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MAY A SUPERNOVA BANG TWICE ?

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ABSTRACT

The Mont-Blanc group reports a burst of neutrinos in the LSD detector occurring the day before the optical discovery of SN1987A. The Kamiokande(K2) and IMB experiments see neutrino bursts $\sim 4\text{h}43\text{m}$ after LSD. The K2 observations at LSD time are said to contradict LSD. I argue that the K2 results strongly support the LSD pulse(!). I critically analyse the data, and prove that all experiments are compatible at all times. I discuss the plausibility and predictive power of a two-neutrino-burst scenario, wherein the progenitor's core first became a neutron star, and subsequently recollapsed into a black hole (or strange star) as matter left behind by a partially-failed-shock-wave accreted on and around the neutron star, with a calculated fall-back time of a few hours.

Shelton's supernova SN1987A was "prediscovered" on February 24th at 10h,39m,21s UT at a visible magnitude $m \sim 6.2$. The "UNO" group operating the LSD neutrino detector reports¹⁾ a burst of 5 events within a 7s interval starting at 2h,52m,36.792s UT on February 23rd. For a conventional Type II supernova the neutrino burst signalling the implosion of the core is expected to precede the explosive light burst by tens of hours: the time for sound to travel from the core to the outskirts of the star. The LSD burst is close to the estimated time at which the light output began to rise. The Kamiokande II collaboration (K2) reports²⁾ a burst of 11 events within 13 seconds starting at 7h,(35 $\pm$ 1m),35.2s UT: almost 5 hours after the LSD burst. The IMB group³⁾ observed 8 events within 6 seconds, the first occurring at 7h,35m,41.37s UT. Within errors K2 and IMB are simultaneous. The K2 and IMB observations are very uncomfortably close to the first confirmed visual image, even if the parent star had lost much of its envelope, or was a blue supergiant⁴⁾ with a relatively small radius $\sim 10^7$ km. Can a supernova, not only become visible at an unexpectedly fast pace, but also emit two widely separated distinct neutrino bursts?

The LSD group estimates¹⁾ the uncertainty of the core implosion time to be 5h, and the probability of five background events occurring in their detector in any 10s interval of this five-hour lapse to be $\sim 3 \cdot 10^{-4}$. In support of the prejudice that supernovas should not emit two pulses of neutrinos spaced by a few hours, the K2 collaboration²⁾ asserts "[We] found no sign of any burst at or around the [LSD] claimed UT". The K2 and LSD efficiencies for the dominant observable process $\bar{\nu}_e + (\text{free})p \rightarrow e^+ + n$ are not so different, and K2 contains 18.4 times more free protons than LSD does: the K2 non-observation sounds like a deadly blow to the LSD result. Before proceeding to undo this fatal conclusion, I comment on the sense in which K2 *strongly supports* the premature LSD burst.

Figure(1) shows the ensemble of data, with their energies as a function of time. The left hand column is at LSD time, the right hand one at K2-IMB time. The K2 plot at LSD time is from a talk by E.W.Baier⁵⁾. The K2 times are reported with millisecond precision and an overall uncertainty of one minute. It is difficult to imagine that the K2 *time differences* in a five-hour interval could be in error by more than a fraction of a second. I have therefore taken the liberty to show a bin that precedes the reported K2 burst by about as much as LSD precedes IMB. This bin happens to be one of the only two (in a 12 minute interval around it) that contains an event well above the nominal low energy threshold-cutoff energy, $E_{TH} = 7.5$ MeV. *The time difference between this "high energy" event and the onset of the later K2 burst is 4h43m(13.2 $\pm$ 2) s, amazingly close to the time difference between the first LSD and IMB events: 4h,43m,4.58s* (the 2s error is an estimate of my ability to read a bad photocopy of a poor transparency). Some 8s after this high energy event, there is another one at threshold, like event #3 in the later K2 burst, considered by the authors²⁾ as part of the signal. This event precedes the onset of the later K2 burst by 4h,43m,(5.2 $\pm$ 2)s. The random probability of K2 finding the "high energy" event²⁾ in the particular 20s interval encompassing the LSD burst is 2.6%. Multiply this by the probability of LSD finding 5 events in a 10s interval ($1.2 \cdot 10^{-7}$). Integrate the combined probability over the 24h period during which the supernova's core implosion certainly took place (in the past light cone of one of the

10s intervals, to be precise). The result, $2.5 \cdot 10^{-5}$, is the probability of the observed 5+1 events being a statistical fluctuation of the background. This is ~ 40 times smaller than the same probability computed without the K2 coincidence, and certainly small enough to justify the search for an explanation.

Supernova neutrinos are expected to have a roughly thermal Fermi energy distribution, modified by neutrino absorption: $d\Phi/dE \sim [E^2 \exp\{-\beta(E/T)^2\}]/[1+\exp(E/T)]$. The temperatures that fit the data of each experiment are such that $\exp(-E_{TH}/T) \gg 1$. The absorption coefficient β is small and uncertain. Thus, I first present the results in the approximation of a Boltzmann spectrum $d\Phi/dE \sim E^2 \exp(-E/T)$. Let L be the total energy output of the supernova, very close to its time-integrated neutrino luminosity. The experimentally measured quantity is $\sim L(\bar{\nu}_e)$. For the sake of presentation, I use $L=6L(\bar{\nu}_e)$, the approximation of energy equipartition between neutrino types. Let n_p be the number of free protons in the target, r the distance to the supernova, and $\sigma = \sigma_0 [E(\bar{\nu}_e)/m_e]^2$, with $\sigma_0 \sim 2.4 \cdot 10^{-44} \text{ cm}^2$ the $\bar{\nu}_e p \rightarrow e^+ p$ cross section at the relevant energies. Let $\epsilon[E(e^+)]$ be the positron reconstruction and detection efficiency, which I approximate with the shape shown in Fig(2c), with $E > E_{TH}$. The expected e^+ energy spectrum ($E(e^+) \sim E(\bar{\nu}_e) = E$) and total number of events, N , are:

$$dN/NdE = \epsilon(E, E_0) x^4 e^{-x} / [24 T < \epsilon >] \quad (1.a)$$

$$N = n_p \sigma_0 L T < \epsilon > / [6 \pi r^2 m_e^2] \quad (1.b)$$

$$< \epsilon > = \int_{x_{TH}}^{\infty} \epsilon(E, E_0) x^4 e^{-x} dx / 24 \quad (1.c)$$

$$x = E/T \quad ; \quad x_{TH} = [E_{TH} + m_n - m_p]/T, \quad (1.d,e)$$

The numerical values of N are:

$$N = A < \epsilon > (L / 3.0 \cdot 10^{53} \text{ ergs}) (T / 1 \text{ MeV}) (50 \text{ kpc} / r)^2 \quad (2)$$

with $A=0.34$ for 90 tons of scintillator(LSD); $A=6.27$ for 2140 tons of water (total K2 volume); and $A=14.6$ for 5000 tons of water (fiducial IMB volume). I assume $r(\text{SN1987A})=50 \text{ kpc}$, and call $L/(3.0 \cdot 10^{53} \text{ ergs}) = L_{SSNU}$, the total integrated luminosity in "standard supernova units".

The relative likelihood of fits with different values of T in a particular experiment can be found by plotting $\Pi_i (dN(T)/N(T) dE_i)$, $i=1, \dots, n$, with proper smearing over the errors in the energies, E_i , of the n data points. The results, borrowed from work with Abbott and Walker⁶⁾, are given in Table 1, with energies and temperatures in MeV's.

	LSD		K2	IMB
(E_o, E_{TH})	(4.5 , 5.5)	(3.5 , 4.5)	(5.5 , 7.5)	(18 , 18)
T	+0.5 0.9 -0.2	+0.7 1.3 -0.3	+0.5 2.6 -0.4	+1.2 4.0 -1.0

Table 1. Optimal Temperatures and their 1σ deviations for the three experiments.

Armed with a measurement of $T(\text{LSD})$, we can proceed to refine the argument in the Kamiokande paper²⁾, contradicting the earlier LSD results. Let $T(\text{LSD})$ be chosen at its most likely value, 0.9 MeV, as in the first column of the table. The value of the ratio of event numbers predicted by Eqs.(1) is $R=N(\text{K2})/N(\text{LSD})=4.4$. Let $P_\mu(m)$ be the Poisson probability to find m events when μ are expected. The probability of finding m events in LSD and n in K2 when μ and $R\mu$ are expected (normalized to the probability of finding what one expects) is:

$$\lambda(\mu, m; R\mu, n) = P_\mu(m) P_{R\mu}(n) / P_\mu(\mu) P_{R\mu}(R\mu) \quad (3)$$

The most likely probability for the situation in which LSD finds $m=5$ events and K2 finds n is the maximum of $\lambda(\mu, 5; R\mu, n)$ as a function of μ : $8.6 \cdot 10^{-3}$, $2.8 \cdot 10^{-3}$ and $5.4 \cdot 10^{-4}$, for $n=2, 1$ or 0 events, respectively. One is tempted to conclude that if K2 sees $n < 3$ events, LSD is in deep trouble. To show how misleading this kind of argument is, let me apply it, *mutatis mutandis*, to the simultaneous K2-IMB observations. K2 observes 11 events with a most likely temperature $T=2.6$ MeV, at which Eqs.(1) predict $R=N(\text{IMB})/N(\text{K2})=0.14$. Maximize $\lambda(\mu, 11; R\mu, 8)$ to find how likely it is for IMB to see 8 events. The answer is $3.5 \cdot 10^{-3}$. Attributing 2 of the 11 K2 events to elastic scattering reduces the combined K2-IMB probability to $1.4 \cdot 10^{-3}$. Yet, there is no question that IMB *did* see ~ 8 events. Who is now in trouble? Clearly the right question to ask is: are the experiments compatible *within errors* ?

The neutrino pulse from a supernova is characterized by two main parameters: its luminosity L , and its temperature T . The proper way to present and compare experimental results is to plot them, with their errors, in an (L, T) plane. For an assumed thermal distribution, the measured temperatures⁶⁾ can be read off Table 1. For a given T , Eq.(2) gives a central luminosity $L_c(T)$, corresponding to the observed number of events, n . The confidence levels of $L(T)$ around $L_c(T)$ are governed by Poisson statistics around a central value n . If n is small, one has limits on $L(T)$ with various Poisson confidence levels, corresponding to the observation n . The function $L(T) \sim [T < \mathcal{E}(T, E_o, E_{TH}) >]^{-1}$ is extraordinarily sensitive to its parameters, since for the measured temperatures all experiments observe the

tail of an abruptly falling energy distribution, electronically cut by the threshold condition $E > E_{TH}$, and weighed by a rapidly rising detection and reconstruction efficiency.

The results of LSD and K2 for the candidate neutrino burst at $\sim 2h, 52m$ are shown in Fig(2). The values of E_0 and E_{TH} given in the insets are meant to reflect the advertised efficiencies^{1,2,5,7}). The K2 results are given as 90% and 95% confidence upper limits, for $n=1,2$ events seen by K2 at LSD time. For the threshold parameters given in Fig(2a), the assumed K2 efficiency (though multiplied by an overall factor 0.85) is presumably an overestimate of K2's total-volume efficiency⁵), see Fig(2c). The assumed LSD threshold efficiency is presumably an underestimate, since $E_{TH} \sim E(e^+)$ for two of the observed events: in terms of making the experiments compatible, Fig(2a) is pessimistic. The overlap of the 90% confidence levels of LSD and K2 ($n=2$) is the region shaded in black. Even the minimum L in this region, $L_{min} \sim 60$ SSNU's, is a far cry from standard supernova lore, that brackets L_{SSNU} around 1, with a maximum uncertainty of a factor of ~ 5 . The horrendous sensitivity of these results to the efficiencies at threshold is illustrated by moving from Fig(2a) to Fig(2b) in which the threshold parameters E_0, E_{TH} have been slightly modified. The 90% confidence overlap increases considerably. The relative probability of the lowest luminosity point in the overlap region, computed with Eq.(3) [with μ now fixed by L] is a very comfortable $\lambda=0.18$: the experiments are compatible. To illustrate the incidence of possible systematic errors, suppose that (within 1 or 2 MeV from the low energy threshold) $E(\text{true})=E(\text{measured})(1+\epsilon)$, for the event energies and for the parameters E_0, E_{TH} , describing the efficiency of a particular experiment. Its confidence contours would shift from $[L, T]$ to $[L, T(1+\epsilon)]$. As an example, the shaded area in Fig(2b) shows to where the K2 limits would move if the K2 energies close to threshold were underestimated by $\epsilon=20\%$. These uncertainties are presumably realistic, given for example⁸) the differences between the calibrated e^- efficiencies and the e^+ efficiencies to be used in this analysis, scintillators see the $e^+e^- \rightarrow 2\gamma$ energy, while the Čerenkov light switches off. In this discussion I have assumed a thermal $\bar{\nu}_e$ spectrum. Supernova models predict an absorption correction: a multiplicative factor $\approx \exp(-\beta E^2/T^2)$ in the expression for dN/dE in Eq.(1a). This makes the tail of the spectrum fall faster than thermal, and increases the K2-LSD compatibility. The final word rests with the experimentalists, but I believe it is abundantly clear that *the K2 results do not infirm the LSD pulse*. Alas, the *combined* LSD-K2 results only constrain L and T to a wide range, between a ridiculous $L_{SSNU}=510^3$, $T=0.5$ MeV and a more sensible $L_{SSNU}=2$, $T=2.7$ MeV.

I display in Fig(3) the observations at K2-IMB time, $\sim 7h, 35m$. The K2 collaboration employs the 2140 ton total volume in the discussion of the LSD burst, but never states the volume in which the events at 7h.35m. occur. But the K2 paper²) states that for $n=9$ $\bar{\nu}_e p \rightarrow e^+ n$ events, and for an *assumed* $\langle E(\bar{\nu}_e) \rangle = 15$ MeV ($T \sim 5$ MeV) the calculated $\bar{\nu}_e$ luminosity is $8 \cdot 10^{52}$ ergs. I use Eq.(2) to "undo" their calculation and "measure" the effective volume to which it refers. The answer is within 10% of the fiducial volume of 780 tons and is

insensitive to small modifications of the threshold efficiencies, given the high assumed value of T . To maintain the benefit of the doubt, I have plotted Figs.(3a) and (3b) for the total and fiducial K2 volumes, respectively. The figures assume $n=11$ K2 events; the K2 contours are to be raised by $11/9$ if 2 events are attributed to elastic ν - e scattering. The IMB results are for $n=8$ events. The 90%-confidence LSD limit corresponds to the observation⁸⁾ of $n=2$ events at K2-IMB time. The K2 and IMB observations, Fig(3), are compatible, particularly if one uses the fiducial K2 volume. The combined allowed values of L and T for the second neutrino burst are also uncertain, somewhere in the range $L_{\text{SSNU}}=10$ $T=2$ MeV; to $L_{\text{SSNU}}=2$, $T=4$ MeV. (The L range would be 4 to 0.8, if one were to use K2's total volume).

To summarize, all experiments are compatible with the assertion that Shelton's supernova banged twice. The second neutrino burst is undeniable. The evidence for LSD's first burst is weaker, but the K2 observations confirm and strengthen it. The combined probability of the first burst being a fluctuation of the backgrounds is $2.5 \cdot 10^{-5} (\Delta t/24\text{h})$, with Δt your favourite uncertainty in the extrapolation of the observed light curve towards $t=0$. Models of the light curve⁹⁾ imply $\Delta t \sim$ few hours around LSD time. They⁹⁾ simply cannot accomodate a bang at K2-IMB time, but this will certainly remain a subject of debate¹⁰⁾.

Let me estimate how the measured values of L and T change, if one removes the approximation of a Boltzmann spectrum $d\Phi/dE \sim E^2 \exp(-E/T_B)$, and uses instead a Fermi spectrum with absorption: $d\Phi/dE \sim [E^2 \exp\{-\beta(E/T_F)^2\}]/[1+\exp(E/T_F)]$. Supernova models constrain β to the range 0.01 to 0.1. Forcing the Fermi and Boltzmann spectra to match in the observed-energy region I obtain, to first order in β ,

$$T_F = T_B (1 + \beta \langle E_i \rangle / T_B) \quad (4.a)$$

$$L_F = (F_2/2!) L_B (1 - \beta [F_4/F_2 - 3 \langle E_i \rangle / T_B]) \quad (4.b)$$

where $\langle E_i \rangle$ is the average neutrino energy of the *observed events*, $F_2/2!=0.9$ and $F_4/F_2=13$, with $F_j=F_j(0)$ moments of the Fermi function. The values of $\langle E_i \rangle / T_B$ are 7.7(+4.4/-3.5) for LSD, 6.3(+1.2/-1.1) for K2, and 8.2(+2.5/-2.1) for IMB. Plug these numbers and an illustrative $\beta=5\%$, into Eqs.(4), to find that T_F exceeds T_B by 20% to 60% for LSD, and by $\sim 25\%$ to $\sim 40\%$ for K2, 30% to 50% for IMB. For the largest[average] modifications of T , L_F/L_B is 1.9[1.3], 1.3[1.2], and 1.8[1.4], for LSD, K2 and IMB, respectively. Provided with a good estimate of β , we could correct our earlier results to accomodate the more elaborate theory. The $\beta=0.05$ exercise illustrates the sensitivity to the theoretical input, and the fact that the values $T_F \sim 4.3$ MeV, $L_F \sim 2.6$ SSNU's for the first neutrino burst; and $T_F \leq 6$ MeV, $L_F \sim 2.6$ SSNU's [or 1.0 SSNU's for K2's total volume] for the second, are within the uncertainties.

There is a third parameter, besides L and T , that characterizes a $\bar{\nu}_e$ burst: its time spread. The neutrino mean free path in the collapsing core is $\lambda = 1/\Sigma_i n_i \sigma_i$, with n_i the number

density of scatterers of type i (e^- , e^+ , nuclei) and σ_i the neutrino cross section on each of them. For a "Chandrasekhar" core in homologous collapse¹¹⁾ $\rho = \rho_0 (T/T_0)^3$, and $\lambda \sim \rho^{-1} \sigma^{-1}$ scales¹²⁾ as $T^{-3} E^{-2}$. The characteristic values of λ are smaller than the core radius: neutrinos are trapped. To escape they must diffuse their way out to a "neutrino-sphere" of radius $R = R_V$, after which the medium becomes "optically" thin (we shall later recall why the abrupt decrease of $\rho(R)$ with R results in a roughly energy independent R_V). I approximate the time dependence of the outgoing flux of neutrinos by the fundamental diffusion mode in a sphere of radius R_V : an exponential with a characteristic time $\tau = 3R_V^2 / (\pi^2 \lambda c)$. Let $\mathcal{L}(\langle E \rangle)$ and $\tau(\langle E \rangle)$ be the luminosity and characteristic time spread of the $\langle E \rangle \sim 3T$ average energy neutrinos. $\mathcal{L}(\langle E \rangle)$ decays as $\exp\{-t/\tau(\langle E \rangle)\}$, and the time integrated luminosity is $L = \tau(\langle E \rangle) \mathcal{L}(\langle E \rangle)$. Following the tradition of optical astronomy, we may empirically determine R_V from the luminosity-temperature ($\mathcal{L}$ - T) relation:

$$\mathcal{L} = [L / \tau(\langle E \rangle)] = (7 N_V / 8) T^4 (4 \pi R_V^2) \quad (5.a)$$

$$\tau(E) = (E/100 \text{ MeV}) (E/T) \tau_0 \quad (5.b)$$

Here $N_V = 3$ is the number of neutrino species, and in Eq.(5.b) I have used $\lambda^{-1} \sim E^2 T^3$ and $R_V \sim T^{-2}$ (at fixed $\mathcal{L}$). The normalisation of τ_0 to 100 MeV is a choice of no consequence. We may proceed to determine $\tau(E)$ and R_V from experiment. The expected distribution of events in time and energy is:

$$dN/N dE dt = (dN/N dE) [\tau(E)]^{-1} \exp\{-t/\tau(E)\} \quad (6)$$

with $dN/N dE$ as in Eqs.(1). The relative likelihood of fits with different values of τ_0 in a particular experiment can be found⁶⁾ by plotting $\Pi_i (dN(\tau_0)/N(\tau_0) dE_i dt_i)$, $i=1, \dots, n$, with E_i and t_i the measured energies and times of the n data points (t_1 , the time from the core's implosion to the emergence of the first neutrino, is also an unknown; its most likely values turn out to be $t_1 < t_2 - t_1$ for the three data sets). The measured values of τ_0 (with T in each experiment fixed at the most likely T_B of Table 1) are given in Table 2. The table also contains the convention-independent quantities of interest: $\tau(\langle E_i \rangle)$, the characteristic time of the observed bursts; and $\tau(3T)$, the much shorter time scale of the overall pulse, most of which consists of unobserved low energy neutrinos. The K2 and IMB results for the quantity of their common interest, $[\tau(3T)]$, are roughly compatible. Table 2 also contains the measured R_V , scaled to $T=5$ MeV, to facilitate comparison with standard supernova^{13,14)} lore:

$$(T/5 \text{ MeV})^2 R_V = R_0 = (37.6 \text{ kms}) (L/3.0 \cdot 10^{53} \text{ ergs})^{1/2} (1 \text{ s} / \tau(3T))^{1/2} \quad (7)$$

where the numerical factor stems from the inversion of Eq.(5.a). The results in Table 2 can easily be modified for $\beta \neq 0$ as in Eqs.(4): $\tau(\langle E_i \rangle)$ stays put, $\tau_F(3T_F) = \tau_B(3T_B) (T_F/T_B)^2$, and $(R_F/R_B) = (T_B/T_F) (L_F/L_B)^{1/2}$. For $\beta=0.05$, the central values of $\tau_F(3.15T_F)$ [and of R_0] would be 1.6s, 1.4s, 0.6s [180 km, 70km, 80km] for LSD, K2 and IMB respectively. [The values of R_0 (K2) employ its fiducial volume; for the total volume, divide them by ~ 1.5].

	τ_0^B	$\tau(<E_i>)$	$\tau(3T_B)$	R_0
LSD	7 ⁺⁵ -3	4.2 ^{+3.0} -1.8	0.76 ^{+0.54} -0.32	240 ⁺⁵⁶⁰ -150
K2	32 ⁺¹⁶ -11	3.4 ^{+1.6} -1.1	0.76 ^{+0.37} -0.24	80 ⁺¹⁰⁰ -22
IMB	0.8 ^{+0.4} -0.3	2.2 ^{+1.1} -0.8	0.29 ^{+0.14} -0.11	100 ⁺¹⁰⁰ -72

Table 2. Characteristic times of the neutrino bursts, in seconds; and neutrino-sphere radii, in kms.

The empirical pulse-duration times and neutrino-sphere sizes are in the expected range. The measurements of R_ν are not very precise, but forget not that the first measurement¹⁵⁾ of the radius of the photosphere of a compact object (The companion of Sirius, 1914) by inversion of its (ℓ -T) relation resulted in a value four times larger than the modern one.

From the point of view of the properties of either burst of neutrinos, SN1987A is not a very unexpected object. But Shelton's supernova is *really peculiar* in that it seems to have banged *twice*. After all, the 4h.43m4.58s lapse between the onsets of the LSD and IMB bursts is by far the best measured property of SN1987A. In what follows I construct a scenario¹⁶⁾ wherein all properties of SN1987A are explained (it is easier to construct a supernova *scenario* than it is to develop a complete model: after decades of analysis and untold hours of computer time, the solutions are still infants). We must explain the observed luminosities and temperatures, the time spread of the bursts (or equivalently why a neutrino sphere was present in both cases) and, not least, the delay between the bangs.

The implosion of the mother-star's core liberates an energy in the form of neutrinos very close to the gravitational binding self-energy of the daughter neutron star(n) :

$$L = k G M_n^2 / R_n = k (M_n / M_\odot)^2 (8 \text{ km} / R_n) \text{ SSNU's} \quad (8)$$

where $k=3/5$ for constant density, $k \approx 1$ for realistic density profiles. M_n is very close to the mother's core mass, estimated to be in the range 1.3 to 2 $M_\odot$. General relativity places a limit $L_{\text{SSNU}} < 8$. The values of L for a BJ or TNI nuclear equation of state¹¹⁾ (representative of the "average" $M(R)$ of sensible models) are $L_{\text{SSNU}}=1.3(2.6)$, for $M_n/M_\odot=1.4(1.8)$. For a "pessimistic" model favouring large radii (e.g. TI) $L_{\text{SSNU}}=1(1.7)$ for the same choices of M_n . The theoretically allowed luminosity range overlaps with the measured ones.

The empirical values of T_B or T_F for the first bang are lower than expected^{13,14)} for *red* giants. To elaborate on this point, let n_i and σ_i be defined as in the paragraph preceding

Eqs.(5). Use the expression $\sum_i \sigma_i = (\rho/m_p) \langle \sigma_0 \rangle (E/m_e)^2$ to define $\langle \sigma_0 \rangle$. Approximate the density profile seconds after the core's implosion by $\rho(R, T) = \rho_0 (T/T_0)^3 F(R)$. Define the neutrino-sphere radius by demanding that the neutrino interaction probability for $R > R_V$ be $f < 1$:

$$(\rho_0/m_p) (T/T_0)^3 (E/m_e)^2 \langle \sigma_0 \rangle \int_{R_V(E)}^{\infty} F(R) dR = f \quad (9)$$

[At this point one could use a rough ansatz such as $F(R) = \exp(-R/R_0)$ to conclude that $R_V(E)$ depends weakly on E and f]. Let R_0 be the integral of $F(R)$ from R_V to ∞ (or 0 to ∞ , since $R_0 \gg R_V$). Use Eq(9) and $E \sim 3T$, to find that T is fixed by $\rho_0 \langle \sigma_0 \rangle R_0 T_0^{-3} T^5 = f m_e^2 m_p / 9$. For different models of a *given* type of star, variations of the parameters are minimized¹²⁾ in the predicted value of T by the extraction of a 5th root. But the progenitor of SN1987A was *not* the customary *red* giant used in detailed Type II supernova work. I am led to conclude that we do not yet know with precision what the temperature of its neutrinos *should* be.

The critical condition for gravitational collapse into a black hole is $2GM(R_c)/R_c = 1$. Imagine a toy neutron star with $\rho = \rho_0$ up to R_n , $\rho = 0$ thereafter. The function $2GM(R)/R$ increases as R^2 up to R_n , decreases as $1/R$ beyond R_n . Let the star be quasi-critical: $2GM(R_n)/R_n = 1 - \epsilon$. Add an odd neutron to the star, or let it cool a fraction of a degree: $2GM/R$ reaches unity at $R_c = R_n$ and the *whole* star collapses. There is no matter outside the horizon to fall inwards, heat up, emit neutrinos and act as a thick neutrino-sphere. Even neutron star models with the largest imaginable "crusts" are very close to this simple picture: this¹⁷⁾ cannot be the explanation of the second neutrino burst.

The hot ejected matter visible in Type II supernovas is supposed¹¹⁾ to be all but the imploded core of the parent star. The core's implosion and rebound generate a shock wave that heats and "evaporates" the rest of the star. Modelling^{13,14)} the production and motion of the shock is one of the hardest problems in physics: it has only been solved for the first few seconds after core collapse. Until very recently, most calculations actually resulted¹⁸⁾ in a shock that stalled: its efficiency to blow up the star was nil. Since stars *do* blow up, the tacit hope of supernova practitioners has always been that the shock's efficiency be 100%. I am going to assume that, in the case of SN1987A, the truth is in between. A fraction of the parent-star's mass density was left behind, with an aftershock density profile $\rho(R)$ and an integrated mass distribution $M(R)$. The time required for the mass left-over at a distance R to fall to a much smaller distance in the vicinity of the neutron star is:

$$t = \pi R^{3/2} / (8 G M)^{1/2} \quad (10)$$

Here $M = M_n$, the neutron star's mass, if the total mass left behind by the shock is relatively small [$M(\infty) < M_n$] and $M = M(R)$ in the opposite, more reasonable, extreme [in the

approximation that the material is in homologous collapse, $M[R(t)] = M[R(0)]$, with $R(t)$ given by the inversion of Eq.(10)]. The mass accretion rate into the vicinity of the neutron star is:

$$dM/dt = (64/3\pi) G M t \rho[R(t)] \quad (11)$$

For a first illustration, assume that the efficiency of the shock to blow up the matter present at different radii, $\epsilon(R)$, is not far from a constant, so that the after-shock density profile can be approximated by the proverbial polytropes. Take the radial size of the polytrope to be the typical dimension of a blue giant: $R_{BG} = 10^7$ km. The results for dM/dt , are shown in Fig.(4), for polytropic indices $n=3$ and $n=1.5$, with the vertical (but not the horizontal !) scale in arbitrary units. The continuous lines are for $M_n \gg M(\infty)$, the dashed lines for the opposite extreme. The time scale could be modified, if necessary, by changing the assumed size of the blue giant [$t/t = (R'_{BG}/R_{BG})^{3/2}$]. It is apparent from Fig.(4) that the "rain" onto the neutron star may be fairly peaked in time, and that the overall time scales are just right. To stress this point, define an average time $\langle t \rangle$ of fall-back of the material: weigh Eq.(10) with the measure dM/dt . The results for $M_n \gg M(\infty)$ are $\langle t \rangle = [3.1h, 7h]$ for $n=[3, 1.5]$. For the opposite extreme, $\langle t \rangle = [3.9h, 9.2h]$ for $n=[3, 1.5]$. These results bracket the observed 4h.43m.4.6s. delay between neutrino bursts more snugly than one had the right to hope. There are situations wherein the function dM/dt would be even more peaked in time than in Fig.(4). Any example where the shock's mass-expulsion efficiency $\epsilon(R)$ decreases with R is of this type. Suppose that $\epsilon(R)$ be inversely proportional to the parent star's density: the remaining material has a constant density profile up to $\sim R_{BG}$. In this case, and for homologous collapse, dM/dt is a delta function at $t_0 = (3\pi/32G\rho)^{1/2}$, independent of R_{BG} . If it so happens that $\rho = 1.53 \cdot 10^{-2}$ gr/cm³, then $t_0 = 4h.43m.6s$; I seem to be getting carried away.

If the neutron star was not there, the collapsing material left over by the shock would equilibrate as a star-like object with a radius, R_s , and a central density, ρ_c , dictated by its composition and mass, M . For an $n=1.5$ polytrope, adequate for relatively cold material:

$$R_s = 7000 \text{ km } (2M_\odot / M)^{1/3} (2/\mu_e)^{5/3} \quad (12a)$$

$$\rho_c = 1.6 \cdot 10^7 \text{ grcm}^{-3} (M / 2M_\odot)^2 (\mu_e / 2)^5 \quad (12b)$$

where $\mu_e \sim 2$ is the baryon-to-electron number ratio, and I have normalized to 2 solar masses of "rain". [Equilibrium solutions for the $n=3$ extreme exist only for fixed mass, other indices will be presently discussed]. But the inner layers of the envelope forming around the neutron star are "eaten" by the surface of its outer crust, and the inner crust is being neutronized, bringing the core closer to gravitational collapse. The sound travel time in the radius R_s is small compared to hours, the overall time of the process: the "uneaten" material obeys Eqs.(12), with $M=M(t)$ the uneaten mass. The envelope is not significantly heated by the large amounts of energy generated in the rain-to-crust and crust-to-core transitions,

since neutrino radiation immediately cools the material to $T=1$ MeV or less. This temperature matches that of the inner part of the accumulating envelope. Predicting in utmost detail the overall process of production of a partially failed shock, reaccumulation onto the neutron star, and collapse into a black hole is not easier than predicting the weather hours after World War III, having forgotten that the Earth rotates. For the last step of the predictions we are greatly helped by the fact that, if $M(t)$ at collapse-time is a few $M_{\odot}$, the characteristic radii and densities of Eqs.(12), and the $T \sim 1$ MeV central temperatures, very closely match the inner properties of He-core stars of mass 150 to 500 $M_{\odot}$. The collapse of these objects into black holes, and the neutrinos emitted in the process, have been studied¹⁴⁾ by Woosley, Weaver and Mayle (WWM) with state-of-the-art numeric and analytic precision. Fractions of a second after our neutron star finally collapses into a black hole, the density profile of the collapsed object and its envelope is essentially the same as that of a WWM star right after the collapse of its core. Let n be the polytropic index of the envelope, M_v the mass inside the neutrino-sphere and v_v the infall velocity at its surface. WWM predict:

$$L_{GR} = L_{CL} (1 - 2GM_v/R_v) ([1+v_v]/[1-v_v]) \quad (13.a)$$

$$L_{CL} = 6L(\bar{v}_e) = 0.73 ([3n-1]/[3n-2])^{10/7} (T_B/5\text{MeV})^4 (R_v/37.6 \text{ km})^2 (\tau(3T_B)/1s) \text{ SSNU's} \quad (13.b)$$

where I have converted WWM's results on $\mathcal{L}(\bar{v}_e)$ into an integrated luminosity, as in Eqs.(5), and I again present results in terms of $L=6\mathcal{L}(\bar{v}_e)$. For the measured values of R_v of Table 2, the relativistic corrections of Eq.(13.a) are small, even if the mass M_v is an inconceivably large 20 $M_{\odot}$, and v_v is set to its maximum (free-fall) value. Substitute the central K2(fiducial volume) parameters of Table 2 into Eqs.(13) to obtain $L_{SSNU}=4.0$ for $n=1.5$ and $L_{SSNU}=3.3$ for $n=2.2$ (the polytropic index advocated by WWM). The predicted luminosities coincide precisely with the range favoured by K2, see Fig(3b). For the total K2 volume the results are equally satisfactory: $L_{SSNU}=1.8[1.5]$ for $n=1.5[2.2]$, see Fig(3a). For IMB the predictions are $L_{SSNU}=2.4[2.0]$ for $n=1.5[2.2]$, again in the favoured domain of Fig(3). How well this exercise works may be emphasized by noticing that given the scaling properties of Eq.(7), Eq.(13) can be rewritten in a form wherein experimental errors largely cancel: $L(\text{predicted})=aL(\text{observed})$, with $a=0.97[1.18]$ for $n=2.2[1.5]$. Since the number[0.73] in Eq.(13.b) is *theory*, this is not a tricky loop in my logic, but an indication of how uncannily well the black hole scenario describes the second neutrino blast. The *predicted* Boltzmann temperature is¹⁴⁾ $T_B= 3.8$ to 4.0 MeV, also in the allowed experimental range, particularly that of IMB.

Should we, to try and test a SN1987A scenario, wait an unspecifiable number of lustrums for another supernova of this novel type to occur in our vicinity? No, there are a variety of predictions and "postdictions" to be made.

The most obvious prediction of a black-hole scenario is that there should not be a left-over intense source of X-rays, pulsating or not, to be eventually uncovered. If there is, a last line of defence of a two-bang picture still remains. It must be admitted that we know very little about the behaviour of baryonic matter at extremely high pressure. Quite possibly

this matter occurs^{11,19)} in a variety of phases, nuclear matter with pion or kaon condensates, "ordinary" and "strange" quark matter... As the material surviving the shock accumulates onto the neutron star, the pressure increases. The inner portions of the star may undergo a rather abrupt first order phase transition into a state of higher density, reproducing to a large extent the black-hole scenario, and leaving behind a compact object whose surface properties resemble those of a conventional neutron star.

In a two-bang scenario one expects the light curve to be very peculiar. For a parent star as "small" as a blue giant, the shock reaches the surface in tens of minutes: the light curve begins to rise soon after LSD time. Some four and a half hours later, at K2-IMB time, the second bang occurs. The radius of the envelope at that time, Eq(12.a), is so small that whatever material is not eaten by the black hole is *violently* expelled in a matter of minutes: it expands and cools off very fast. Ignoring the difficult problem of shadowing and interactions between the two shells of outgoing matter, I expect the visible luminosity to be described by a conventional "theta-function-like" light curve⁹⁾ starting tens of minutes after LSD time, with an additional short lived contribution¹⁰⁾ starting to rise ~ 5 hours later. This may be precisely what is needed to fit the data, and it might even abide by the debated Jones' finderscope limit: $m > 7.5$ at 9h.22m. UT on February 23rd; 1h.47m. after K2-IMB time.

An obvious question, on which there is no data yet, is whether or not IMB should have seen events at LSD time. For $T_B = 2$ MeV, $L_B = 3$ SSNU's, a reasonable choice for which LSD and K2 are not particularly in disagreement, and for $E_o(\text{IMB}) = E_{TH}(\text{IMB}) = 18$ MeV, Eqs.(1) predict 0.5 IMB events. For a more optimistic $T_B = 2.8$ MeV, $L_B = 2$ SSNU's, the prediction is 3.9 events. These numbers could easily be wiped out by a small neutrino absorption correction, $\beta \neq 0$. The situation is obscure and marginal, unless the IMB collaboration can lower their threshold.

In the time interval Δt between the two bangs, the neutron star core grew from its mass at birth, M_n , to the critical mass of gravitational collapse, M_c . The difference of gravitational binding energies was mainly radiated in the form of neutrinos, produced in the core-crust interface. The predicted luminosity is $L(\Delta t) = L(M_c, R_c) - L(M_n, R_n)$, with $L(M, N)$ as in Eq.(8). Assume $M_n = 1.4 M_\odot$, the "standard" mass of the parent-star's Chandrasekhar core. The calculated $L(\Delta t)$ is 2.3[1.7] SSNU's for a BJ or TNI [TI] equation of state. The temperature of these neutrinos should be $T_B \sim \text{few MeV}$, as usual. Can they be seen above background in the period Δt ? The best placed experiment is K2, whose background is the smallest: an expected $\sim 20[35]$ events above $E = 11[7.5]$ MeV, for $\Delta t = 4\text{h}.43\text{m}$. Let the signal have a compromise $L_{SSNU} = 2$. For an assumed $T_B = 2.6$ MeV[5 MeV], Eqs.(1) predict 6[13] signal events in K2's fiducial volume, and 14[30] events in the total volume. These numbers are not significantly above background. But the signal is presumably peaked in an interval of order one hour, the time during which the accretion of material on the neutron star peaks. The signal might significantly exceed the background in that bin. With a little luck, Kamiokande might make a significant contribution to the credibility of the two-bang scenario, and that of the LSD burst.

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Note added. As this work was being typed, I received a paper²⁰⁾ by J.N. Bahcall et al. carefully analysing the IMB-K2(total volume) data. Their figures refer to the combined results, and cannot effortlessly be compared to mine. The effort made, we agree.

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FIGURE CAPTIONS

- Fig. 1 Energies and timings of the events in the different detectors. The left(right) column corresponds to LSD (K2-IMB) time. To guide the eye, the threshold K2 energy, $E_{TH}(K2)$, is superimposed on LSD's data.
- Fig. 2 a) and b) (L,T) plots at LSD time, showing the region allowed by the LSD and K2 data, for two choices of the parameters describing the threshold efficiency as in the inset c), where the full line is the shape of my approximation, the dotted lines are K2's efficiency drawn in the scale $E_0=5.5$ MeV, $E_{TH}=7.5$ MeV.
- Fig. 3 (L,T) plots at K2-IMB time, for two choices of the effective volume in which the 11 K2 events occur.
- Fig. 4 Mass accretion rate onto the vicinity of the neutron star as a function of time, for polytropic indices $n=1.5$ and 3. The full lines are for $M_n \gg M(\infty)$, the dotted lines for $M_n \ll M(\infty)$. The vertical scales are unnormalized.

- Figure 1 -

- Figure 2 -

- Figure 3 -

- Figure 4 -