

## Thermal Effects on Black Hole Formation in Failed Core-Collapse Supernovae\*

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We investigate several aspects of black hole formation in failing core-collapse supernovae using 1D general-relativistic hydrodynamic simulations. We use the open-source code GR1D and incorporate into it nucleon-nucleon Bremsstrahlung, a crucial neutrino pair-production channel. We focus on how various thermal effects can influence the postbounce supernova evolution towards black hole formation. By performing simulations with and without nucleon-nucleon Bremsstrahlung, we investigate the sensitivity of black hole formation to thermal support in the protoneutron star. We also investigate delayed black hole formation by artificially driving explosions in an extreme model that is initially thermally supported above the maximum baryonic cold neutron star mass but then collapses to a black hole after neutrino cooling removes sufficient thermal support.

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## 1. Introduction

The majority of the stellar-mass black holes (BHs) present in the modern universe are expected to form by the collapse of protoneutron stars in core-collapse supernovae (CCSNe). There are several channels through which this can occur: *(i)* the supernova shock fails to be reenergized and accretion pushes the PNS over its maximum mass, leading to collapse (c.f. [11, 10, 3, 6]), *(ii)* fallback after a successful CCSN can lead to PNS collapse [13], and *(iii)* nuclear phase transitions or PNS cooling may cause the PNS to collapse during its cooling phase (e.g., [1]).

In this contribution to the proceedings of the 11th Symposium on Nuclei in the Cosmos, we investigate several aspects of BH formation in CCSNe that are related to thermal effects. In §2, we briefly outline the simulation code we use to study core collapse and BH formation and discuss our implementation of nucleon-nucleon Bremsstrahlung, a recent addition to our code. In §3.1, we show that in failing CCSNe this interaction increases the neutrino luminosity, removes thermal support, and causes the PNS to collapse to a BH earlier than when the interaction is not included. Finally, in §3.2, we artificially drive explosions in which the resultant PNS is thermally supported above the maximum baryonic PNS mass. Using this approach with an extreme model, we demonstrate delayed BH formation due to PNS cooling.

## 2. Methods

### 2.1 GR1D

We use the open-source, spherically-symmetric, general-relativistic (GR) Eulerian hydrodynamics code GR1D, which is available at <http://stellarcollapse.org>. We refer the reader to Ref. [5] for the full details of GR1D and give here only a brief description. GR1D follows the formalism of Romero et al. [7], which uses the radial gauge and polar slicing gauge condition in spherically-symmetric GR. This reduces the metric to a diagonal form with two metric functions that are determined by hydrodynamic variables. GR1D is designed to follow the evolution of stars beginning from the onset of core collapse to BH formation. Its GR hydrodynamics module utilizes high resolution shock capturing methods. GR1D makes use of several microphysical equations of state (EOS), also available online at <http://stellarcollapse.org>, and uses a 3-neutrino leakage/heating scheme (described in §2.2). Here, we make use of the EOS from Lattimer & Swesty (1991) [4] with an incompressibility of  $K_0 = 220 \text{ MeV}$  (LS220).

### 2.2 Neutrino Treatment & Nucleon-Nucleon Bremsstrahlung

GR1D uses a hybrid neutrino leakage scheme based on the schemes of [9] and [8] and includes the standard reactions therein. It includes three neutrino types,  $\nu_e$ ,  $\bar{\nu}_e$ , and  $\nu_x = \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$ . The neutrino emission rates, both energy and number, are determined from an interpolation between the diffusion and free streaming limits. These emission rates are combined with a parameterized neutrino heating scheme to calculate the total energy emitted from a zone. The parameterization of our heating scheme, via the scale factor  $f_{\text{heat}}$ , allows us to drive artificial explosions. Full details of GR1D's neutrino leakage/heating scheme can be found in [5]. An application of our parameterized heating scheme can be found in [6].

A process for neutrino pair production not included in the leakage schemes of [9, 8] is nucleon-nucleon Bremsstrahlung (NNBrems), i.e.  $N + N \rightarrow N + N + \nu\bar{\nu}$ . NNBrems dominates the neutrino pair production at high matter densities. In CCSNe, this regime is very optically thick and NNBrems is a subdominant contributor to the total neutrino luminosity. However, during PNS cooling or NS-NS or NS-BH mergers, emission from NNBrems may be considerable. As a thermal neutrino pair-production process, we include NNBrems into GR1D to investigate its effect on BH formation. We use the single neutrino pair emissivity for NNBrems from [2]<sup>1</sup>,

$$Q_{nb} = 2.0778 \times 10^{30} \zeta \left( X_n^2 + X_p^2 + \frac{28}{3} X_n X_p \right) \rho_{14}^2 \left( \frac{T}{\text{MeV}} \right)^{5.5} \text{ ergs cm}^{-3} \text{ s}^{-1}, \quad (2.1)$$

where  $\rho_{14}$  is the matter density in units of  $10^{14} \text{ g cm}^{-3}$ ,  $T$  is the matter temperature in MeV,  $X_n$  and  $X_p$  are the mass fractions of neutrons and protons respectively and  $\zeta$  is a factor that absorbs all interaction ambiguities. We adopt the value of  $\zeta = 0.5$  following [2]. For GR1D, we require the single-neutrino emissivities (both energy and number). Absorptive opacities are not needed (but could be obtained via Kirchhoff’s law), since GR1D’s leakage scheme includes opacity contributions only from scattering and from charged-current absorption processes. With the publication of this proceedings article, we have updated GR1D (to v1.03) to include NNBrems as an option in the leakage scheme.

### 3. Results

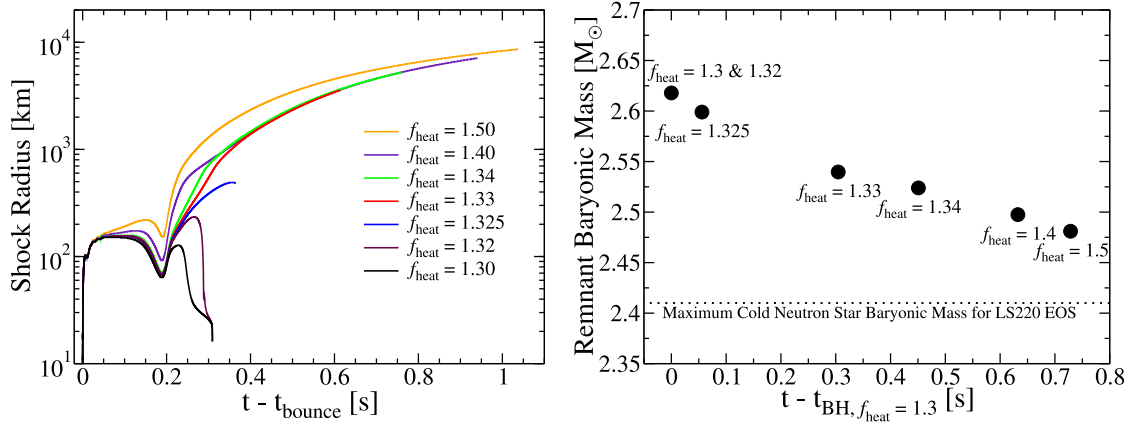
#### 3.1 Nucleon-Nucleon Bremsstrahlung

We perform 12 simulations in which we investigate the effect of NNBrems in BH-forming core collapse simulations. We choose 6 progenitor models from the “ $u$  series” of Woosley et al. (2002) [12], namely the 35, 40, 45, 50, 60, and  $75 M_\odot$  models with metallicities of  $10^{-4} Z_\odot$ . These models have large iron cores at the onset of core collapse and, as we shall see, form BHs very soon after bounce. They yield large temperatures in their PNSs and therefore are ideal for studying thermal effects. For each model we run simulations with and without the NNBrems emissivities (Eq. 2.1) included in our neutrino leakage scheme. Table 1 presents the results of these simulations, we include the time to BH formation and the total neutrino energy emitted between bounce and BH formation.

Model		$u35$	$u40$	$u45$	$u50$	$u60$	$u75$
NNBrems	$t_{\text{BH}}$ [s]	0.522	0.478	0.578	0.747	0.630	0.311
	$\nu$ -energy [B]	257	260	277	281	233	184
No NNBrems	$t_{\text{BH}}$ [s]	0.526	0.482	0.582	0.749	0.635	0.311
	$\nu$ -energy [B]	249	253	268	273	229	179

**Table 1:** Effect of NNBrems on time to BH formation and total emitted neutrino luminosity until BH formation. The progenitor models are taken from the  $10^{-4} Z_\odot$  model set of [12] and simulated with the LS220 EOS. 1 B =  $10^{51}$  ergs.

<sup>1</sup>[2] mistakenly included the  $\zeta$  factor in the numerical constant as well as in the expression for  $Q_{nb}$ . We use the corrected expression here (Burrows, *private communication*, 2010).



**Figure 1:** Shock radii (*left panel*) for the *u75* model of [12] with 7 values of  $f_{\text{heat}}$ . For each value of  $f_{\text{heat}}$ , we plot in the *right panel* the baryonic mass of the PNS after accretion has ceased versus the time each model remains stable. Less massive PNS remain stable for longer times. The dotted line indicates the maximum cold neutron star baryonic mass for the LS220 EOS.

NNBrems results in a slightly higher<sup>2</sup> ( $\sim 3\%$ ) average neutrino luminosity as is demonstrated by the higher total energy emitted in neutrinos. This is due to the increased neutrino emissivity in the dense core of the PNS where NNBrems dominates. The extra loss of thermal energy from this region reduces the thermal pressure, thus removes thermal pressure support from the PNS. This, in turn, lowers the maximum PNS mass and causes the dynamical collapse of the PNS to begin at somewhat earlier times ( $\Delta t \sim O(\text{ms})$ ) compared to the case with no NNBrems.

### 3.2 Thermal Effects

Due to thermal pressure support, the maximum gravitational mass of a PNS in a CCSN environment can be significantly higher than the cold neutron star (CNS) value [6]. In extreme models with soft EOS, or in models with a hyperonic EOS, it is also possible that the *baryonic* mass of the PNS can exceed its CNS value. An interesting case arises when, during a core-collapse event, the shock is successfully reenergized but enough material has accreted onto the PNS so that it exceeds its maximum CNS baryonic mass. Initially stable, the PNS cools via neutrinos. Since baryonic mass is conserved, once sufficient thermal support is lost, no stable configuration exists and the PNS will collapse to a BH. We perform simulations with the *u75* model from [12] and we artificially adjust the amount of neutrino heating via the scale factor  $f_{\text{heat}}$  (see [5] for details) to achieve explosions. The *u75* is an extreme model. In a failing CCSN, it forms a BH roughly  $\sim 300$  ms after bounce with a baryonic (gravitational) mass of  $\sim 2.62$  ( $\sim 2.44$ )  $M_{\odot}$ . For comparison, the LS220 EOS has a maximum CNS baryonic (gravitational) mass of  $\sim 2.41$  ( $\sim 2.04$ )  $M_{\odot}$ . Due to the presence of a compositional interface located at a baryonic mass coordinate of  $\sim 2.5 M_{\odot}$ , where the density drops by  $\sim 50\%$ , it is possible to launch explosions very close to the time of PNS collapse and achieve the scenario discussed above. In the right panel of Fig. 1, we show the baryonic mass

<sup>2</sup>NNBrem is a more dominant contributor to the neutrino luminosity in lower ZAMS mass progenitors, i.e.  $8 M_{\odot} \lesssim M \lesssim 20 M_{\odot}$ . In these models the temperatures are typically lower and NNBrem, which scales  $\propto T^{5.5}$ , becomes comparable to other neutrino pair-production processes, which scale  $\propto T^9$ .

of the PNS at BH formation for 7 different values of  $f_{\text{heat}}$ . The left panel shows the shock position until BH formation for these same models. In the  $f_{\text{heat}} = 1.30, 1.32,$  and  $1.325$  models, the PNS never ceases to accrete material. In the remaining models, as  $f_{\text{heat}}$  increases, the shock is reenergized at earlier times leaving PNSs with increasingly smaller baryonic masses. As neutrinos extract thermal energy from the PNS, the latter becomes unstable and collapses to a BH. The timescale for neutrino cooling is typically 10-100 s, but in the case of the extreme  $u75$  model, BH formation happens within  $\sim 1$  s for these values of  $f_{\text{heat}}$ . For this particular model, we find that NNBrems does not have an observable effect due to the extremely high temperatures (50 – 100 MeV) in the outer regions of the PNS. As mentioned in §3.1, very high temperatures lead to the dominance of other neutrino pair-production processes over NNBrems at early post-explosion times. As an aside, hyperonic EOS can have a much lower maximum CNS baryonic mass but still support large PNS baryonic masses when the temperature is high [10]. In this case, the above scenario can occur for a much larger range of progenitors and extreme models do not need to be invoked.

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