Strange Pathways for Black Hole Formation

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Immediately after they are born, neutron stars are characterized by an entropy per baryon of order unity and by the presence of trapped neutrinos. If the only hadrons in the star are nucleons, these effects slightly reduce the maximum mass relative to cold, catalyzed matter. However, if strangeness-bearing hyperons, a kaon condensate, or quarks are also present, these effects result in an increase in the maximum mass of up to $\sim 0.3 M_\odot$ compared to that of a cold, neutrino-free star. This makes a sufficiently massive proto-neutron star metastable, so that after a delay of 10–100 seconds, the PNS collapses into a black hole. Such an event might be straightforward to observe as an abrupt cessation of neutrinos when the instability is triggered.

1. INTRODUCTION

Many fundamental and intrinsic properties of neutrinos play a crucial role in astrophysical phenomena such as core-collapse supernovae. Neutrinos drive supernova dynamics from beginning to end: they become trapped within the star’s core early in the collapse, forming a vast energetic reservoir, and their eventual emission from the proto-neutron star is prodigious enough—containing nearly all the energy ($\sim 10^{53}$ ergs) released in the explosion—to dramatically control subsequent events.

The large neutrino flux from a proto-neutron star (PNS) plays at least two potentially important roles in the supernova environment. First, the supernova explosion itself may depend on neutrino heating to propel a shock stalled by accretion. Second, the neutrino-driven wind off the PNS that develops after shock lift-off may be a suitable site for the synthesis of heavy elements produced by the rapid neutron capture, or $r$-process, whose production site remains obscure. Further progress in these issues will depend upon a thorough understanding of the PNS neutrino emission.

The neutrinos of all flavors ($e, \mu, \tau$) emitted from newly formed neutron stars in supernova explosions are the only direct probe of the mechanism of supernovae and the structure of proto-neutron stars. The handful of neutrino events observed from SN 1987A\textsuperscript{[1,2]} attest to this fact. More intriguingly, the three flavors of neutrino fluxes from a Galactic supernova could be distinguished by the new generation of neutrino detectors. The supernova neutrino signals would furnish an opportunity to probe the properties of neutrinos and dense matter in regions that are inaccessible to terrestrial experiments.

2. EVOLUTION OF PROTO-NEUTRON STARS

A proto-neutron star (PNS) forms in the aftermath of a successful supernova explosion as the stellar remnant becomes gravitationally decoupled from the expanding ejecta. The essential microphysical ingredients that govern the macrophysical evolution of the PNS in the so-called Kelvin-Helmholtz epoch, during which the remnant changes from a hot and lepton-rich PNS to a cold and deleptonized neutron star, are the equation of state (EOS) of dense matter and its associated neutrino opacity. Among the characteristics of matter that widely vary among EOS models are their relative compressibilities (important in determining the theoretical neutron star maximum mass), symmetry energies (important in de-

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terminating the typical stellar radius and in the relative $n, p, e,$ and $\nu_e$ abundances) and specific heats (important in determining the local temperatures). These characteristics play important roles in determining the matter’s composition, in particular the possible presence of strange components (such as hyperons, a kaon condensate, or quark matter) \[3\]. These characteristics also significantly affect calculated neutrino opacities \[4–7\] and diffusion time scales.

The evolution of a PNS proceeds through several distinct stages \[3,8,9\] and with various outcomes. Immediately following core bounce and the passage of a shock through the outer PNS’s mantle, the star contains an unshocked, low entropy core of mass $M_c \approx 0.7 M_\odot$ in which neutrinos are trapped. The core is surrounded by a low density, high entropy ($s = 5 - 10$) mantle that is both accreting matter falling through the shock and rapidly losing energy due to beta decays and neutrino emission. The mantle extends to the shock, which is temporarily stationary at a radius of about 200 km prior to an eventual explosion.

After a few seconds, accretion becomes less important if the supernova is successful and the shock lifts off the stellar envelope. Extensive neutrino losses and deleptonization of the mantle will have led to loss of lepton pressure and collapse of the mantle. If enough accretion occurs, the star’s mass could exceed the maximum mass of the hot, lepton-rich matter and it collapses to form a black hole. In this event, neutrino emission is believed to quickly cease \[10\].

Neutrino diffusion deleptonizes and heats the core on time scales of 10–15 s. The core’s maximum entropy is reached at the end of deleptonization. Strangeness could now appear, in which case the maximum mass will decrease, leading to another possibility of black hole formation \[11\–17\]. If strangeness does not appear, the maximum mass instead increases during deleptonization and the appearance of a black hole would be less likely.

The PNS is now lepton-poor, but it is still hot. While the star has zero net neutrino number, thermally produced neutrino pairs of all flavors are abundant and dominate the emission. The star cools, the average neutrino energy decreases, and the neutrino mean free path increases. After approximately a few to 100 seconds (this time depends on the form in which strangeness appears), the star becomes transparent to neutrinos and finally achieves a cold, catalyzed configuration.

Neutrino observations from a galactic supernova will illuminate these stages. The observables will concern time scales for deleptonization and cooling and the star’s binding energy. Dimensionally, diffusion time scales are proportional to $R^2(c\lambda)^{-1}$, where $R$ is the star’s radius and $\lambda$ is the effective neutrino mean free path. This generic relation illustrates how both the EOS and the composition, which determine both $R$ and $\lambda$, influence evolutionary time scales. Additional EOS dependence enters through the rate at which the lepton number is lost from the star. The total binding energy is a stellar mass indicator.

3. RESULTS OF SIMULATIONS

Detailed calculations of the evolution of PNSs, studying the sensitivity of the results to the initial model, the total mass, the underlying equation of state (EOS) and the possible presence of hyperons and kaons, have been performed \[16,18\]. Pons, et al. \[18\] show that the major effect on the neutrino signal before the onset of any possible metastability is the PNS mass: larger masses give rise to larger luminosities and generally higher average emitted neutrino energies. In addition, it was found that mass windows for hyperonic metastable models could be as large as $0.3 M_\odot$, ranging from baryon masses $M_B = 1.7 M_\odot$ to $2.0 M_\odot$. The lifetimes of these stars decrease with stellar mass and range from a few to longer than 100 s. The detection of neutrinos from SN 1987A over a timescale of 10-15 s is thus consistent with either the formation of a stable PNS or a metastable PNS containing hyperons, as long as its mass was less than about $0.1 M_\odot$ below the maximum mass for cold, catalyzed hyperonic matter. Larger PNS masses would lead to a collapse to a black hole on a timescale shorter than that observed.

A similar situation could be encountered if the EOS allowed the presence of other forms
of “exotic” matter, manifested in the form of a Bose condensate (of pions or kaons) or quarks [11,21]. Recently Pons, et al. [20] have studied the effect of kaon condensation on PNS evolution, by employing an EOS which includes the effects of finite temperature and neutrino trapping [19]. The phase transition from pure nucleonic matter to the kaon condensate phase was described by means of Gibbs’ rules for phase equilibrium, which permit a mixed phase. In the models explored there, the central densities were not large enough to allow a pure condensed phase to exist.

Pons, et al. [20] classify stars of different masses in three main groups: i) stars in which the central density does not exceed the critical value for kaon condensation, ii) stars that can form a mixed phase core at the end of the Kelvin-Helmholtz epoch but remain stable, and, iii) kaon condensed metastable stars that become unstable and collapse to a black hole at the end of the Kelvin-Helmholtz epoch. For stars in which the effects of kaon condensation are small (this could be either because the star’s mass is low enough to permit only a very small region of the mixed phase or because condensation occurs as a weak second order phase transition), the differences of the predicted neutrino signal compared to PNSs composed of pure nucleonic matter are very small.

In Fig. 1, the evolution of stable (1.7 M⊙) and metastable stars are compared. Both the central baryon number densities and kaon fractions YK are displayed. In each case, the time at which kaon condensation occurs is indicated by a diamond. Asterisks mark the times at which the evolution of metastable stars could not be further followed in our simulations, i.e., when a configuration in hydrostatic equilibrium could not be found. At this time, the PNS is unstable to gravitational collapse into a black hole. For the stable star, kaons appear after about 40 s. Thereafter, the star’s central density increases in a short interval, about 5 s, until a new stationary state with a mixed phase is reached. The evolution of the metastable stars is qualitatively different, inasmuch as the central density increases monotonically from the time the condensate appears to the time of gravitational collapse. It is interesting that the lifetimes in all cases shown lie in the narrow range 40–70 s (see Fig. 1). They decrease mildly with increasing MB.

In Fig. 2 the lifetimes versus MB for stars containing hyperons (npH) and npK stars are compared. In both cases, the larger the mass, the shorter the lifetime. For kaon-rich PNSs, however, the collapse is delayed until the final stage of the Kelvin-Helmholtz epoch, while this is not necessarily the case for hyperon-rich stars.

4. SIGNALS IN DETECTORS

In Fig. 3 the evolution of the total neutrino energy luminosity is shown for different models. Notice that the drop in the luminosity for the stable star (solid line), associated with the end of
the Kelvin-Helmholtz epoch, occurs at approximately the same time as for the metastable stars with somewhat higher masses. In all cases, the total luminosity at the end of the simulations is below $10^{51}$ erg/s. The two upper shaded bands correspond to SN 1987A detection limits with KII and IMB, and the lower bands correspond to detection limits in SNO and SuperK for a future galactic supernova at a distance of 8.5 kpc. The times when these limits intersect the model luminosities indicate the approximate times at which the count rate drops below the background rate $(dN/dt)_{BG} = 0.2$ Hz.

The poor statistics in the case of SN 1987A precluded a precise estimate of the PNS mass. Nevertheless, had a collapse to a black hole occurred in this case, it must have happened after the detection of neutrinos ended. Thus the SN 1987A signal is compatible with a late kaonization-induced collapse, as well as a collapse due to hyperonization or to the formation of a quark core. More information would be extracted from the detection of a galactic SN with the new generation of neutrino detectors.

In SNO, about 400 counts are expected for electron antineutrinos from a supernova located at 8.5 kpc. The statistics would therefore be improved significantly compared to the observations of SN 1987A. A sufficiently massive PNS with a kaon condensate becomes metastable, and the neutrino signal terminates, before the signal de-
creases below the assumed background. In SuperK, however, up to 6000 events are expected for the same conditions (because of the larger fiducial mass) and the effects of metastability due to condensate formation in lower mass stars would be observable.

5. WHAT CAN WE LEARN?

The calculations of Pons, et al. [19] show that the variations in the neutrino light curves caused by the appearance of a kaon condensate in a stable star are small, and are apparently insensitive to large variations in the opacities assumed for them. Relative to a star containing only nucleons, the expected signal differs by an amount that is easily masked by an assumed PNS mass difference of 0.01 – 0.02 M⊙. This is in spite of the fact that, in some cases, a first order phase transition appears at the star’s center. The manifestations of this phase transition are minimized because of the long neutrino diffusion times in the star’s core and the Gibbs’ character of the transition. Both act in tandem to prevent either a “core-quake” or a secondary neutrino burst from occurring during the Kelvin-Helmholtz epoch.

Observable signals of kaon condensation occur only in the case of metastable stars that collapse to a black hole. In this case, the neutrino signal for a star closer than about 10 kpc is expected to suddenly stop at a level well above that of the background in a sufficiently massive detector with a low energy threshold such as SuperK. This is in contrast to the fact that, in some cases, a first order phase transition appears at the star’s center. The manifestations of this phase transition are minimized because of the long neutrino diffusion times in the star’s core and the Gibbs’ character of the transition. Both act in tandem to prevent either a “core-quake” or a secondary neutrino burst from occurring during the Kelvin-Helmholtz epoch.

6. MATTER WITH QUARKS

Strangeness appearing in the form of a mixed phase of strange quark matter also leads to metastability. Although quark matter is also suppressed by trapped neutrinos [14,21], the transition to quark matter can occur at lower densities than the most optimistic kaon case, and the dependence of the threshold density onYL is less steep than that for kaons. Thus, it is an expectation that metastability due to the appearance of quarks, as for the case of hyperons, might be able to occur relatively quickly.

Steiner, et al. [21] have demonstrated that the temperature along adiabats in the quark-hadron mixed phase is much smaller than what is found for the kaon condensate-hadron mixed phase. This could lead to core temperatures which are significantly lower in stars containing quarks than in those not containing quarks. The temperature as a function of baryon density for fixed entropy and net lepton concentration is presented in Fig. 4, which compares the cases (s = 1, YL = 0.4) and (s = 2, Yν = 0) both including and ignoring quarks. The introduction
of hyperons or quarks lowers the Fermi energies of the nucleons and simultaneously increases the specific heat of the matter, simply because there are more components. In the case of quarks, a further increase, which is just as significant, occurs due to the fact that quarks are rather more relativistic than hadrons. The combined effects for quarks are so large that, in some cases, an actual reduction of temperature with increasing density occurs along an adiabat. This effect indicates that the temperature will be smaller in a PNS containing quarks than in stars without quarks.

The large reduction in temperature might also influence neutrino opacities, which are generally proportional to $T^2$. However, the presence of droplet-like structures in the mixed phase [23], not considered here, will modify the specific heat. In addition, these structures may dominate the opacity in the mixed phase [24]. However, a PNS simulation is necessary to consistently evaluate the thermal evolution, since the smaller pressure of quark-containing matter would tend to increase the star’s density and would oppose this effect. Calculations of PNS evolution with a mixed phase of quark matter, including the possible effects of quark matter superfluidity [25] are currently in progress and will be reported separately.

7. OUTLOOK

7.1. Neutrino Interferometry

A titillating possibility would be a Hanbury-Brown Twiss interferometric analysis using the neutrinos detected on earth to determine the radial extent of the neutrinosphere. For this purpose, sufficient statistics and both accurate time and energy resolutions in the detectors would be needed.

7.2. $\pi^-$ and $K^-$ Dispersion Relations Through $\nu$-Nucleus Reactions

The experimental program that would do the most to illuminate theoretical issues permeating neutrino interactions in dense matter would be studies of neutrino reactions on heavy nuclei, the only direct way of probing the matrix elements of the axial current in nuclear matter. Pioneering suggestions in this regard have been put forth by Sawyer & Soni [26,27], Ericson [28], and Sawyer [29]. The basic idea is to detect positively charged leptons ($\mu^+$ or $e^+$) produced in inclusive experiments

$$\bar{\nu} + X \rightarrow \mu^+ \ (\text{or} \ e^+) + \pi^- \ (\text{or} \ K^-) + X \ (1)$$

which is kinematically made possible when the in-medium $\pi^-$ or $K^-$ dispersion relation finds support in space-like regions. The sharp peaks at forward angles in the differential cross section versus lepton momentum survive the 100-200
MeV width in the incoming GeV or so neutrinos from accelerator experiments. Calculations of the background from quasi-elastic reactions indicate that the signal would be easily detectable.

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