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Prompt Subsidence of a Protoneutron Star into a Black Hole

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Prompt Subsidence of a Protoneutron Star into a Black Hole†

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Abstract

A newly formed protoneutron star, prior to the loss of neutrinos, will consist of a charge-neutral mixture of neutrons, protons, electrons, muons and trapped neutrinos in the lowest energy state available under these circumstances. However, in a few seconds, the neutrinos will escape, enabling the interior of the star to find a lower energy. We study two possibilities: (1) A significant number of baryons will, through the weak interaction, convert to hyperons. (2) Hadronic matter may convert to quark matter in the interior where the pressure is high. In either case the resulting softer equation of state will not support as large a range of stars either in mass or baryon number. Therefore, beyond the *baryon number* of *either* of the above *equilibrated* sequences there is a significant range of protoneutron stars that possess no hydrostatically *stable* configurations after neutrino loss. They will subside into a black hole on the time-scale of neutrino loss, about ten seconds, and after the processed material of the presupernova star has been ejected. The uncertainty as to which of the two possibilities for the ground state actually holds is due mainly to the imperfect description available for the quark matter phase of cold charge-neutral baryonic matter. We discuss these mechanisms in connection with the apparent absence of a neutron star in SN1987A and the possible deficit of neutron star - supernova associations.

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Prompt Subsidence of a Protoneutron Star into a Black Hole

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1 Introduction

Evolved stars with masses $> 8M_{\odot}$ are believed to collapse either directly into a black hole, or to a metastable protoneutron star, with the rest of the star ejected in a supernova. The protoneutron star is hot and lepton rich. The neutrinos produced during the collapse of the core of the progenitor star by the inverse beta decay of protons are trapped for a duration of about ten seconds by the hot dense material of the compact star. It will otherwise contain a charge neutral admixture of neutrons, protons, electrons, and muons in a close to equilibrium proportion. If the baryon number is not too great, the protoneutron star will deleptonize, cool, and evolve quickly to a stable neutron star. Alternatively, we discuss two ways in which a protoneutron star, formed with a baryon number (or mass) above a critical value, will subside into a black hole following escape of the initially trapped neutrinos and long after the processed stellar material of the progenitor star has been ejected in a supernova explosion. The observation of the neutrino signal from SN1987A, but the absence of a pulsed signal or evidence of a neutron star in the light curve of the supernova remnant, suggest that in this case a supercritical protoneutron star *may* have been formed which collapsed to form a black hole subsequent to the neutrino emission. In any case, the processes described here presumably are responsible for the collapse of some protoneutron stars after the supernova explosion and neutrino signal, and may be relevant to any disparity in neutron star birthrates and type II supernova rates in the galaxy.

In a number of papers it has been shown that the ground state of dense charge-neutral *hadronic* matter should contain a significant fraction of hyperons, and that the resulting softening of the equation of state compared to that of a charge neutral mixture of neutrons, protons and leptons reduces the limiting mass of neutron stars by an amount of the order of one half a solar mass (Glendenning 1985; Glendenning 1987; Glendenning & Moszkowski 1991; Kapusta & Olive 1990). The possible significance of this for supernova has been previously noted (Glendenning 1987). However, only recently was it realized how the strength of hyperon couplings to the meson fields, relative to the nucleon couplings could be empirically constrained (Glendenning & Moszkowski 1991). This involved simultaneous constraints of (1) neutron star masses, (2) hypernuclei and (3) the binding of the Lambda hyperon in nuclear matter. It is thus now possible to discuss with some confidence the quantitative role

of hyperons in neutron stars. Some nucleons, at the high densities of neutron star matter, will convert to hyperons because the high Fermi energies of neutrons and protons favor the dispersal of baryon number among a greater number of species since this is energetically more favorable. Some of the decay products of the conversion, – neutrinos and gammas, – will diffuse out of the star, lowering its energy and making the conversion irreversible (Glendenning 1985). However, this final ground state is not accessible to a newly formed neutron star until after the trapped neutrinos have escaped. This has been estimated to take a few seconds (Burrows & Lattimer 1986). Prior to this, it is possible that a more massive protoneutron star has been formed than ultimately can be supported by the softer equation of state of the fully equilibrated matter containing hyperons. Protoneutron stars formed in a certain mass and baryon number range will therefore suffer the almost immediate collapse to a black hole.

An alternative, but similar mechanism to the one described, concerns the possibility that upon deleptonization, the hadronic matter converts to an equilibrium quark matter phase containing u,d and s quarks. This also happens only because it softens the equation of state. The greatest uncertainty in assessing which mechanism actually will operate arises because of the absence of a good description of the conversion of charge-neutral baryonic matter to the quark phase. We employ the so-called MIT bag model with its description of free quarks and a shift in vacuum energy density by a constant B.

We discuss in further detail the early demise of protoneutron stars by both of these mechanisms and the mass and baryon number range for which such is likely to occur. In both cases we find a substantial window of $> 0.5M_\odot$ into which a protoneutron star mass may fall and be temporarily stabilized prior to deleptonization and ultimate subsidence into a black hole. Brown and Bethe (1994) have previously suggested that many stars in the mass range 18-30 $M_\odot$ produce black holes instead of neutron stars. They proposed kaon condensation as a possible destabilizing influence on protoneutron stars in a window of about $0.2M_\odot$ (Thorsson, Prakash & Lattimer 1994), that is augmented by about $0.04 - 0.1M_\odot$ by thermal and lepton pressure in the protoneutron star prior to deleptonization (Bombaci, Prakash, Prakash, Ellis, Lattimer & Brown 1994). In our estimate, we do not count the small thermal and lepton contribution affects, so that they may be added to our window in estimating its full width.

2 Hyperonization

Hyperonization refers to the conversion of nucleons to hyperons so as to relieve the high pressure of the nucleons and achieve a lower energy of dense neutron star matter (charge neutral and stable). In the absence of trapped neutrinos in a protoneutron star, the conversion would proceed on the weak interaction time-scale, since this governs the decay of associated kaons. The diffusion out of the star of the kaon decay products, – neutrinos and gammas, – makes the conversion irreversible (Glendenning 1985). The fact that the masses of the hyperonized sequence of stars lie *lower* than

the sequence for which this possibility is artificially foreclosed, informs us that the above outlined scenario can operate, in principle. However we wish to show that fine tuning of the mass or baryon number of the protoneutron star is not necessary, – that there is a significant range for which subsidence would occur. So it is a robust mechanism.

In earlier work involving the compatibility of neutron star masses, hypernuclei and the binding of the Lambda in nuclear matter, the couplings of hyperons to the meson fields compared to nucleon couplings were constrained, but only within a range (Glendenning & Moszkowski 1991). (The range is centered at $x_\sigma \approx 0.6$ in the notation of the cited paper, and is the value used here.) Moreover, two other relevant properties of nuclear matter can be assigned only reasonable ranges, the compression modulus for symmetric matter, $K = 240 - 300$ MeV and the nucleon (Dirac) effective mass at saturation, $m^\star/m = 0.7 - 0.78$ (related to the Landau effective mass by $m^\star_{\rm Landau} = (m^{\star 2} + k_0^2)^{1/2}$ where k_0 is the Fermi momentum at saturation density of nuclear matter). It is this mass that is most closely related to observables (Jaminon & Mahaux 1989). The lower value of K in the above range is supported by a recent analysis of Myers & Swiatecki (1994) involving a large number of nuclear data and a relationship between the compression of finite nuclei and infinite matter. The upper limit is suggested by the breathing mode of chains of Sn and Sm nuclei (Sharma, Borghols, Brandenberg, Crona, van der Woude & Harakeh 1988). For any choice in these ranges, the couplings can be determined for symmetric matter, and then with the same couplings, the theory can be solved for neutron star matter. However, even if an impeccable theory of dense neutron star matter were available, and it is not, there would remain inherent uncertainties in the equation of state due to the above experimental ones. Therefore, we have to show that within the uncertainties there is an extensive range of baryon number for which a protoneutron star would find no stable configuration after deleptonization and hyperonization. Using the theory discussed in detail previously (Glendenning 1985; Glendenning & Moszkowski 1991), we compute two cases that span the uncertainties. Sequences of stellar masses as functions of baryon number for these extreme cases are shown in Fig. 1. The sequences for n,p,e matter, representative of protoneutron stars for which hyperonization is delayed by the presence of trapped neutrinos, are shown by dotted lines. The solid dots mark the mass limit for the sequences. The segments that turn back in baryon number correspond to configurations that lie beyond the mass limit in a plot of mass vs. central density. For given baryon number, A, the mass is larger on these segments and so the star is unstable and of no interest. The solid lines represent stars composed of hyperonized neutron star matter, the final ground state. The non-overlapping segment of the dotted lines, H-P, (which on the scale shown, are otherwise coincident with the long solid ones) represent protoneutron stars whose baryon number exceeds that of any stable configuration of hyperonized stars. Therefore, when hyperonization commences during diffusion of neutrinos out of the protoneutron star, these initially stable configurations will begin to collapse. We see that in both cases the mass range of protoneutron stars that would suffer such a fate is about $1/2\ M_\odot$. Since this is the case for such a wide variation of the corresponding nuclear properties within their range of uncertainty, it surely is representative of the exact values, were they known.

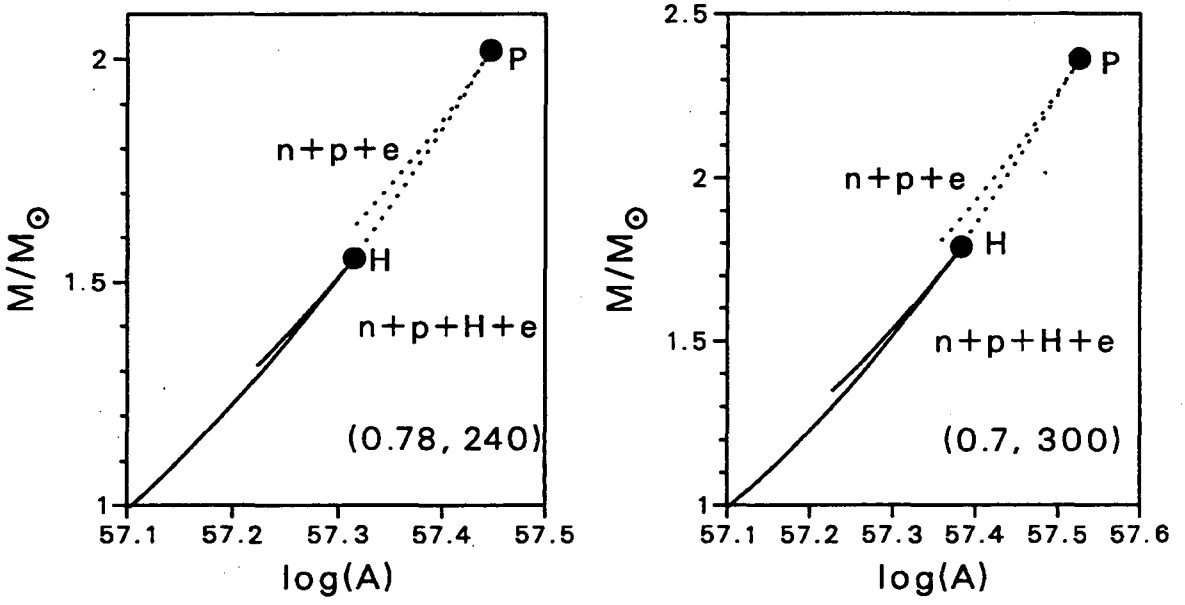


Figure 1: For two choices of saturation values for symmetric matter of the nucleon effective mass, m^*/m and compression modulus, K/MeV, (shown in parenthesis) masses of protoneutron stars (n+p+e) and hyperonized neutron stars (n+p+e+H) are shown as a function of baryon number, A. The region between the two mass limits (marked by bullets) are the range of protoneutron stars having A for which there is no stable configuration.

However, theory and the observables by which it can be constrained are not sufficiently well known as to predict a limiting mass with the same degree of certainty. We can only say, based on the span of the parameters used, that it likely lies between 1.5 and 1.8 $M_\odot$.

One can say something qualitative about the lifetime of the protoneutron stars that have baryon number falling above the point 'H'. As explained, protoneutron stars with baryon numbers that place them between the points 'H' and 'P' have no stable configuration after *complete* deleptonization. Those that lie closer to 'H' will be stabilized for a longer time, since intermediate stages of hyperonization will still support them. In other words, there is a continuum of sequences of partially hyperonized stars whose termination points lie between 'H' and 'P', with complete hyperonization corresponding to 'H' and none to 'P'. Therefore a star at 'P' has no temporarily stable partially hyperonized configuration, whereas one closer to 'H' has many that can still support its baryon number against collapse for some short time before total deleptonization and hyperonization to the absolute ground state. This takes of the order of ten seconds and is the lifetime expected for a protoneutron star whose baryon number (or mass) just exceeds the limit at 'H', while a shorter life is expected for those nearer 'P'. As already remarked, those lying below 'H' are absolutely stable upon hyperonization.

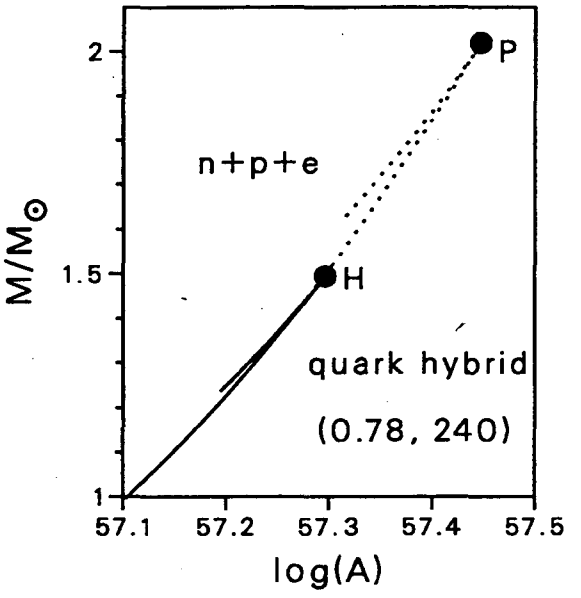
We say a few words about temperature and the role of leptons in the protoneutron star before escape of the electron neutrinos, since the above calculations were carried out for zero temperature. Thermal pressure is not very important even in protoneutron stars, where the temperature may be as high as 10-20 MeV (Burrows & Lattimer 1986). In any case thermal and lepton pressure can *only* raise the range of temporarily stable *protoneutron* stars by an estimated $0.04 - 0.1 M_{\odot}$ (Bombaci, Prakash, Prakash, Ellis, Lattimer & Brown 1994). On the other hand, the temperature drops in a few seconds to the order of several MeV and so is negligible on the scale of baryon masses and their differences and so can have only negligible affect on the mass limit of *hyperonized* stars, and none whatsoever within minutes. These affects, if taken into account, therefore, can only increase the limiting mass of protoneutron stars and thereby extend the window for prompt subsidence into black holes.

3 Quark Matter

As the pressure within a neutron star increases toward its center, a critical value may be reached at which quarks that are normally confined in hadrons are deconfined over the interior región of the star. Such a star has a neutron star mantle, interior to which is a mixed phase of hadronic and quark matter and possibly a central core of pure quark matter. We call it a hybrid star. We assume, as is frequently done, that the phase transition from cold charge-neutral hadronic matter to quark matter is of first order. For the most part, lattice gauge calculations concern *hot baryonless* matter (zero baryon chemical potential), in the static quark approximation, and shed little light on the order of the phase transition for *cold baryonic* matter.

It has been realized recently that the pioneering work of Baym and Chin (1976) and of Chapline and Nauenberg (1976) on this phase transition in neutron stars, employed idealizations that had foreclosed the possibility of a mixed or co-existence phase of hadronic and quark matter in the gravitational field of the star (Glendenning 1991; 1992). This foreclosure was related to the fact that neutron star matter was treated as a simple substance, having only one conserved charge. Instead, it is a complex substance having two, in consequence of which the pressure is a continuously changing function of the proportion of the two phases, and not a constant, as in the earlier treatments. As found by several authors, the mixed phase is expected to occur at roughly 1/3 of the density of the pure quark phase found in the earlier works, under similar model assumptions, or 2 to 3 times nuclear density (Glendenning 1991; Heiselberg, Pethick, & Staubo 1993; Pandharipande & Staubo 1993). Using the method described in (Glendenning 1992), but with the Lagrangian in (Glendenning 1985), we compute the sequence of stars for which, under the conditions of Gibbs phase equilibrium, the transition from hadronic matter to mixed phase to pure quark matter takes place at increasing depth within those stars (the higher mass ones), for which the criteria are satisfied. The coupling constants in neutron star matter are fixed by insuring that they yield $m^*/m = 0.78$ and $K = 240$ MeV for symmetric matter, and hyperon couplings are fixed as described in (Glendenning & Moszkowski

Figure 2: Similar to Fig. 1 but in which hadronic matter undergoes a transition to a mixed phase and at greater depth in the star a pure quark phase comprising the sequence labeled "hybrid". The bag constant is $B^{1/4} = 185$ MeV and $\alpha_s = 0$. For the hadronic case the corresponding symmetric matter has $m^*/m = 0.78$, $K = 240$ MeV.

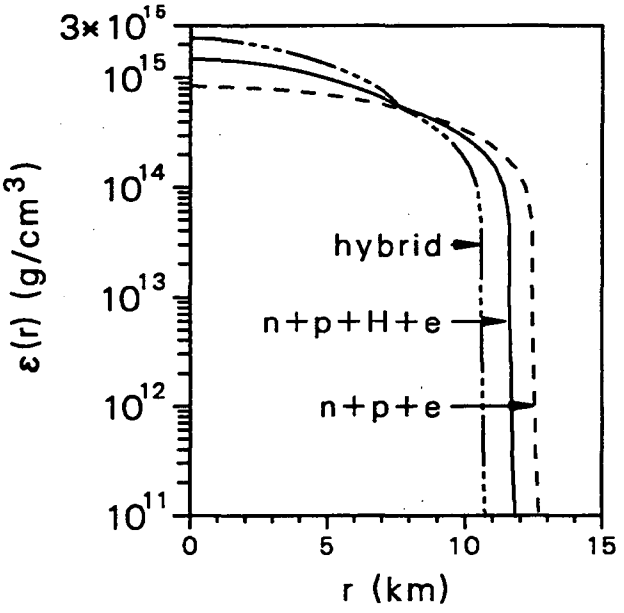


1991) with $x_\sigma = 0.6$ so as to ensure compatibility between neutron star masses, hypernuclear levels and the Lambda binding energy in nuclear matter. For the bag constant we choose a value $B^{1/4} = 185$ MeV, that places the nucleon mass well below the energy per baryon in equilibrium strange quark matter (Farhi & Jaffe 1984). It is interesting that the hadronic matter in the *mixed phase* is partially hyperonized, as in Glendenning (1992). We compare in Fig. 2 the stable hybrid star sequence (solid line) with the sequence that is temporarily stabilized by the trapped neutrinos, similar to Fig. 1. Again there is an extensive range of baryon number above 'H' for which the temporarily stabilized stars (n+p+e) have no stable configuration when the matter undergoes the transition to the lower energy state. Hence the collapse of protoneutron stars with masses above about $1.5M_\odot$. As in the case of hyperonized stars, this number is somewhat uncertain from the point of view of uncertainties in the nuclear parameters from which the coupling constants in the hadronic phase are determined, as well as uncertainties attached to the use of the bag model representation of quark matter.

4 Density Profiles

It is of some interest to see for a typical example, the change in the stellar configuration for those protoneutron stars that *do* have a stable final state of hyperonized matter or of quark matter, ie those that have baryon number that falls in the range of the solid line below 'H' in Figs. 1 and 2. The three configurations, – the protoneutron star stage, and the two possible final ground states, hyperonized stars or hybrid stars – are compared in Fig. 3 for the same baryon number. (The temperature is here taken as zero. The small temperature of the protoneutron star would be mainly reflected

Figure 3: Mass-energy profile of protoneutron star (dashed) and hyperonized neutron star and hybrid star having the same A and mass $1.49M_\odot$ for the case $m^*/m = 0.78$, $K = 240$ MeV. Note the more compact configuration of the ground state whether it be a hyperonized neutron star or a hybrid.



in the lower density tail of the star, giving it a larger radius.) The comparison is made for stars of fixed $A = 1.974 \times 10^{57}$, and mass $1.49M_\odot$ (slightly larger for the (n,p,e) configuration). It can be seen that the protoneutron star composed of the (n,p,e) charge neutral matter, subsides into a denser and more compact configuration as the matter in the interior hyperonizes or converts to quark matter. There will be a modest spin-up in angular velocity as this happens. The moments of inertia of protoneutron star, hyperonized and hybrid star are 11.95, 10.37 and 8.964 in units $M_\odot - \mathrm{km}^2$ so that the hyperonized and quark stars would spin-up by factors of 1.15 and 1.33 respectively, over the angular velocity of the protoneutron star.

5 Discussion

It is believed that the core of a massive evolved star collapses either directly into a black hole or forms a hot lepton rich protoneutron star which deleptonizes to form a stable neutron star. A third possibility is that the protoneutron star, in the second instance, has a supercritical baryon number that is larger than that of stable evolved neutron stars and so subsides promptly into a black hole after deleptonization. The latter two eventualities would both eject heavy elements into the universe in a supernova event signaled by a neutrino pulse of a few seconds duration. They differ in the final fate of the core and possibly in the duration of the neutrino signal. The width of the window for prompt subsidence, and the frequency with which it is populated, is relevant to the outcome of particular events, like SN1987A, as well as to understanding the statistics on supernova-pulsar associations.

We considered two mechanisms that could destabilize a protoneutron star by softening the equation of state of the stellar material upon deleptonization. They are

hyperonization of some of the nucleons or conversion of hadronic to quark matter in the stellar interior. Although the relevant nuclear parameters by which the equation of state of neutron star matter can be constrained, are not known well enough to yield a confident prediction of the maximum neutron star mass, within their uncertainties, the window of temporary stability is a substantial amount, – about half a solar mass.

Subsidence to a black hole or to a stable hyperonized or hybrid star is triggered by deleptonization and therefore takes place *during* that era, which has a time-scale of the order of ten seconds. The process is regulated by neutrino loss since the other two time-scales, – hydrodynamic, $\tau_{\rm hydro} \approx 10^{-3}$ sec, and weak interaction, $\tau_{\rm weak} \approx 10^{-10}$ sec, which governs transformation of nucleons to hyperons, – are small compared to it. Unlike direct collapse, the neutrinos produced in the inverse beta decay during collapse of the presupernova core will not suffer extinction by the subsidence of the protoneutron star into a black hole *if* the baryon number is only moderately supercritical. However, if it is toward the upper end of the window for only temporary stability, the signal will be shortened and its tail infinitely red-shifted as the star sinks toward the horizon. Whether the protoneutron star is subcritical and collapses to a stable hyperonized or hybrid star, or is supercritical and collapses to a black hole, neutrinos produced in any case will form the tail of the neutrino signal.

Neutron stars near the upper mass or baryon limit of stability, may still suffer collapse to a black hole on a much longer time-scale of hours to months or years if they are hovering at the limit of evolved neutron stars and there is sufficient mass fallback, expected to be $\sim 0.1 M_{\odot}$. The physics is quite complicated (Colgate 1971, Chevelier 1989, Houck and Chevelier 1991). Because of the longer time-scale we do not include this as a lowering of the window for prompt subsidence. Moreover, the window for accretion induced collapse is small compared to the two mechanisms that we describe.

In the cases that a neutron star is the final ground state, the contracting protoneutron star (Fig. 3) may execute damped oscillations about the final configuration, producing a surplus of hyperons (or quark matter) compared to the final equilibrium state of the star, and then a deficit, as the density oscillates. However, the diffusion time-scale for neutrinos and gammas produced as decay products of associated kaons is very long compared to the hydrodynamic time-scale, so no signal of the density oscillations would be observable in these radiations. However if the oscillations were not purely radial pulsations they would produce gravitational radiation since all stars rotate. Indeed, the density dependance of the shear viscosity in a rotating star would possibly cause deviations from purely radial pulsations. However, we do not pursue this possibility here.

The neutrino signal from SN1987A informs us that a protoneutron star was formed, at least temporarily. No pulsed radiation has been observed. Continuing observation of the light curve of the remnant produces somewhat conflicting conclusions as to the possible contribution of a neutron star. Several authors find pulsar activity plausible (Gunji, Kamae, Miyazaki, Sekimot, Takahashi, Tamura, Tanaka, Yamaoka, Yamagami, Naomachi, Murakami, Braga & Neri 1992; Kumagai, Nomoto, Shigeyama, Hashimoto & Itoh 1993). However, the interpretation of the light curve does involve considerable modeling of the evolution of the remnant. Woosley, Pinto

& Hartmann (1989) calculate expectations for the light curve based on two possibilities for emission from a neutron star – that it is powered by accretion of fallback material similar to the X-ray pulsator, Her X-1, or a somewhat poorly defined assumption that a Crab-like pulsar resides inside the remnant. Sources of these two types with various multiples of their intensity were considered. Likewise, Arnett & Fu (1989) computed the light curve into the future under several scenarios for a central neutron star or without one. The light curve is now accounted for by the radioactive decay of ^{44}Ti (decay constant 78 yrs) with no sign of an additional source. A strongly magnetized star should have made its presence known either in the light curve or in a surrounding synchrotron nebula. It has been recently argued that a weakly magnetized accreting neutron star should contribute to the light curve at the Eddington luminosity, well above the luminosity observed, while a black hole should contribute at a level substantially below that presently observed and attributed to the decay of ^{44}Ti (Brown & Weingartner 1994). These conclusions also are supported by earlier detailed calculations of Chevelier (1989) and Houck and Chevelier (1991). So a black hole is compatible with the present luminosity. This conclusion is possibly further buttressed by Maeder (1992) who finds that a progenitor with mass above $20 - 25 M_{\odot}$ is likely to collapse directly to a black hole. The progenitor of SN1987A, – Sk-69°202, – was at the lower end of this threshold, and so possibly hovered on the edge of direct collapse to a black hole. Instead, the long neutrino signal rather convincingly indicates that a protoneutron star was formed (Burrows 1988), at least, temporarily. The continued absence of evidence of a neutron star (Chevelier 1992) lends some weight to the hypothesis that the protoneutron star collapsed after emission of the trapped neutrinos. Whether or not continuing observation of the remnant and search for pulsed radiation from the site of SN1987A reveals a pulsar, which in view of the arguments of Brown and Weingartner (1984) seems unlikely, one of the mechanisms discussed here may be responsible for turning high mass protoneutron stars into black holes of mass 1.5 - 2.4 $M_{\odot}$ *after* the processed stellar material has been ejected in a supernova and the neutrino signal of the event has been emitted. In this connection it may be noted that there is some indication that about one half of the supernovae in our galaxy leave no promptly observable star (Helfand & Becker 1984). This conclusion may have to be tempered with the recent evidence that many neutron star - supernova associations may be manifested in a previously unexplored signal, – the recent interaction of a high velocity pulsar, up to 500 km/s, with the remnant, which would produce a radio visible bow shock around the pulsar, with attendant characteristics of the radio emission, as it plows into the remnant (Frail, Goss & Whiteoak 1994).

Our calculations suggest that the mass threshold of protoneutron stars that will subsequently subside into black holes begins between 1.5 - 1.8 $M_{\odot}$, depending on the choice of nuclear parameters in the uncertain range with which they are known *if* the central (and more plausible) value of the ratio of hyperon to nucleon coupling is chosen (Glendenning & Moszkowski 1991). Otherwise the range would be 1.44 - 2 $M_{\odot}$, the lower value being the very precise measurement of the more massive star in the Hulse-Taylor binary (Taylor & Weisberg 1989). If however, the recent analysis of nuclear data which yields $K = 234$ MeV (Myers & Swiatecki 1994), is

given greater weight, and we think it should, then the range would revert to the one noted at the beginning of the paragraph. The mass threshold for prompt subsidence is of course also the maximum possible mass of evolved *stable* neutron stars, – stars that have achieved a beta-stable admixture of nucleons and hyperons, or formed a quark core. Although the above threshold has the quoted uncertainty because of the imprecision with which two relevant nuclear constraints are known, the window in which protoneutron stars will be temporarily stabilized extends upward from the threshold by a robust amount of $\sim 1/2M_{\odot}$ in any case. This could be extended by an additional $\sim 1/10M_{\odot}$ due to thermal and lepton pressure in the hot lepton rich protoneutron star. However, as discussed, protoneutron stars produced in the lower part of the window will survive the longest, and presumeably be able to emit a $\sim$ 12s long neutrino signal as observed in SN1987A. Certainly the lower part of the window for collapse, and perhaps all of it, is compatible with estimates of the masses involved in core collapse (Woosley & Weaver 1986) and ejecta fallback (Michel 1988).

The imperfection of theories of dense matter and the imprecision with which nuclear parameters are known that are relevant constraints on the coupling constants does not permit a confident prediction of whether only hyperonization of the neutron star represents its final ground state if its baryon number is below the critical value corresponding to subsidence, or whether a transition to quark matter occurs in the central region of the star. Even in this latter eventuality, some degree of hyperonization will occur in the hadronic regions of the mixed phase. The figures quoted above for the range in which the limiting neutron star mass should lie represent a reduction from those found from most models of neutron stars, and correspond either to hyperonization of neutron star matter (Glendenning 1985) with an improved understanding of the hyperon coupling constants (Glendenning & Moszkowski 1991) or to conversion of hadronic matter to quark matter in the higher pressure regions of the star (Glendenning 1991,1992).

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