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SUPERNOVA 1987A AND ITS IMPLICATIONS TO NEUTRINO PHYSICS*

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Abstract:

We review the reported neutrino events from the supernova SN 1987A and present a critical analysis of these events for their implications on the mechanism of stellar collapse as well as for neutrino physics.

1. Introdution

The sighting of a supernova, named SN 1987A, in the Large Magellanic Cloud (LMC) has led to a great excitement in the scientific community. The earliest optical detection was reported (IAU Circular 4316) on the 24th of February 1987. Immediately following the optical detection various experimental groups reported observations of neutrino events. The Mont-Blanc underground neutrino observatory (Aglietta et al. 1987a) has reported five events beginning at 2:52:36.79 (UT) lasting seven seconds above a 7 MeV threshold on the 23rd of February 1987. The Kamiokande II (KII) detector in Japan observed (Hirata et al. 1987) a neutrino burst on the same day at 7:35:35 (UT) (with an error of one minute). During a time interval of 13 seconds they have reported 12 events above a 7.5 MeV threshold. At about the same time (7:35:41.45 UT) the Irvine-Michigan-Brookhaven (IMB) collaboration has reported (Bionta et al. 1987) detection of 8 events in an interval of 6 seconds

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* Work done in collaboration with N.D.Hari Dass, D.Indumathi and A.S.Joshipura

above a 20 MeV threshold. Events have also been reported by the Baksan Valley experiment in Soviet Union; three events occurring in six seconds within a minute of the IMB - KII burst. The detection of neutrinos from SN 1987A is important from many points of view. From the astrophysical angle, it provides valuable information about stellar collapse leading to the formation of a white dwarf or a neutron star or possibly even a black hole (Trimble 1982, 1983; Bethe & Brown 1985; Burrows 1987). In contrast to photons (optical, radio, etc.) which get trapped in the envelope , the neutrinos from collapse escape almost unscathed thus providing a more direct glimpse of the core. Their detection is about as close as one can get to directly observing gravitational collapse. Thus the importance of a direct confrontation (Bahcall et al. 1987; Hari Dass et al. 1987a,b) between neutrino detection and supernova theory can hardly be overstated .This adds a new dimension to the neutrino physics which has already played a decisive role in shaping our understanding of stellar structure.

Astrophysical considerations apart, detection of neutrinos from supernova can, in principle, throw light on such issues as neutrino mass (Hari Dass et al. 1987a; Bahcall and Glashow 1987; Arafune & Fukugita 1987; Sato & Suzuki 1987; Arnett & Rosner 1987; Kolb et al. 1987), mixing (Cowsik 1987; Hari Dass et al. 1987b) and interaction with matter, whose clear understanding lies at the very foundation of our picture of fundamental laws of nature. In fact as we shall see later, even without assuming a detailed picture of the core collapse, it is possible to set an upper limit on the mass of the lightest species of neutrinos.

We are concerned with neutrinos in this review. Their detection on the earth, about 170,000 light years away for the first time is an important clue enabling us to reconstruct the events leading to the collapse. In the next section we outline the estimates for neutrino fluxes and temperatures based on the supernova mechanism. In sec.3 we give a discussion of the experimental data. Sec.4 is devoted to the implications for the neutrino mass. Some exotic possibilities like the decay, oscillation are considered in sec.5.

2. Neutrino Fluxes and Spectrum

Before discussing the experimental situation we consider here the theoretical expectations for the flux of neutrinos and their average energy. During the dynamical phase lasting a few milliseconds ν_e's are emitted copiously following electron capture $p\,e^- \rightarrow n\,\nu_e$. Some ν_e's may also be emitted following $n \rightarrow p\,e^-\,\bar{\nu}_e$ but the flux would be negligible as decay time is much longer than the dynamical time scale. The energy carried away by neutrinos from e^- capture can be calculated roughly on the basis that half the number of nucleons participate in the capture process and that their average energy is around 15 to 20 MeV at a chemical potential of 24 MeV (Mayle et al. 1987). The total energy estimate for ν_e, here after called "burst ν_e" is thus around 10^{53} ergs (Trimble 1983; Bethe & Brown 1985; Burrows & Lattimer 1986; Burrows 1987). This could well be an over estimate (Mayle et al. 1987; Schramm 1976) however as we shall see later approximately this much energy would be needed to interpret the first event as the burst event in KII.

The remainder of neutrinos are emitted during the thermal phase through the pair production process such as $e^+e^- \rightarrow \nu\bar{\nu}$, $nn \rightarrow nn\ \nu\bar{\nu}$ etc. where ν stands for any type of neutrino, e, μ, τ. While the last two types are produced through neutral current weak interaction, the electron type neutrinos are produced via both charged and neutral currents. The energy emitted in $\bar{\nu}_e$ has been estimated by Wilson (1984) to be roughly 1/5th of the total energy thermally emitted, i.e. 6×10^{52} erg based on an extrapolation of the calculation done up to 1 sec.to entire cooling phase.According to Burrows and Lattimer (BL) (1986), for 1.4 M core about 2.3×10^{52} erg in ν_e, 3.0×10^{52} erg in $\bar{\nu}_e$ and 1.5×10^{53} erg in other species are emitted during the first 20 seconds of the Kelvin Helmoltz cooling phase of the neutron star.However in Wilson's calculation the total energy emitted in $\bar{\nu}_e$ in the first second is about 2×10^{52} erg which is much larger than 0.9×10^{52} erg in the BL model for the first one second.The estimates in this phase are rather crucial for detectability in the KII and IMB detectors.

There are differences between BL model and Wilson's estimates with regard to the spectrum also.Wilson's estimates for the average energy of $\bar{\nu}_e$ during the first second is 13 MeV (core mass of 1.4 MeV) and 12 MeV for ν_e.The BL estimates are significantly lower,namely,8.75 MeV and 8.5 MeV for $\bar{\nu}_e$ and ν_e But BL have stressed quite clearly that their calculation is not as reliable as Wilson's in the first 0.5 sec.Also their analysis makes certain assumption which,while not crucial to the long term evolution of the neutron star,could alter the emission $\bar{\nu}_e$ emission characteristics.They have also stressed that their t=0 could be different from others'.On the basis of these remarks,we have combined the Wilson and BL models in such a way that during the first 0.5 seconds the average of $\bar{\nu}_e$ falls from 18 to 13 MeV,while radiating 1.35×10^{52} erg and from 13 to 10 MeV,while radiating 0.65×10^{52} erg during the next 0.5 sec.

The variation may be assumed to be approximately linear in time,a feature found in the BL model for the first .5sec.Here one should also ensure that the rate at which the average energy falls with time is proportional to the rate at which the energy is radiated.Thus the astrophysical basis for analyzing the events due to neutrinos from supernova can be provided by this extrapolated model which coincides with the BL model for t > 0.5 seconds and agrees with Wilson's for the spectrum and flux in one second.

In terms of the temperature of the neutrinosphere the average energy is approximately $\surd 7$ T. Thus if we take 13 MeV to be the average, the temperature $\simeq$ 5 MeV. This average energy is somewhat less than the Boltzman average since the spectrum is rather poor in high energy (Bethe et al. 1980) due to neutrino opacity (Mayle et al. 1987). Often one chooses the same temperature for μ,τ type neutrinos as well (Burrows and Lattimer 1986), however it is likely that the temperature of these neutrinos is a factor 2 higher than electron type neutrinos (Bahcall et al. 1987), leading to a higher average energy, 15 to 17 MeV.

As we shall see later, even though it is hard to gain a quantitative understanding of all features mentioned here because of the limited statistics of the data, we can nevertheless see a broad agreement between the theoretical ideas and observed features.

3. The data and its interpretation

The data on the detection of neutrinos is mainly from the Mont-Blanc (Aglietta et al. 1987a), Kamiokande II (KII) (Hirata et al. 1987) and IMB (Bionta et al. 1987) groups. In Table I we give a summary of these detector characteristics.

TABLE I : Summary of detector characteristics

	Mont-Blanc	Kamioka	IMB
Detector Material	C_nH_{2n+2} ($n \simeq 10$)	H_2O	H_2O
Size	90 tons	3000 tons (2140 tons)	5000 tons (3300 tons)
No.of electrons	3.11×10^{31}	7.1×10^{32}	11×10^{32}
No.of free protons*	0.834×10^{31}	1.42×10^{32}	2.19×10^{32}
Threshold	6 - 7 MeV	7.5 MeV	20 MeV
Energy Resolution	20%	22%	25%
Angular Resolution	-	28	15

* Interaction with nuclei is not expected to yield observable signals.

Observation of neutrinos have been made by all the three groups as well as by the Baksan Valley detector. These events are summarized in Table II.

Notice that the Mont-Blanc events occurred nearly five hours before the KII-IMB events. This is rather hard to explain since the total duration of neutrino emission in the supernova including the burst and the cooling times cannot exceed few tens of seconds (Burrows & Lattimer 1986). Apart from this there is also the question regarding the number of events. Since the number of free protons in Mont-Blanc is a factor 18 smaller than in KII, for every event in Mont-Blanc due to $\bar{\nu}_e p \to e^+ n$, there should be correspondingly 18 events in KII detector assuming same efficiency. However taking into

TABLE II : A Summary of the detected events

Event	Time	Electron Energy (MeV)	Angle with respect to LMC
(1) Kamiokande II: (7:35:35 UT)			
1	0.0	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	35.4 ± 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	12.439	8.9 ± 1.9	91 ± 39
(2) IMB: (7:35:41:45 UT)			
1	0.0	38	74
2	0.42	37	52
3	0.65	40	56
4	1.15	35	63
5	1.57	29	40
6	2.69	37	52
7	5.01	20	39
8	5.59	24	102
(3) Mont-Blanc: (2:52:36:79 UT)			
1	0.0	7	
2	3.86	8	
3	4.22	11	
4	5.91	7	
5	7.01	9	

* May not be ascribed to Supernova as it is below threshold

account the difference in detector efficiency and the threshold Aglietta et al. (1987b) claim that about 12 ± 8 interactions should be seen in KII detector at about the same time as Mont-Blanc observation. By looking at the data close to this time in KII one finds four, somewhat uncertain, events (Beier et al. 1987) in a time span of 10 seconds.

Thus if it is true there were indeed two separate pulses due to the supernova, it spells trouble for the simple picture of stellar collapse. The interpretation then has to be modified to include two possible bursts-first due to the formation of a neutron star and the second due to its collapse into a blackhole (DeRujula 1987). We shall leave out any further discussion of the Mont-Blanc events and concentrate on the KII and IMB data.

From the description of the neutrino emission given in sec. 2, one expects the electron capture ν_e's (burst) to arrive first while the thermal neutrinos of all flavours arrive later. The total duration during which these are emitted being approximately one second. These are then detected through the following reactions.

$$\nu_e e^- \to \nu_e e^- \ ; \ \sigma_1 = 8.9 \times 10^{-45} \ E_\nu \ cm^2 = \sigma_1^\circ \ E, \qquad (3.1)$$

$$\bar{\nu}_e e^- \to \bar{\nu}_e e^- \ ; \ \sigma_2 = 3.7 \times 10^{-45} \ \bar{E}_\nu \ cm^2 = \sigma_2^\circ \ E, \qquad (3.2)$$

$$\nu_\mu e^- \to \nu_\mu e^- \ ; \ \sigma_3 = 1.45 \times 10^{-45} \ E_\nu \ cm^2 = \sigma_3^\circ \ E, \qquad (3.3)$$

$$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^- \ ; \ \sigma_4 = 1.24 \times 10^{-45} \ \bar{E}_\nu \ cm^2 = \sigma_4^\circ \ E, \qquad (3.4)$$

$$\bar{\nu}_e p \to e^+ n \ ; \ \sigma_5 = 8.18 \times 10^{-44} \ \bar{E}_\nu^2 \ cm^2 = \sigma_5^\circ \ E^2 \qquad (3.5)$$

where the energies are given in MeV units. All the cross sections are calculated in the standard model (Commins & Bucksbaum 1983). The angular distribution of electrons for reactions (3.1) to (3.4) is peaked in the forward direction while the angular distribution in the case of (3.5) is isotropic. Because of larger cross-sections for (3.5) this will be the favoured detection mode for a given flux of thermal neutrinos in which all species carry approximately equal energy.

From Table II, the first two events in KII clearly point in the direction of the supernova. Therefore these may be ascribed to the burst ν_e's which are expected to arrive first. The probability that an event out of 12 can be found in a cone of 20° is only 0.36 if the distribution is isotropic. Thus it is possible only one out of these two can be ascribed to $\bar{\nu}_e p \to e^+ n$. If we thus take the first event to be due to burst ν_e, the remaining events resemble an approximate isotropic pattern as shown in Fig.1 (Sato & Suzuki 1987).

Further the observed time difference between the first two events is approximately 0.107 sec, which is atleast 10 times larger than the dynamical times during which the electron capture takes place unless the neutrino ν_e has a mass of approximately 4eV in which case the low energy (the second event) ν_e would arrive after 0.107 seconds. But this would require a ν_e flux of 1.5×10^{53} erg which is higher than expected from supernova models.

How do the data features compare with the supernova models in detail? We shall concentrate on the Kamiokande data without reference to the Mont-Blanc as that would require two burst scenario. The neutrino flux on the earth from a supernova at a distance D (measured in units of 10 Kpc) away is

$$\phi_\nu = \frac{6.11 \times 10^{12}}{D^2 (\bar{E}_\nu/\mathrm{MeV})} (E_T/10^{53}\mathrm{erg}) \text{ per cm}^2, \qquad (3.6)$$

where E_T is the energy radiated as neutrinos, E_ν is the average neutrino energy. The total number of events is then given by

$$\# \text{ of events} = \sigma_i \, \phi_\nu \, N_{p(e)}, \qquad (3.7)$$

where $N_{p(e)}$ is the number of target particles (protons or electrons) given in Table I. As a result, events due to reactions (3.1) to (3.4) are independent of the average neutrino energy, while the events due to $\bar{\nu}_e p \to e^+ n$ depend

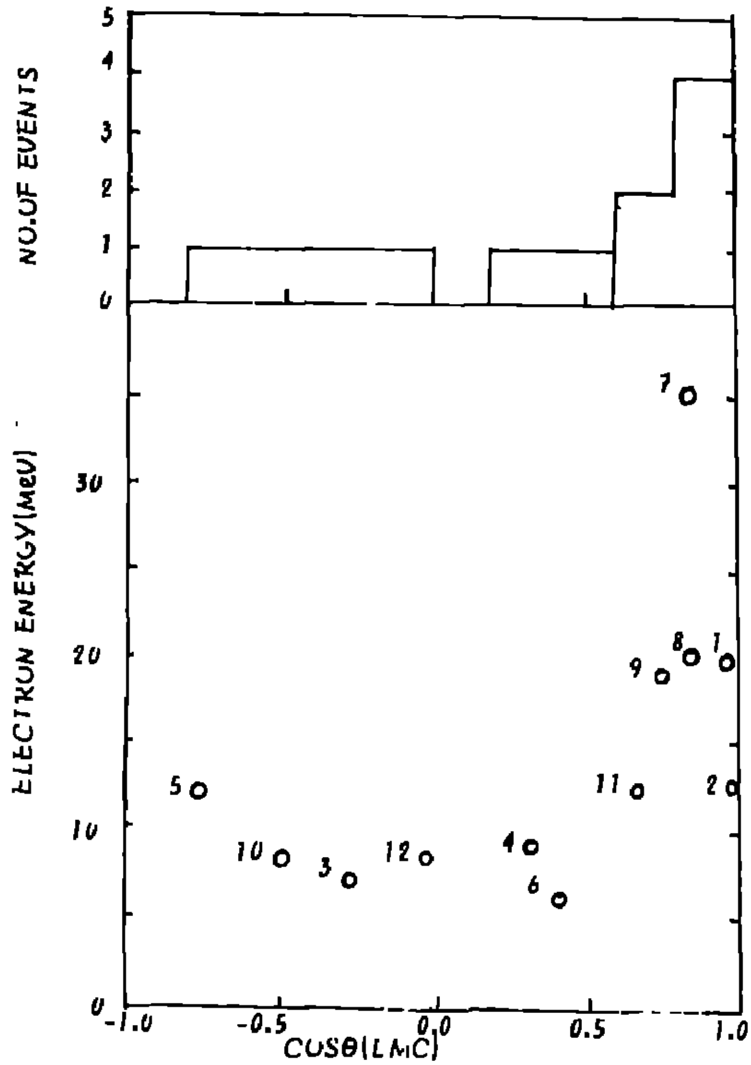

FIG. 1 Angular distribution of events, with respect to LMC supernova in the KII detector. Also shown is the event histogram in Cos θ bins.

linearly on the average. It should be emphasized that with time the average energy falls approximately linearly while the rate of neutrino emission slows down.

Assuming an energy of 10^{53} erg in burst ν_e's the flux is

$$\phi_{\nu_e} = 2.465 \times 10^{11} / (\bar{E}_{\nu_e} /\mathrm{MeV}) \text{ per cm}^2 \qquad (3.8)$$

at a distance of 50 kpc. This leads to 1.56 events due to $\nu_e e^- \rightarrow \nu_e e^-$, where the electrons are emitted practically in the same direction. Based on astrophysical estimates the average energy should be in the range 15-20 MeV for which the detector efficiency is almost 100% in KII facility while these energies are below threshold for IMB detector. The event # 1 therefore is in conformity with these estimates.

Regarding the e^+ events produced via (3.5), we need to concern ourselves with only the $\bar{\nu}_e$'s emitted in the first one second as $\bar{\nu}_e$ emitted later may be well below threshold. If the energy is around 2×10^{52} erg (see sec.2) the flux is

$$\phi_{\bar{\nu}_e} = 4.93 \times 10^{10} / (\bar{E}_{\nu} \text{ in MeV}) \text{ per cm}^2 \qquad (3.9)$$

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 13 MeV due to proton neutron mass difference. Combining these features with the flux and spectrum of our extrapolated model (see sec.2) we find about 8.5 events - or about 7 events with the detector efficiency folded in. In Table III we give a detailed breakup of events including those due to ν_μ, ν_τ and their anti particles which add up to a meagre 0.5 events.

TABLE III: Events expected from the extrapolated model

Time	$\nu_e e^- \to \nu_e e^-$	$\bar{\nu}_e e^- \to \bar{\nu}_e e^-$	$\nu_i e^- \to \nu_i e^-$ $i=\mu,\tau$	$\bar{\nu}_e p \to e^+ n$
Burst	1.56	-	-	-
0-1 sec	0.19	0.13	0.12	8.5

Thus comparing the prediction based on this extrapolated model with the observations of KII collaboration (Table II), the following picture emerges: Event # 1 is most likely a burst event. This is justified by the direction as well as the fact it precedes all other events. It is most likely that # 2 is not due to burst neutrinos but $\bar{\nu}_e$'s since this interpolation leads to a completely isotropic distribution of other events. Event # 3 has been discounted by the KII group as the energy is below the 8 MeV threshold. We also argue that events # 7,8,9 may not be identified with $\bar{\nu}_e$ induced events. The fact that these are highly angle correlated makes it unlikely that these are $\bar{\nu}_e$ induced. On the other hand these three do not point to LMC within one standard deviation which should be the case if these are ν_e induced.

Assuming these to be ν_e induced, the total energy at the source in ν_e alone has to be approximately 3.5 x 10^{53} erg which is too large in view of the current astrophysical thinking. From what is known about the spectra during formation and cooling it is very hard to explain the observed high energy of these events. Without these, the angular distribution of the rest of the events is remarkably isotropic.

The average energy of $\bar{\nu}_e$ as observed in KII, when all events are weighted equally is 14.1 ± 1.1 MeV and without # 6 this average goes up to 15 ± 1.2 MeV. If we exclude # 7,8,9 in addition leads to an average energy of 10.6 ± 1.04 Mev. Similarly when all events are weighted with appropriate detector efficiencies the total energy flux in $\bar{\nu}_e$ is 7.8 x 10^{52} erg (4.4 x 10^{52} erg without # 3,7,8,9). This is considerably higher than the 2 x 10^{52} erg which was used by us to calculate the $\bar{\nu}_e$ events in Table III since the observed energies are lower than our energies. The total energy in all species should be approximately 5-6 times the energy in $\bar{\nu}_e$.

From the foregoing discussion we can conclude that there is a broad agreement with the expectations from the supernova theory. However the main problem lies in the time profile of the events in KII. These are bunched in three clusters; the first 6 events in 0.686 sec, the next 3 events inbetween 1.5 and 2 sec. While the last three events are seen between 9 and 12.4 sec. No events are seen in between. Sato & Suzuki (1987) have shown that this may be due to the temperature of the neutrino sphere and / or the flux oscillation based on the simulations of Wilson's group (Mayle et al. 1987; Wilson 1986; Mayle & Wilson 1986). These simulations do show that such oscillation of the neutrino sphere is possibly caused by the intermittent mass accretion on to the core. However the amplitude of these oscillations is rather small and one also needs to assume that the diffusion lasts a full 12 seconds which may be a bit too long considering the detector energy cut.

4. Limits on the Neutrino Mass

According to BL(1986) the mean energy of the neutrinos remains above the threshold for 1 to 2 seconds and then it drops below the threshold. The pulse duration in the KII detector is about 12.4 sec one has to find an explanation of this lengthening of the pulse duration. If we ignore for the time being the detailed picture of time profile during the 12.4 seconds, a way of explaining this would be to attribute a mass to the neutrinos – $\nu_e, \bar{\nu}_e$. Several authors have made use of this fact. The calculations fall into essentially two categories: (1) Without assuming any model, but based on observed energies, one can demand that the duration of the pulse in the supernova should be less than 12.4 seconds for some mass m_ν and in any case it should not exceed 12.4 seconds (Arnett & Rosner 1987; Kolb et al. 1987). (2) On the other hand the mass m_ν may be calculated based on an astrophysical model, like BL, and assuming that a duration Δ, given by the model, becomes 12.4 seconds in the detector.

Let t_o denote the time taken by light to travel the distance 50 Kpc between SN1987a and the earth,

$$t_o = 4.72 \times 10^{12} \text{secs.} \qquad (4.1)$$

if the neutrino has a mass $m_\nu \ll \bar{E}_\nu$ (average energy), then

$$t_{obs} = t_{em} + t_o \; (1 + m_\nu^2 / 2.E_\nu^{-2}) \qquad (4.2)$$

where t_{em} is the emitted time in the supernova and t_{obs} denotes the observed time. Therefore the pulse width observed is given by,

$$\delta t_{obs} = \Delta + t_o \frac{m_\nu^2}{2} \left(\frac{1}{\bar{E}_\nu^2(\text{final})} - \frac{1}{E_\nu^2(\text{initial})} \right) \qquad (4.3)$$

In the model independent analysis of Arnett & Rosner (1987), the Δ is calculated as a function of mass m_ν using the observed times and energies given by K.II. If one takes all the events 1 to 12 (excluding # 6) the Δ is never less than 10 seconds and begins to grow appreciably for m_ν>23 eV, for all events. Excluding the events 10–12 as due to some late burst, the rest of the events are confined to 2 sec interval. This interval can be reconciled without much difficulty with astrophysical models and the data is then consistent with m_ν= 0. If one takes events # 1 to # 5 as candidates for a pulse emitted under 1 sec, then $m_\nu \leq 9.4$ eV. A more detailed analysis by Kolb, Stebbins and Turner (1987) also yield approximately similar conclusions.

A somewhat different view point has been taken by Cowsik (1987) and has also been alluded to by Bahcall et al. (1987). If one assumes that the first six events are due to $\bar{\nu}_e$ and the later events, because of the temporal gap, are due to the decay or oscillation of a heavy neutrino into $\bar{\nu}_e$, then all the 12 events can be reconciled with approximately instantaneous emission. The masses then turn out to be 4.6 eV for the first six events and 22 eV for the last six events (Fig. 2).

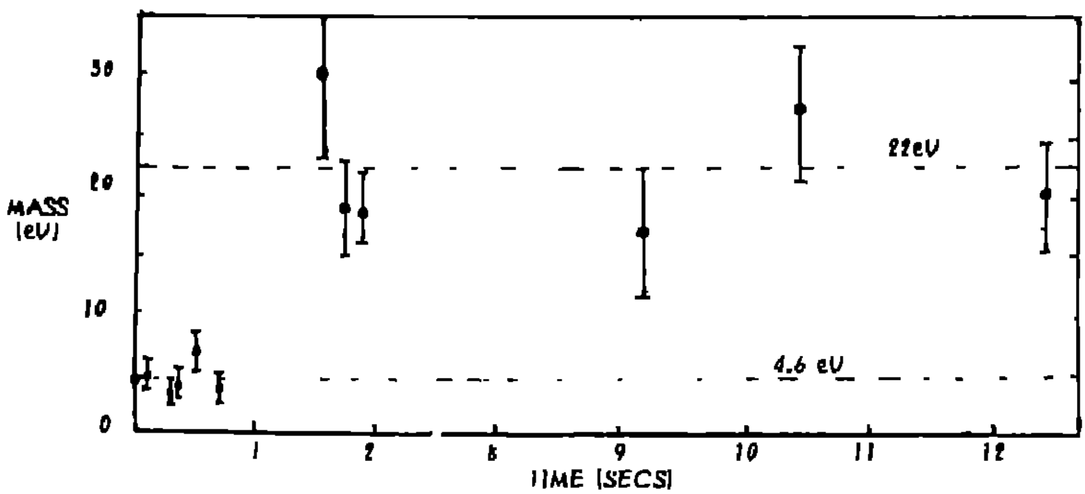

FIG. 2 Masses of the neutrino detected, derived under the assumption that the first six events are due to $\bar{\nu}_e$ and the later events due to decay or oscillation of heavy neutrino

The decay hypothesis can be ruled out within the standard model since the lifetime for, $\bar{\nu}_\mu, \bar{\nu}_\tau \rightarrow \nu_e \bar{\nu}_e \bar{\nu}_e$ say, with a mass 22 eV is much higher than the flight time between supernova and the detector. The oscillation seems unlikely since the oscillation probability is low (< 0.13) and the flux estimates would then exceed reasonable limits obtained on the basis of astrophysical models.

Consider the model dependent analysis (Hari Dass et al. 1987) based on the extrapolated model outlined in sec. 2. In this picture it will be hard to accommodate the events # 7, 8, 9 without drastically altering the picture of neutrino emission. In addition suppose that the last three events are not genuine thermal events. The Wilson model predicts five approximately equally spaced events within 0.5 sec, a feature remarkably close to the observed pattern of events as shown in Fig. 3a.

The problem then would be to find a proper explanation for the last three events which account for nearly 10^{52} erg of energy emitted. We might then say that these events are due to further accretion of matter (Sato & Suzuki 1987).

If this possibility is rejected and the last three events are genuine thermal events, the following conclusions are hard to avoid: The neutrino mass is non-vanishing and is of the order of $\simeq$ 25eV. A histogram of expected events is displayed in Fig. 3b. We 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 10MeV or higher till as late as 4.5 seconds after the burst ν_e's have left the core, the mass still has to be around 18eV. The sequence of early events is however not good when the mass is in excess of 10eV. Even if one assumes that low energy ν_e leave the core before the high energy ones, contrary to the currently held belief, the above conclusions cannot be evaded if the last three events are taken seriously.

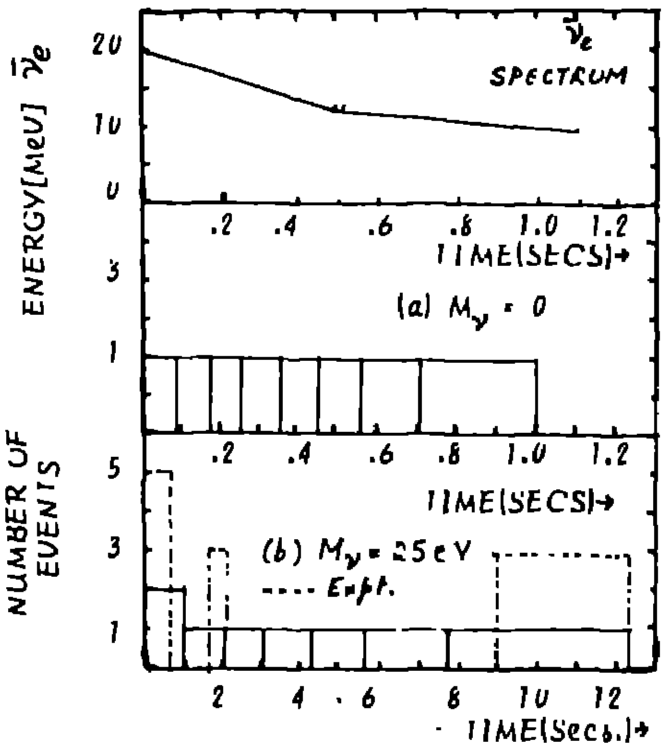

FIG. 3 Comparison of two models (see text).

5. Remarks on other possibilities

From the discussions in the previous sections, we see that while the Wilson-BL model provides a qualitatively acceptable picture of the KII events, satisfactory explanation of all aspects of observed events is indeed very difficult. In the model dependent analysis we have tended not to take the actual values of the observed energies very seriously as they do not seem to fall into any observed pattern. Nevertheless, the model that we have used nearly reproduces, on the average, the observed energies when events # 7,8,9 are not included.

Until now we have not commented on the IMB events. The data consists of 8 pulses, 6 of which occur in the first 2.7 sec, and the remaining 2 in the last 0.6 sec. The whole pulse lasted 6 sec. The average energy in the first bin is 36 ± 9 MeV while in the second bin it is 22 ± 5.5 MeV. Both these facts, pulse structure and average energy, are not in conformity with the KII data. In addition the cosθ histogram peaked in the direction 20°– 40° away from the LMC and is not isotropic. Because of detector malfunction, their cosθ distribution is of dubious value. However if we take the cosθ distribution and average energies seriously, then these events resemble events # 7,8,9, of the KII detector which we have ventured to call anomalous. The flux for such events in KII is 0.53 x 10^{52}erg (average energy 25 ± 3.2 MeV) and in IMB it is 0.4 x 10^{52}erg if interpreted as $\bar{\nu}_e$ events. If these are interpreted as due to ν_e, then one obtains 2.34 x 10^{53}erg for KII and 2.74 x 10^{53}erg for IMB. Inspite of the similarities in flux and angular distribution, there are differences in the rate at which these events occur; one per 0.2 sec in KII and one energy 0.26 sec in IMB. It is conceivable that these differences are due to characteristics of Poisson distribution with small number of events. These events need to be investigated further.

The time profile of KII events, namely the bunching of 12 events into three groups separated in time, has led to various speculations. One such is that by Sato & Suzuki (1987) as already mentioned before. Neutrino oscillations have also been considered as a possible source by Cowsik (1987), Minakata et al. (1987) and Arafune et al. (1987). The work of Cowsik (1987) has already been mentioned previously. The other authors have shown that by taking the effect of the earth into account the possible observation of prompt ν_e from SN1987a at KII is compatible with the solution of solar neutrino puzzle of MSW effect. The analysis exploits the fact that once transformed neutrino ν_e in the outer region of the star can be transformed back to ν_e on its travel through the earth's crust, and there by detected by KII. If the neutrino travels as a heavier eigen-state (mass $\simeq$ 22eV) in vacuum, one may have an explanation for the complicated structure observed in the KII data.

The possibility of a heavier flavour $\bar{\nu}_h$ decaying in to $\bar{\nu}_e$, preferably, has been considered by us (Hari Dass et al. 1987). Given the laboratory limits on the mixing $|U_{eh}|^2 \lesssim 10^{-3}$, the life time for the decay is $\gtrsim 10^4$ secs and therefore the $\bar{\nu}_e$ from this decay will be delayed by six minutes or more compared to the $\bar{\nu}_e$ coming directly from the supernova. These $\bar{\nu}_e$'s therefore cannot account for the observed delay in the KII data which is of the order of seconds.

Interestingly, however, the non-observance of such events due to $\bar{\nu}_e$ after six minutes and above the background can be used to set limits on the flavour mixing parameter $|U_{eh}|^2$. In fact these new limits present a substantial improvement over the laboratory limits. We shall briefly summarize the procedure: Consider the decay of a heavy flavour $\bar{\nu}_h$ (we are interested in decay modes involving $\bar{\nu}_e$ as the detector is more efficient towards $\bar{\nu}_e$). In principle it could decay into any of the following final states, $\bar{\nu}_h \rightarrow \nu_e \bar{\nu}_e \bar{\nu}_e, \bar{\nu}_e \gamma, \bar{\nu}_e \gamma\gamma, \bar{\nu}_e e^+ e^-$. In order that all the $\bar{\nu}_e$ reach the detector, the life time should be much smaller than the transit time, 4.7×10^{12} seconds. This rules out all except the last decay mode which has a life time of 10^4 seconds according to the present laboratory limits in the mass range 1 to 10 MeV for $\bar{\nu}_h$. According to KII a flux of 8×10^{52} erg is radiated in $\bar{\nu}_e$ ascribing all events to $\bar{\nu}_e$ alone. If we assume the same flux in $\bar{\nu}_e$, consistent with astrophysical models, and a spectrum similar to $\bar{\nu}_e$ as in our extrapolated model (at slightly higher average energy of 17 MeV) we obtain about 4 events due to $\bar{\nu}_e$ from the decay. In KII a probability of

0.33/day (or one event in 3 days) is sufficient to separate it from the background (Suzuki 1986). Therefore, the maximum detectable spread for four events is 12 days, soon after the original burst. Since no such events have been reported we assume they have not been seen above this background which immediately leads to the limits on the mixing $| U_{eh} |^2$ shown in Fig.4.

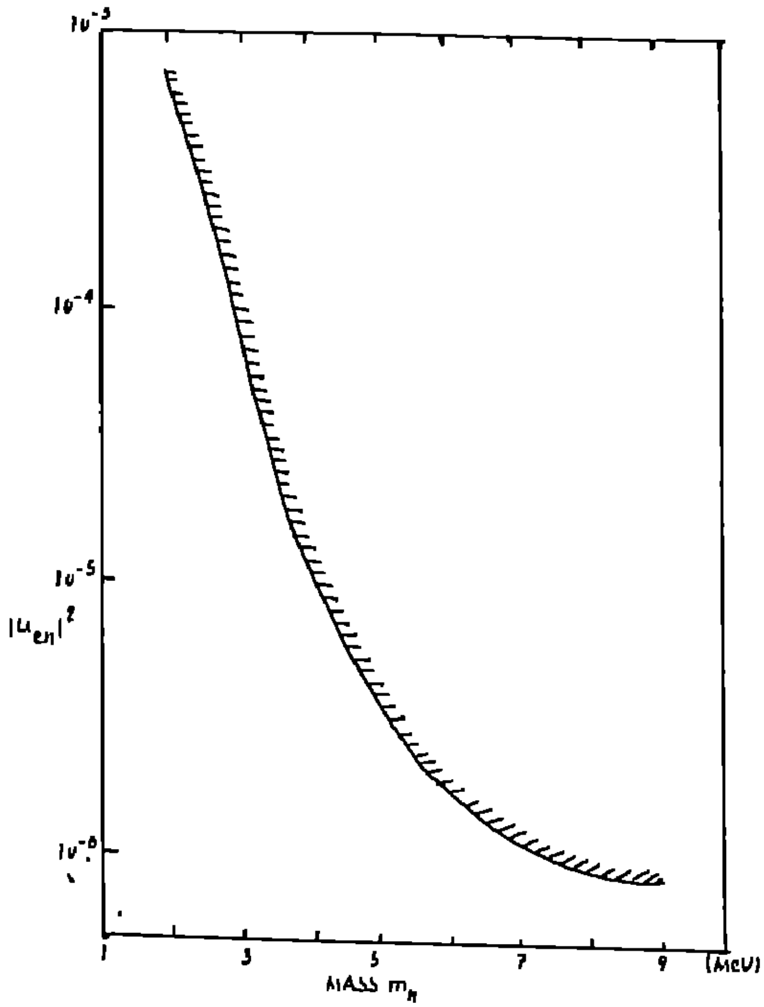

FIG. 4 Limits on the mixing as a function of the mass of heavy neutrino

These limits are a considerable improvement over the lab limits $|U_{eh}|^2 \lesssim 10^{-3}$ and are complementary to those obtained by Dar et.al.(1987) based on the non-observance of γ rays from e^+e^- annihilation.

The characteristics of the events may also be pointing to the fact that the supernova consists of matter rather than antimatter (Barnes et al.1987). In the latter case, the burst would consist of $\bar{\nu}_e$ rather than ν_e one would expect a larger number of events induced due to burst $\bar{\nu}_e$ in the first few milliseconds. At present, the poor statistics cannot rule out the possibility of a supernova being antimatter. However, this may be possible to detect with proposed larger detector like DUMAND.

We conclude with a few remarks on other detectors: In principle the calorimetric detectors with iron as the target material, like the Frejus tunnel detector (Barloutand et al.1982) or the KGF detector (Krishnaswamy et al.1982) can be used for detection of neutrinos from supernova. Unfortunately none of these is at present suited for such a task because of the higher threshold as well as the thickness of the plates. The neutrinos interacting with the target can induce a super-allowed Fermi transition $0^+ \rightarrow 0^+$ with a Q^- value of 8.11 MeV. This means that the detector threshold should be 5 MeV or less for electrons to detect a 13 MeV neutrino. Electrons of this energy have range of a fraction of a centimeter. Assuming this to be done, we expect one event from burst and one cooling event from SN1987a for approximately 2 Kilotons of iron. Neither Frejus with one kiloton (3mm thick plates) nor the KGF with 0.14 kiloton (1 cm thick) is in a position to detect this. However if the explosion occurs in our own galaxy (distance $<$ 10 Kpc) one would expect 25 events in each phase and with reduced detector thresholds even these detectors should be able to see some events. 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 detectors should be considered seriously. For all detectors such galactic supernova explosion offer the exciting possibility of measuring ν_μ, ν_τ masses also, a prospect that cannot be contemplated for laboratory experiments in the near future.

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