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SUPERNOVA 1987A:
18 Months Later

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ABSTRACT

An overview of the significance for physics of the closest visual supernova in almost 400 years is presented. The supernova occurred in the Large Magellanic Cloud (LMC),$\sim$ 50 kpc away. The supernova star was a massive star of $\sim 15 - 20 M_{\odot}$. Observations now show that it was once a red-giant but lost its outer envelope. The lower than standard luminosity and higher observed velocities are a natural consequence of the pre-supernova star being a blue rather than a red [supergiant]. Of particular importance to physicsts is the detection of neutrinos from the event by detectors in the United States and Japan. Not only did this establish extra-solar system neutrino astronomy, but it also constrained the properties of neutrino. It is shown that the well established Kamioka–IMB neutrino burst experimentally implies an event with about 2 to 4 x 10^{53}ergs emitted in neutrinos and a temperature, $T_{\bar{\nu}_e}$, of between 4 and 4.5 MeV. This event is in excellent agreement with what one would expect from the gravitational core collapse of a massive star. A neutrino detection, such as that reported earlier in Mt. Blanc, would require more than the rest mass energy of a neutron star to be converted to neutrinos, if it were to have its origin in the LMC. Thus it is probably unrelated to the supernova. The anticipated frequency of collapse events in our Galaxy, will also be discussed, with a rate as high as 1/10 year shown to be not unreasonable.

INTRODUCTION

On February 23, 1987, light *and neutrinos* from a supernova explosion in the Large Magellanic Cloud (LMC) first reached Earth. Since the LMC is ~50 kpc away (a satellite of our Milky Way Galaxy), this was the closest visual supernova since Kepler observed one almost 400 years ago. It has been designated SN 1987A. Most of our knowledge of supernovae has come either from observations of outbursts in distant galaxies, too far away to obtain neutrino fluxes, or from studies of old remnants in our galaxy, thus missing the fireworks. The occurrence of a supernova nearby while neutrino detectors were operating, as well as sophisticated electromagnetic radiation detectors of various types, as enabled much to be learned about supernovae. In addition, the pre-supernova star had been observed, so that we can finally know the true nature of the exploding object. This should tell us much about stellar evolution. This review will follow the Physics Reports article of Schramm and Truran.[1]

Supernova physics can be split broadly up into three subdivisions. The first is the physics related to the light curve, which is a consequence of the supernova shock hitting and heating the pre-supernova star's envelope and of energy output from radioactive decay and/or a remnant pulsar. Such physics is dominated by plasma phenomena and hydrodynamics, with atomic physics entering in as atomic lines become important. The second area involves the nuclear physics related to the synthesis of the heavy elements in the pre-supernova evolution of the star, as well as to the explosive nucleosynthesis occurring in the outburst itself. In case of some supernovae (Type I's) the nucleosynthesis dominated the light curve due to radioactive decay heating; radioactive decay is also important for SN 1987A although this is not a Type I! The third subdivision is the elementary particle physics of the central core collapse and the consequent neutrino outburst, in the massive star scenario (Type II) which is associated with SN 1987A. The core-collapse physics involves nuclear-matter physics, as a neutron star is formed, and energy transport in these regions of the star is dominated by neutrino physics. In addition, the formation of a compact object like a neutron star or a black hole requires that the binding energy ($\sim 2 \times 10^{53}$ ergs for a neutron star) must be radiated away, and neutrinos are the most effective way to do this.[2] It is the escape of these neutrinos that neutrino detectors had hoped to observe.

For SN 1987A, neutrino were definitively detected by the Kamioka[3] and IMB[4], and detectors, making this ***the birth of extra-solar system neutrino astronomy.*** Such a neutrino detection can immediately provide important constraints on neutrino properties. The length of travel automatically tells us that $\gamma\tau_{\bar{\nu}_e} > 1.7 \times 10^5$ yr, where γ is the relativistic factor and $\tau_{\bar{\nu}_e}$ is the anti-electron neutrino lifetime. (Note that the detectors were mainly sensitive to $\bar{\nu}_e$, thus most constraints are on $\bar{\nu}_e$.) Also, the duration of the detected neutrino bursts provides an upper limit on the mass, $m_{\bar{\nu}_e}$. It is only an upper limit, since the spreading in time of the neutrino signal might also be due to the intrinsic duration of the neutrino emission. More papers have been written on m_ν from SN 1987A than the number of neutrinos that were detected. The major differences between the papers is what assumptions made about the intrinsic spread of the emitted burst versus what part of the observed burst might be due to finite mass induced spreading. We will argue that the SN 1987A does not provide mass limits significantly stronger than those obtained in the laboratory from tritium end point studies. It will also be shown that, since a stellar collapse presumably produces all types of neutrinos, the detection of $\bar{\nu}_e$'s indicates that there are not too many other types, since otherwise the share of the binding energy radiated as $\bar{\nu}_e$'s would reduce the flux to unobservable levels. This argument also constrains axion and majoron properties.

A major problem regarding neutrinos from SN 1987A is that, while one burst was detected definitively by Kamioka[3] and IMB[4], with a possible detection by Baksan[6] another burst was reported earlier by Mt. Blanc[5] and not seen by the other detectors. While it is difficult to understand how Mt. Blanc could have seen something without Kamioka (a much larger detector with *almost* the same energy threshold) seeing it too, as emphasized by de Rujula[7], it is not impossible that a low temperature $\bar{\nu}_e$ burst could replicate the observations, but such a burst would require far more energy radiated as neutrinos than the rest mass energy of a neutron star.[8] Therefore, we argue that this earlier detection is unrelated to the supernova.

While discussing other astronomical implications of the Supernova, it is worth noting that Branch and Wagoner[9] have used the Baade-Wesselink method (luminosity-temperature-radius-distance relations for an expanding supernova shell) to obtain a distance to SN 1987A consistent with other distances used for the LMC. This supports the supernova derived distance scale, which leans towards smaller values of the Hubble constant ($H_o \sim 60 km/sec/mpc$).

Let us now review our expectations with regard to supernovae in general and compare these with the 1987A observations.

STELLAR EXPECTATIONS AND OBSERVATIONS

One significant outgrowth of observational studies of Supernova 1987A has been the unambiguous identification of the stellar progenitor as Sanduleak -69 202. The most unusual although not totally expected feature of the stellar progenitor is the fact that it was a **blue** supergiant. Standard descriptions for the expected massive star progenitors of Type II supernovae generally assume that they should evolve to red supergiants prior to the ignition of core carbon burning and thus may be expected subsequently to explode as red supergiants. It might also be noted that traditional supernova lore was naturally biased towards the red giant progenitor for Type II's since standard Type II light curves require a large radius progenitor to achieve the high luminosities normally observed. Low luminosity Type II's coming from blue progenitors would be missed in most studies.

However, it was known to stellar evolutionists prior to SN 1987A that massive stars could also undergo final collapse as blue stars. This could occur either because some massive stars might never become red [10,11] or because some massive stars after becoming red giants contract back to the blue before final collapse [12]. Each of these possibilities is sensitive to assumptions about convection, mass loss, and metalicity.

One of the new developments for SN1987A has been the identification [13] of a circumstellar shell around SN1987A indicating that the star losts its redgiant envelope. If mass loss is large it is certainly possible for the star to find itself in the blue rather than red at the time time of its final collapse. If such mass loss is enhanced by metalicity then the number of expected collapses in the Milky Way might be enhanced due to having missed the lower luminosity blue progenitor SN in other similar galaxies. We will return to this point later.

NUCLEOSYNTHESIS AND LIGHT CURVE EXPECTATIONS AND RESULTS

The hydrogen features in the spectrum of Supernova 1987A confirm that it is a Type II supernova. By definition, Type I's have little or no hydrogen, Type II's have hydrogen. Such supernovae are the expected products of the evolution of massive stars $M \gtrsim 10M_{\odot}$. The higher temperatures prevailing in the cores of massive stars are sufficient to ensure that carbon, oxygen, neon, and silicon thermonuclear burning phases will proceed through the formation of a core composed of iron-peak nuclei, surrounded by a mantle of matter enriched in intermediate mass elements. The structure and composition of presupernova stars of 15 $M_{\odot}$ which reveal these features[14] are shown in Figure 1 The predicted mass of heavy elements ejected in the subsequent supernova for this core is 1.24 $M_{\odot}$.

The mass fraction in the form of iron peak nuclei predicted to be ejected in a Type II supernova event is a function of the prevailing temperature and density conditions in the vicinity of the mass cut, at the boundary of the collapsing core. All massive stars have similiar cores (to $\sim 10\%$) thus measuring the Fe yield tells us much about core collapse supernovae [15].

The extent of iron production specifically in Supernova 1987A is relevant to two issues: the detection of gamma rays from the decay of ^{56}Co and the possible role of decay heating in defining the late stages of the decline of the light curve. In particular, nucleosynthesis calculations predict that nuclei of mass A = 56 are formed in situ as ^{56}Ni ($\tau_{1/2} = 6.10$ days; average decay energy 1.72 MeV) which, following supernova ejection, decays through ^{56}Co ($\tau_{1/2} = 78.76$ days; average decay energy 3.58 MeV) to ^{56}Fe. The longer lifetime of ^{56}Co allows the possibility of detection of gamma rays from ^{56}Co a year or more after the initial explosion.

LIGHT CURVE OBSERVATIONS

The light curve peaked about 90 days after its initial rise and its rise to maximum was very gradual. Expectations for the subsequent development of the light curve depend on this energy source. Observations now confirm that the energy source is radioactive decay heating. The time dependence of heating due to ^{56}Co decay is

$$\sim 1.3 \times 10^{42} exp(-t/113 days) ergs^{-1} \left(\frac{M_{56}}{0.1 M_{\odot}} \right)$$

where a mass $0.07_{\odot}$ of ^{56}Ni ejected is the best fit to the light curve. Confirmation that the light curve was ^{56}Co powered has come from the Solar Maximum Mission (SMM) which measured the two characteristic gamma ray lines at 0.8 and $1.2 MeV$[16].

This simultaneously confirms both our light curve and nucleosynthetic ideas.The fact that the x-rays and the x-rays (GINGA, MIR) came earlier than expected indicates that the ejection was not smooth and raditive but involved mixing and inhomogenieties as Pinto, Woosley, Namoto and others [17] have argued.

NEUTRINO EXPECTATIONS

This section of the review will borrow heavily from the *Comments* article of Schramm[8].

For over 20 years, it has been known that the gravitational collapse events thought to be associated with Type II supernovae and neutron star or black hole formation are copious producers of neutrinos.[2] In fact, the major form of energy transport in these objects comes from neutrino interactions. It has long been predicted that the neutrino fluxes produced by these events would be high enough that if an event occurred within the galaxy, it could be detected.

It has been well established in the models of Arnett[18] and Weaver et al.[19] that massive stars with $M \gtrsim 8M_\odot$ evolve to an onion-skin configuration with a dense central iron core of about the Chandrasekhar mass surrounded by burning layers of silicon, oxygen, neon, carbon, helium, and hydrogen. Collapse inevitably occurs when no further nuclear energy can be generated in the core. A more compact blue envelope would naturally lead to higher velocities and lower luminosities than with extended red envelopes It would also result in hours rather than days between core collapse and the light outburst. A supernova display is seen if the star's envelope can be ejected. To have such an ejection occur while allowing the core to collapse to a neutron star or black hole depends on the detailed physics of the core's equation of state and the neutrino transport of energy and momentum, as well as the hydrodynamics.

Bethe and Brown[20] and Baron et al.[21] have argued that, provided the equation of state of matter above nuclear density is very soft, stars in the mass range $10 \lesssim \mathrm{M} \lesssim 16\mathrm{M}_\odot$ may explode due to the prompt exit of the shock wave formed after the core bounces upon reaching supra-nuclear density. For stars with $16 \lesssim \mathrm{M} \lesssim 80\mathrm{M}_\odot$, the shock wave stalls on its exit from the core and becomes an accretion shock. Wilson et al.[22] have shown that such stars may eventually ($\sim$ 1 second later) eject their envelope as a result of neutrino heating in the region above the neutrinosphere and below the shock. (The delayed ejection can also occur in the lower mass collapses if the initial bounce does not produce an explosion.) In fact, if collapse to a black hole was delayed by a few seconds after bounce, the neutrino spectra and mass ejection should not be affected by the later formation of the black hole. Obviously the above scenarios are sensitive to the stiffness of the core equation of state which is still poorly known at and above nuclear mass densities.

As was first emphasized by Arnett and Schramm[23], the ejecta have a composition which fits well with the observed 'cosmic' abundances for the bulk of the heavy elements.

Regardless of the details of collapse, bounce, and explosion, it is clear that to form a neutron star the binding energy, $\epsilon_B \approx 2 \times 10^{53}$ ergs must be released. The total light and kinetic energy of a supernova outburst is about 10^{51} ergs. Thus, the difference must come out in some invisible form, either neutrinos or gravitational waves. It has been shown[24] that gravitational radiation can at most carry out 1% of the binding energy for reasonable collapses because neutrino radiation damps out the non-sphericity of the collapse[25] Thus, the bulk ($\gtrsim$ 99%) of the binding energy comes off in the form of neutrinos.

It is also well established[26] that for densities greater than about 2×10^{11}

g/cm^3, the core is no longer transparent to neutrinos. Thus, as Mazurek and Sato [27] independently established, the inner core has its neutrinos degenerate and in equilibrium with the matter. For electron neutrinos, the 'neutrinosphere' has a temperature such that the average electron neutrino energy is around 10 MeV.[28] This was established once it was realized that the collapsing iron core mass is $\sim 1.4 M_\odot$, due to the role of the Chandrasekhar mass in the pre-supernova evolution. Since the μ and τ neutrinos and their antiparticles only interact at these temperatures via the neutral, rather than the charged, current weak interaction, their neutrinosphere is deeper within the core.[26,28] Therefore, their spectra are hotter than that for the electron neutrino. The electron antineutrino opacity will initially be dominated by charged current scattering off protons but as the protons disappear, it will shift to neutral current domination. Thus the effective temperature for $\bar{\nu}_e$'s changes from that for ν_e's to that for ν_μ and ν_τ's.

The average emitted neutrino energy is actually quite well determined for the peak of the neutrino distribution and is very insensitive to model parameters. The peak occurs at the highest temperature for which neutrinos can still free stream out of the star; that is, where the neutrino mean free path, $[n\langle\sigma\rangle]^{-1}$, is comparable to the size of the core, R. This can be expressed as

$$R \simeq 1/n\langle\sigma\rangle \tag{1}$$

where n is the number density $= \rho/m_n$, ρ being the mass density and m_n the nucleon mass. Collapsing stars are well described by adiabatic physics. Thus density and temperature are related as

$$\rho = \rho_0 (T/T_0)^3 \tag{2}$$

For a Fermi distribution the average energy $\langle E_\nu\rangle = 3.15 T_\nu$ (using T in energy units). The effective neutrino cross section in stars[22] can be expressed as

$$\langle\sigma\rangle \approx \sigma_0 \langle E_\nu^2\rangle/2 \approx 12\sigma_0/2T_0^2 \left(\frac{T_\nu}{T_0}\right)^2$$

Inserting this into eq. 1 and solving for T

$$\frac{T_{\nu_e}}{T_0} = \left[\frac{2m_n}{R\rho_0 12\sigma_0 T_0}\right]^{1/5} \tag{3}$$

The neutrino temperature, T, varies only as the 1/5 power of the input. Thus, large uncertainties get minimized. [If R is put at its upper limit from the size of the core, then $R \propto 1/T$. The limiting relationship has T proportional to the 1/4 power, which is still quite insensitive.] Using reasonable values $\sigma_0 \simeq 1.7 \times 10^{-44}$ and $\rho_0 = 10^{10}$ gm/cm^3 at $T_0 = 1$ MeV, with the characteristic size of the region $R \simeq 5 \times 10^6$ cm (c.f. ref 29). Then

$$T_{\nu_e} \approx [340]^{1/5}\text{MeV} \simeq 3.2\text{MeV}$$

or

$$\langle E_\nu\rangle \approx 10\text{MeV}$$

. This is in good agreement with detailed numerical results. For ν_μ and ν_τ's only neutral current interactions are relevant so σ is lower and R is smaller yielding on average temperature about twice that for ν_e's. For $\bar{\nu}_e$'s the average energy increases with time until the protons disappear since they start out with charged current interactions off protons but as the protons disappear they only have neutral correct interactions so their temperature goes to the neutral current value for $< E\bar{\nu}_e >$ of about 15MeV.

It should also be noted that since the interaction cross sections in the star are proportional to the square of the neutrino energy, the lower energy neutrinos can escape from deeper in the star. Thus, the energy distribution of the emitted neutrinos is not a pure thermal distribution at the temperature of the neutrinosphere.

While the general scenario for collapse events is well established, the detailed mechanism for the ejection of the outer envelope in a supernova as the core collapses to form a dense remnant continues to be hotly debated. Therefore, most theorists working on collapse prior to SN 1987A have focused on these details in an attempt to solve the mass-ejection problem. As a result, most of the pre-1987 papers in the literature are concerned with the role played by neutrinos internal to the stellar core, rather than the nature of the fluxes which might be observed by a neutrino detector on earth. In particular, while it has been known since the early 1970's[28] that the average energy of the emitted neutrinos was about 10 MeV, with neutrino luminosities of a few 10^{52} ergs/sec, the detailed nature of the emitted spectra was only recently explored in detail by Mayle, Wilson, and Schramm[29,30]. Their calculation emphasized the high-energy neutrinos which are easier to detect. The diffusion approximation used in most collapse calculations does not treat the high-energy tail of the spectrum accurately. A large temperature gradient exists in the neutrinosphere region. For the high-energy neutrinos, the matter's temperature at one optical depth is relatively low compared to the temperature at one optical depth of the mean-energy neutrino. Thus, an appreciable fraction of the high-energy neutrinos originate in the higher temperature region and travel several mean-free paths before exiting the star. Therefore, for neutrinos whose energy is far above the mean energy, the multi-group, flux-limited-diffusion approximation is suspect. To confirm this, Mayle et al. constructed a computer code that integrates the Boltzmann equation more directly.

In addition to the basic energetic arguments, there is the basic neutronization argument [28]. The collapsing core has $\sim 10^{57}$ protons that are converted to neutrons via

$$p + e^- \rightarrow n + \nu_e$$

to form a neutron star. (This process is also called deleptonization by some authors.) Each ν_e, so emitted from the core, carries away on the average 10 MeV, thus around 1.3×10^{52} ergs are emitted by neutronization ν_e's. this is $\lesssim 10\%$ of the binding energy. The remainder of the neutrinos come from pair processes such as

$$e^+ + e^- \rightarrow \nu_i \bar{\nu}_i$$

where $i = e$, μ, or τ, with ν_μ and ν_τ production occurring via neutral currents, and ν_e via both charged and neutral currents. The recognition[28] in the 1970's that the bulk of the binding energy comes out in all neutrinos via neutral currents is important to understanding the observations. (The first focus on the role of neutral currents was their coherent scattering and its impact on opacity, however, it was also recognized that emission of all species occurred via neutral currents, but this fact was not the central focus of the early papers.)

Since some fraction ($\lesssim 50\%$) of neutronization occurs as the shock hits the core's neutrinosphere, whereas the pair ν's come from the 'thermally' radiating core, the timescale for an initial neutronization ν_e burst will be much less ($\lesssim 10^{-2}$ sec) than the diffusion time ($\sim$ seconds) that governs the emission of the bulk of the flux. Some so-called 'advection/convection' models increase the initial ν_e burst by convecting high-T, degenerate core material out. These models have higher-energy ν_e's with larger fluxes, and suppress the $\bar{\nu}_e$ fluxes.

For most models about half of the thermal neutrino emission comes out in the first second. The remaining comes out over the next few tens of seconds as the hot, newborn, neutron star cools down via Kelvin-Helmholz neutrino cooling to become a standard 'cold' neutron star. Burrows and Lattimer[31] carried out detailed cooling calculations prior to SN 1987A. Most other authors cut off their calculations either after the bulk of the neutrino emission occurred or mass ejection was established. Detailed models for the bulk of the neutrino emission [29,30] seem to find that the pair processes yield an approximate equipartition of energy in the different species. The ν_μ and ν_τ's have a higher energy per ν, thus their flux is down to preserve this equipartition.

Despite the explosive mechanism, for stars in the range $10 \lesssim M \lesssim 16 M_\odot$ the most distinctive structure in the neutrino signal is the initial neutronization burst and the bulk emission comes during the Kelvin-Helmholz cooling phase. However, in the delayed explosions seen by Wilson et al.[29,30], for stars with $M \gtrsim 16$, besides the burst, the neutrino luminosity shows an oscillatory behavior superimposed on an exponentially decaying signal. The oscillations in luminosity are related to oscillations in the mass accretion rate onto the proto-neutron star. The physical nature of the instability that is responsible for the oscillations in luminosity and mass-accretion rate is described in Mayle et al.[29], and in more detail in Mayle's Ph.D thesis. After the envelope is ejected, the luminosity will smoothly decrease as the remaining binding energy is emitted during the Kelvin-Helmholz cooling. Models without the accretion phase go directly from the neutronization burst to Kelvin-Helmholz cooling. Those models thus have the emission fall off with a single characteristic cooling time. However, models with an accretion phase have a high average emission rate for a second or so after the neutronization burst before the mass ejection and onset at the cooling phase with its dropping emission.

It is important to remember that the average neutrino luminosity, mean neutrino energy, and total emitted energy depend only on the initial iron-core mass and are relatively independent of the explosive mechanism. Because the opacity is less for the ν_μ and ν_τ's, they are emitted from deeper in the core where temperature is higher. Thus, they have a higher average energy. The calculations of Mayle et al.[29] find $E_{\nu_\mu} \simeq E_{\nu_\tau} \approx 2E_{\nu_e}$. The easier-to-observe $\bar{\nu}_e$ start out with energy comparable to ν_e's and gradually shift over to the $\nu_\mu - \nu_\tau$ energy as their emission continues from progressively deeper in the core.

Each spectrum for neutrino species is reasonably well fit by a Fermi–Dirac (F–D) distribution with temperature T. However, in the detailed spectral analyzer that Mayle et al.[29] carried out, it was found that the higher-energy neutrino fluxes were indeed higher than the single-temperature, F–D fit to the peak.

By using simple, model-independent arguments, one obtains a crude estimated $\bar{\nu}_e$ counting rate for an H_2O detector

$$n = \frac{(1-f_n)\epsilon_B}{2N_\nu \langle E_\nu \rangle} \frac{\langle \sigma \rangle}{4\pi r^2} \frac{2}{18} \frac{M_D}{m_p}$$

where f_n is the fraction radiated in the neutronization burst, $\langle E_\nu \rangle$ is the average neutrino energy, $\langle \sigma \rangle$ is the average cross section above threshold. [It should be noted that the cross section goes as $P_e E$ not E_ν^2, (see discussion Appendix to ref. 8) r is the distance to the LMC ≈ 50 Kpc, M_D is the mass of the detector, m_p is the proton mass, and N_ν is the number of neutrino flavors. (For the Mt. Blanc liquid-scintilator detector, one should multiply by 1.39 for the average number of free protons in $H_{2+2n}C_n$.) Using F–D statistics yields

$$\langle \sigma \rangle = \frac{\int_{E_c}^{\infty} \bar{\sigma} \frac{E^4 dE}{1+e^{E/T}}}{\int_0^{\infty} \frac{E^2 dE}{1+e^{E/T}}}$$

where E_c is the low-energy cut-off and $\bar{\sigma} \equiv \sigma / E_\nu^2$.

For the 2.14 kiloton Kamioka detector, this yields 11 counts. Similarly, for the Mt. Blanc detector with 0.09 kilotons, times 1.39 extra, free protons in the scintillator, a simple prediction is ~ 0.6 counts. IMB is a little more difficult because its threshold is not below the peak $\bar{\nu}_e$ counting rate. In addition, it is totally dominated by the high T tail where a constant T may not be an ideal approximation. However, a reasonable estimate using their efficiencies, thresholds and integrals over F–D distributions gives a prediction of 7 counts. (Note that IMB now uses 6 kilotons as their active mass rather than the 5 kilotons reported in their initial announcement.)

To estimate the expected number of electron scattering events one must do a bit more if threshold effects are to be included. Electron scattering yields a very flat energy distribution. When such a flat energy distribution is combined with a finite temperature F-D distribution for the initial neutrinos one finds an expected energy distribution for the scattered electrons which is quite peaked at low energies. If pure constant temperature F-D distributions are assumed for the neutrinos the total number of scattering is expected to be $\lesssim 0.5$ for 10 capture events. If the high energy tails are supressed by absorption as in Imshennik and Nadyoshen [32] ,then the expected scattering rate is even lower. However, if the high energy super-thermal tails of Mayle et al. are included, one finds that for every 10 $\bar{\nu}_e$ absorptions, one expects about 0.7 to 1 ν_e scattering and about 0.7 $\nu_x e$ scattering, where ν_x is either ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$, or $\bar{\nu}_e$. We can understand why the scattering rate is $\sim 1/15$ even though the cross section ratio at 10 MeV is ~ 80 by remembering that there are five electrons for each free proton in an H_2O target. In addition, at a given energy

$$(\sigma_{\nu_\tau^e} + \sigma_{\nu_\mu^e} + \sigma_{\bar{\nu}_\tau^e} + \sigma_{\bar{\nu}_\mu^e} + \sigma_{\bar{\nu}_e^e}) / \sigma_{\nu_e^e} \simeq 1.$$

Thus, if fluxes are equal, the rate is doubled. Actually, average energy of other species is about twice that of ν_e, but fluxes are reduced accordingly to roughly maintain equipartition of energy per neutrino species, thus keeping scattering constant. The difference in expected number of scatterings is an important probe of the high energy tail.

For the 615-ton C_2Cl_4 Homestake there are 2.2×10^{30} ^{37}Cl atoms. As seen from the Appendix to ref. 8 8, the cross section is not a simple integer power of E_ν, however, it seems to fall roughly between an E^3 and E^4 relationship for the range of interest. For temperatures above 5 MeV, the peak contribution to the thermal average would be coming from energies above 30 MeV where the cross section no longer rises as rapidly and the expected counting rate no longer continues to rise with temperature. In the standard case, one expects about a half of a count above the background. Similar to the solar case, ^{37}Cl is once again a potentially sensitive thermometer and yields interesting null constraints.

All the predictions described above assume a simple, spherical symmetric collapse. If large amounts of rotation or magnetic fields were present (with energies comparable to the binding energy) then the standard model would be altered with different time scales and different core masses and binding energies, since such conditions would alter the initial core mass as well as the dynamics.[61] We will see that the Kamioka/IMB neutrino burst fits the standard assumptions well so that the collapse which created that burst did not have significant rotation or magnetic fields.

Before SN 1987A, it was also obvious that a supernova, if detected by its neutrinos, would constrain neutrino properties. In particular, if the neutrinos got here, we'd have a lifetime limit. If the time pulse wasn't too spread out, that would mean a mass limit on those neutrino types that were clearly identified. Also, from the number of $\bar{\nu}_e$ counts, one could constrain N_ν since if N_ν was large, the fraction of thermally produced $\bar{\nu}_e$'s would go down. In addition, neutrino mixing could be constrained by detecting different types and comparing; with Mikheyev–Smirnov[33] matter mixing, as parameterized to solve the solar neutrino problem, $\nu_e \to \nu_\mu$ (or ν_τ), and ν_μ (or ν_τ) $\to \nu_e$, but nothing happens in the antineutrino sector. Such mixing would eliminate seeing the initial ν_e burst, but give higher energies to the later, thermal ν_e since they'd be mixed ν_μ's (see Walker and Schramm[34]). Of course, non-solar Mikheyev–Smirnov can be used if antineutrino mixing is seen. All of these effects will be examined with the data from SN 1987A.

NEUTRINO OBSERVATIONS

As mentioned before two "neutrino" bursts have been reported. Before discussing the plausibility of the first event, it is important to note that there was clearly neutrino detection on February 23rd near 7h 35m U.T. Thus, unquestionably *extra solar system neutrino astronomy has been born!* Let us now examine the burst Mt. Blanc reported on February 23rd, at 2:52 U.T. with five events which was unsubstantiated by the other three detectors. While lack of concordance is easy to understand for IMB and Baksan, due to their higher thresholds, the lack of a strong concordant signal, significantly above background, is difficult with regard to Kamioka. The Kamioka detector is 2140 tons, compared to 90 tons for Mt. Blanc, and the thresholds are similar. (Mt. Blanc was designed to detect $\bar{\nu}_e$'s from collapses in our galaxy, not the LMC.) Thus, many people have dismissed this first event as an unfortunate statistical accident. *A posteriori* statistics are difficult. While the chance of background exactly duplicating this event configuration eight hours before the visual outburst is low, perhaps the more relevant question is: What is the chance of background producing any plausible signal within two days prior to the visual detection? If any plausible signal is defined as three or more events (only three events were clearly above background) in less than or equal to 30 seconds, a chance occurrence becomes quite reasonable and many have assumed this explanation. In fact, seven months later this group did observe what clearly was a background burst of 5 counts in $\sim$ 10 sec. However, one should be cautious in following popular opinion too rapidly. Detections near threshold can be tricky, and statistics of small numbers are notoriously suspect. In fact, while both thresholds are indeed low, Mt. Blanc is lower. In particular, Mt. Blanc sees positrons down to $\sim$ 5MeV whereas Kamioka does not see significant positrons below $\sim$ 7 MeV. Furthermore, Mt. Blanc sees total energy including e^+e^- annihilation thus it is capable of detecting incoming neutrinos down to 5.3 MeV whereas Kamioka must add 1.3 MeV to get their neutrino energies, yielding their lower bound on detectable neutrinos of 8.3 MeV, about 3 MeV above Mt. Blanc.

Kamioka did report that they had two background counts in the 10-minute interval centered at the Mt. Blanc event which is consistent with their background. They also scanned their sub-threshold background and saw no enhancement at this time. Thus Kamioka appears to have no strong evidence for concordant events with Mt. Blanc at the early time. It has been shown [8] that the event energies and counts from the Mt. Blanc burst are only fit by low temperatures ($T \sim 1MeV$) and high luminosities ($\gtrsim 10^{54} ergs$).

Let us suspend our theoretical prejudice and ask if such a high-luminosity, low-T event did occur, could Kamioka not have seen it? In fact, as first noted by de Rujula[7] a minimal Kamioka detection cannot be totally excluded because the implied Mt. Blanc burst temperature is so low, and the thresholds are different. Even zero events is not impossible if the temperature of the neutrino distribution were low enough. To get less than a few counts at Kamioka requires neutrino temperatures under 1 MeV. Lower temperatures yield higher flux in order to get 5 events at Mt. Blanc. To avoid a Kamioka conflict would require $T \leq 1$ MeV and $E_{TOTAL} \gtrsim> 10^{55} ergs$! Not only is this greater than a neutron star rest mass but it is comparable to or greater than the rest mass of the whole Sanduleak star. The time structure of the Mt. Blanc event burst is also peculiar with one event four seconds before the rest. Some have also cited concordant gravitational wave detector noise in Italy and Maryland in coincidence with the Mt. Blanc burst as significant. However, these are room temperature detectors with lots of noise and would imply $\gtrsim 1000\ M_\odot$ emitted in gravitational waves. Furthermore Piran [35] has argued that the coincidences do not seem to be statistically self consistent. The Mt. Blanc burst would necessitate an initial collapse event that is quite different from standard models. Models with large magneticfields and/or rotation, such as Symbalisty et al.[61] have low temperatures, but it is hard to imagine an event which radiates a *minimum* of several neutron star *rest masses* in neutrinos, or has a very non-thermal distribution. The non-standard event must then be followed by a subsequent collapse five hours later to a black hole or a dense, strange-matter star looking very much like a normal collapse, as we shall see. An alternative is that this event was not in the LMC but was *much* closer, thus reducing the energy requirements but requiring a remarkable timing coincidence. Given all these problems, we quote Eddington: "Observations should not be believed until confirmed by theory". Unlike Kamioka and IMB, it should be remembered that the Mt. Blanc detector was actually constructed to look for collapse neutrinos; unfortunately it was optimized for collapses within 10 kpc.

Let us now turn our attention to the well established Kamioka/IMB burst. (For a detailed discussion, the fact that Mt. Blanc and Baksan may also have signals is irrelevant other than to show that detectors $\sim 1/20$ the mass can have $\sim 1/10$ the counts, due to statistics of small numbers plus possible background subtraction uncertainties.) Figure 2 is a plot showing the energy and timing of the Kamioka and IMB events. (Kamioka's event no. 6 is ignored as being below their criteria for a definitive event.) Almost all the counts concentrate in the first few seconds, as one expects in collapse models. The last events from IMB are the lowest energy ones of 20 and 24 MeV, which are the ones with the greatest uncertainty due to background subtraction. Note also that the IMB late counts nicely fill in the 6 second gap in the Kamioka data.

To examine consistency let us use the number of counts and mean energies measured in the experiments to determine the implied temperature and energy emitted in $\bar{\nu}_e$'s. Such estimates require detailed consideration of efficiency and threshold effects. Figure 3 is a plot of the implied neutrino luminosity and temperature from the IMB and Kamioka events[8]

While one might expect (from Mayle et al.) IMB to measure a slightly higher T, it is interesting that there is nevertheless a region of overlap where both data sets yield the same T_{ν_e} and $\epsilon_{\bar{\nu}_e}$. It is particularly satisfying that this region of overlap is exactly where one might have expected a standard gravitational collapse event to plot, namely, $\epsilon_T \sim 2 \times 10^{53}$ ergs, $T \sim 4.5$ MeV. Similar conclusions were reached by Sato and Suzuki[37] and Bahcall et al.[36] using a different treatment than has been applied here. Once T and ϵ_T are determined one can use the luminosity–temperature relationship to solve for the radius, R, of the neutrinosphere and obtain, in our case, a few tens of kilometers, in reasonable agreement with the standard models. It might be noted that when one examines the data in detail,[8] it doesn't seem to make much difference whether the IMB data includes the two low points or not; the other uncertainties dominate. Similarly, it doesn't seem to matter, with regard to the Kamioka data, whether of not the first few or the last three events are included. It is worth noting that the above analysis is very crude. The boundaries used in Figure 3 do not have a quantitative statistical meaning since systematic as well as statistical uncertainties were mixed in obtaining them. Nonetheless, the results are suggestive and more detailed analyses seem to yield similar conclusions.

The angular distribution for Kamioka is shown in Figure 4. From the isotropic rate background and the angular resolution, there appears to be a slight excess directed events (note, Kamioka initially claimed two probable scatterings, but their second event is not given an angle of 40°, not 18°, Koshiba private communication). Since $\bar{\nu}_e + p$ would yield an isotropic distribution, the number of directed electron scattering events should be relatively small, as might be expected by the ratio of cross sections. Using the results of the Mayle et al, one expects ~ 1.5 to 2 such events or two for their 15 $M_\odot$ model in reasonable agreement with the observations. One also expects that $\sim 50\%$ of these scattering events are higher energy ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$, or $\bar{\nu}_e$ events. This also fits well since the highest energy Kamioka events have $\cos\theta > 0.7$. It is also intriguing that the first event has $\cos\theta$ closest to unity. Remember that the initial 0.01 sec neutrino burst is expected to be ν_e's with no $\bar{\nu}_e$'s but statistics of one are not very convincing. It is interesting to note that models with no high energy tail would predict less than 1/2 a scattering event. Since the data seems to require 1 or 3 scattering, it is reasonable to argue that the data do lean towards models with high energy tails over models with pure constant T distributions and certainly models with absorption supressed tails run into difficulty.

The angular distribution for IMB is more problematic[38]. Initially the failure of one of the 4 power supplies was thought to bias the data but subsequent Monte Carlo analysis showed that the effect was not significant. The IMB distribution peaks at $\sim 45°$ with most of the events forward and no significantly backward scattered events. It clearly is not fit by an isotropic source however if it is recognized that at high energy and with the particular detector then $\bar{\nu}_e + p$ should yield $\sim 1 + 0.2\cos\theta$, not isotropic and with a high E tail giving ~ 1 e-scattering then the distribution is at an $\sim 8\%$ probability so it is not too ($\lesssim 2\sigma$) unlikely. (The $1 + 2\cos\theta$ distribution by itself is at $< 3\%$ probability level.) However, the alternative of some new physics cannot be trivially excluded.[38]

While discussing ν_e scattering, its worth noting that the ^{37}Cl experiment of Davis was operating at the time of the Supernova, and has seen no excess over a standard run.

Another constraint on ν_e's comes from interactions with ^{16}O which would be backward peaked at high energy. No data shows any evidence for this.

The total time spread of the IMB/Kamioka events (see Figure 2) shows that ν-emission (or at least detection) lasted for ~ 10 sec. The duration of neutrino emission varies in different collapse models due to the equation of state, the total mass of the collapsing core (is it slightly greater or less than $1.4 M_\odot$?) and the dynamics (prompt vs. accretion). Longer timescales favor soft equations of state and higher core masses ($1.4 - 1.6$ vs. $1.2 - 1.3 M_\odot$) and thus favor accretion versus prompt mechanisms. However, until we have a collapse in our Galaxy with a more detailed time evolution of the ν-signal it will be hard to make detailed statements on the collapse mechanism.

Independent of detailed collapse models, we can use the detection of neutrinos from SN 1987A in the Kamioka and IMB detectors to constrain neutrino properties.

Neutrino Lifetime and the Equivalence Principal

Obviously, if $\bar{\nu}_e$'s made it over 50 Kpc, they must have a lifetime τ such that

$$\gamma\tau \gtrsim 1.6 \times 10^5 \mathrm{yr}$$

where γ is the relativistic factor ($\gamma = E_\nu/m_\nu$). Of course, to have decay requires $m_\nu > 0$. Since γ for ν's from the sun is $\sim 1/10$ of, γ's from supernovae (assuming $m_{\nu_e} = m_{\bar{\nu}_e}$) this means that neutrino decay is not a solution to the solar neutrino problem unless one combines decay with special mixing assumptions[39]. Further restrictions can be made on photo decays ($\nu \to x + \gamma$) by the non-coincidence of γ-rays with the ν's arguing that no type of neutrino undergoes such a process within the light travel time [40]. One can also use the lack of ionization in the region surrounding the Supernova to constrain[41] $\nu_e \to e^+e^- + x$

Recently Tremaine and Krauss (1988)[42] have extended the arguments to show that the equivalence principal itself is tested to high accuracy by the trivial fact that the ν's made it from the LMC to earth within a few hours of the photons from the light curve.

Neutrino Mass

Since the neutrino bursts were relatively narrow in timespread, despite the energies being spread out over a range of about a factor of two, it is obvious that there cannot be too significant of a neutrino rest mass. While the relationship between mass, timespread and energy is derived in freshman physics the world over, the key here is to decide the significance of the time and energy spread, and to estimate what the intrinsic spread was in the neutrino burst in the absence of finite masses. It is these assumptions that have yielded more neutrino mass preprints than neutrino events observed. (Thus, we will not bother to reference them.)

Before discussing what we can say in a "model-independent" manner, it is important to emphasize that all we get model-independently is an upper limit on the mass, since it is certainly possible that the timespread is just due to intrinsic emission time, and not any mass effects. Thus, all papers claiming finite masses rather than upper limits are intrinsically model-dependent. In addition, since most, if not all, of the counts are $\bar{\nu}_e$'s, it is only reasonable to measure neutrino-mass limits for $m_{\bar{\nu}_e} = m_{\nu_e}$, not for any other neutrino species unless assumptions about mixing are made. (Of course anything else, like a fine-tuned photino, that interacts in H_2O with a rate similar to $\bar{\nu}_e$, and is produced in supernovae, would also be limited.)

Let us now plug some values into the standard relation for the mass implied by two particles of energy, E_1 and E_2, emitted at the same time, but arriving 50 Kpc away with a separation Δt.

$$m \lesssim 20\text{eV}\left(\frac{E_1}{10\text{MeV}}\right)\left[\frac{(\Delta t/10\text{sec})}{(r/50\text{Kpc})}\frac{(E_2/E_1)^2}{(E_2/E_1)^2-1}\right]^{1/2}$$

Model-independently, the simplist thing to do is to assume that the entire 13 sec spread of Kamioka was due to this effect. (IMB, with its higher energies, isn't able to constrain things as well.) Schramm[8] and Kolb[40] et al. argue that with these assumptions alone it is really difficult to get limits much better than $30eV$. Once we admit that the supernova limit is greater than the Zurich experimental limit[43] of $m_{\nu_e} < 20$ eV, the whole game becomes irrelevant, except for the curiousity that by having the supernova take place in LMC, the values come out very close to terrestrial laboratory measurements.

Alternative games of assuming two or more neutrino types of different mass run into the problem of low cross section for detection of all but $\bar{\nu}_e$. In addition, if the three late Kamioka events were a different neutrino with $m \sim 20$ eV, compared to the earlier burst with $m_{\bar{\nu}_e} \ll 20$ eV, one also has trouble understanding why these late events don't show any strong directional character, since they would then be electron-scattering events for either a $\nu_\mu + \bar{\nu}_\mu$ or $\nu_\tau + \bar{\nu}_\tau$. While it would be wonderful to have $m_{\nu_\tau} \approx 20$ eV, to give us the hot dark matter of the universe, this supernova cannot be used to prove it (or disprove it).

If specific models are assumed, slightly tighter limits can be obtained. For example, using maximum liklihood. Bahcall and Spergel and Burrows [49] find $m_{\nu_e} \lesssim 16eV$ if all 19 events are used and the relative timing of Kamioka and IMB is optimized and a recent study by Loredo and Lamb [45] finds in $_{\nu_e} \lesssim 23eV$ taking background into account and Wilson and Piran [46] find a limit of $25eV$. Stronger claims seem to be fading as more careful analyses are carried out.

Number of Neutrino Flavors, Axions and Majorons

A limit to the number of neutrino flavors N_ν (with $m_\nu \lesssim 10$ MeV), , can be derived[8,47] from observation of the supernova-produced $\bar{\nu}_e$'s. The argument is based on the fact that in an equipartition of emitted neutrino luminosities among all flavors, the more flavors, the smaller the yield per flavor. Since $\bar{\nu}_e$ is only one flavor, this means that a detection of $\bar{\nu}_e$'s tells you immediately that the dilution by flavor could not have reduced the luminosity of $\bar{\nu}_e$'s below detectability. The limit derived [8] is

$$N_\gamma \lesssim 7$$

This number is not as restrictive as cosmological bounds but is comparable to current accelerator limits[48].

The same argument can be used to limit any other sort of particle that might be emitted by the supernova and dilute the $\bar{\nu}_e$ energy share. Using the fact that axions can escape from the higher T central core even though neutrinos cannot, we [49]) can further restrict axion coupling $f_a \gtrsim 3 10^{10} GeV$ which is better than current red giant limits[50] and closely approaches the cosmological[51] upper bound of $f_a \lesssim< 4 \times 10^{12}$ GeV thus saying that the only allowed axion is cosmologically interest. Similarly, Fuller et. al.[52] have shown that this supernova tightly constrains majorons with Frieman[53] arguing that it may eliminate them altogether.

Neutrino Mixing

If neutrino mixing occurs between emission and detection, it can obviously alter things. If the mixing is simple vacuum oscillations and the mixing length is short compared to 50 Kpc, then the chief effect will be an increase in the average ν_e, and to a lesser extent $\bar{\nu}_e$, energy, due to the oscillations with the higher energy ν_μ's and ν_τ's. Since we only reliably detect $\bar{\nu}_e$'s, this energy enhancement would be difficult to resolve. While some supernova models may need such enhancements to understand the IMB counts, others such as Mayle et al. do not; thus, no definite statements on mixing can occur. (The possibility of the electron scattering events having high energy is also still in the noise.)

Let us now address the matter mixing such as Mikheyev and Smirnov, and Wolfenstein[33] (MSW) have proposed. Walker and Schramm[34] have applied this to stellar collapse scenarios. If this is indeed the solution to the solar neutrino problem, then only $\nu_e \leftrightarrow \nu_\mu(\nu_\tau)$ mixing is possible, not $\bar{\nu}_e \rightarrow \bar{\nu}_\mu(\bar{\nu}_\tau)$. Thus, the solar neutrino solution would not enhance $\bar{\nu}_e$ fluxes. It would deplete the initial neutronization burst. Since ν_μ cross sections are down by $\sim 1/6$, the possibility of seeing a neutronization scattering is significantly reduced. Thus, if the possible scatterings are real, standard adiabatic MSW is not the solution to the solar neutrino problem. However, proving that the first one or two events in an eleven event distribution are really scattering rather than isotropic background is fraught with statistical difficulties.

If we drop the solar neutrino solution and go to general MSW mixing, then we can mix $\bar{\nu}_\mu(\bar{\nu}_\tau)$ into $\bar{\nu}_e$, which might enhance the energy slightly, but would otherwise do little. No effect would occur for the electron scattering ν_e's. As in the case of vacuum oscillations, no definitive statement can be made.

Neutrino Charge and Magnetic Moment

Barbelini and Cocconi [54] have shown that any neutrino electric charge would cause a spreading of the neutrino burst. They show that the observations limit the absolute value of any such charge to $\lesssim 10^{-7} \mid e \mid$. Lattimer and Cooperstein and Mohapatre et al. [55] argue that if the neutrino had a magnetic moment $\gtrsim 10^{11}$ to $10^{-13} \mu_B$ it would yield unobserved effects such as more rapid proto-neutron star cooling or the possible existence of large numbers of $50 MeV$ nuetrino events. Their limits may be quite relevant to the solar neutrino problem since they exclude the simplist version of Okun's solution [56] of neutrinos flipping in the magnetic field of the sun. However, back scattering by a heavy a heavy right handed Z^0 could duck these constraints [56].

COLLAPSE RATES

Over the last 1000 years there have been only 5 visual supernovae in the Milky Way Galaxy, implying at first glance a rate of 1/200 years. However if we look at galaxies like our own, that is standard evolved spiral Sb and Sc galaxies we find rates in other galaxies[57] of 1/30 to 1/60 years. (with an additional uncertainty due to the Hubble constant.) Obviously our galaxy's low rate is probably the result of most of our galaxy being obscured from view by dust in the disk. In fact the 5 historical supernovae were all in our sector of the galaxy implying a minimal enhancement of a factor of 5 to a value of 1/50 yr to include the entire disk volume. Now that we can detect collapses by neutrinos alone, we don't need to worry about the obscuration of our disk, so the rates in other galaxies where we sample their entire disk might be more relevant. However with neutrino detectors we only see Type II supernovae thus at first glance the rates quoted may be on the high side since these include all types ("neutrinoless" Type IA's account for $\sim$1/4 of the supernovae in such direct counting of supernovae in such galaxies). Such direct counting of supernovae is fraught with uncertainties. For example SN 1987A would probably not have been included since it was so underluminous, and Type I's may get "overcounted" due to there high luminosity. If the fraction of blue star collapsing is only minimally related to metalicity then 1987A-like events could enhance the rates for the high metalicity disk populations. Of course, if the blue progenitors only occur in metal poor populations, SN 1987A would not alter the statistics for the Milky Way. Similarly, other underluminous collapses, such as Cassiopeia A would not be detected.

An alternative approach is to do statistics on stellar types. Bahcall and Piran[58] argue that the rate of formation of all stars $\gtrsim 8M_\odot$ is $\sim$ 1/8 yr from using a Salpeter mass function and a constant star formation rate. All such stars presumably undergo collapse. Of course the Salpeter mass function is probably most uncertain for these more massive stars, and the assumption of a constant rate can be argued. Pulsar formation rates and supernova remnant statistics do not help much since they have so many possible systematic errors.

We do know that from the 2% heavy element content of our galaxy and the assumption that $\gtrsim 1M_\odot$ of heavies is ejected per collapse that the $10^{11}M_\odot$ disk requires 2×10^9 ejections over the 15×10^9yr history of the galaxy. Thus our average Type II rate is $\sim$ 1/7yr. Since many galactic evolution models seem to have roughly constant nucleosynthesis rates[59] this limit is also not a bad estimate and is in good agreement with the Salpeter rate estimate. The fact that it is higher than the rates observed in similar galaxies may argue that many supernovae are indeed underluminous and were missed in the surveys. (Of course, the average could also come from a high rate early on and a low present rate. Such a model also fits some galactic evolution models.) Recent nucleochronology arguments [60] support a constant rate to within a fractor of $\sim$ 2 and Arnett et al. [15] argue that Type II's dominate over Type I's. All in all a rate in our galaxy of 1/10 to 1/20 years seems quite reasonable.

SUMMARY

This supenova in the LMC has proven to be one of the most exciting astrophysical events of the century. It has already taught us much about supernova physics and more should be forthcoming as heavy element spectra and the remnant come into view. We now know that blue as well as red stars collapse, that SN luminocities for blue progenitors are indeed lower than for red ones and velocities are higher.

The neutrinos from SN 1987A have proven that our understanding of the basic energetics of gravitational collapse was quite reasonable once we included neutral current effects. Given that we now know what a neutrino burst looks like, we should have confidence that if a collapse occurs anywhere in our galaxy, regardless of the visibility of the SN, we should observe it. We expect a rate of a collapse every 10 years or so and the neutrino flux will be up by $1/r^2$.

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