μ, ν_τ masses also, a prospect that cannot be contemplated for laboratory experiments in the conceivable future.

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Note added: After we completed this work we came across two papers by J. N. Bahcall, A. Dar and T. Piran, [*Nature*, (*London*) 12th March 1987] and by J. N. Bahcall and S. L. Glashow [*Nature*, (*London*), submitted on Friday, 13th March 1987] discussing the observed neutrino events.

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NEWS

HOW DOES THE HUMAN COMPUTER WORK? — PART 1

by Dr Kevan Martin, UK Medical Research Council Anatomical Neuropharmacology Unit, Department of Pharmacology, Oxford University.

The human brain is a triumph of miniaturisation, the most remarkable computer in the world. Yet its nerve cells process only 100 or so instructions per second in contrast to the half-a-million that a microcomputer may handle. This makes the speed at which we perform very complex operations all the more astonishing. One of the most complicated tasks we are capable of is visual perception, which goes on in the cerebral cortex. Scientists are now steadily gaining information about how the cortical 'microchip' works: technically formidable operations such as injecting a recognisable 'lable' into single nerve cells through a glass tube only one-half a micrometre in diameter are producing detailed information that is extremely valuable, not only in understanding our visual processes but in building the parallel processing systems that so-called fifth generation computers will use. (*Spectrum*, No. 204, 1986, p.2 – British Science News, British Information Services, British High Commission, New Delhi 110 021).