Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Black-Hole Formation in Potential γ-Ray Burst Progenitors

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Abstract. We present the results of a study by Dessart *et al.* (2012), where we performed stellar collapse simulations of proposed long-duration γ-ray burst (LGRB) progenitor models and assessed the prospects for black hole formation. We find that many of the proposed LGRB candidates in Woosley & Heger (2006) have core structures similar to garden-variety core-collapse supernova progenitors and thus are not expected to form black holes, which is a key ingredient of the collapsar model of LGRBs. The small fraction of proposed progenitors that are compact enough to form black holes have fast rotating iron cores, making them prone to a magneto-rotational explosion and the formation of a proto-magnetar rather than a black hole. This leads us to our take-home message, that one must consider the iron-core structure (eg. $\rho(r), \Omega(r)$) of evolved massive stars before making assumptions on the central engine of LGRBs.

Keywords. (stars:) supernovae: general, gamma rays: bursts

1. Introduction

A great puzzle in massive star evolution is to understand the necessary departures from the general core collapse scenario to produce a LGRB in addition to a SN explosion, as spectroscopically confirmed in, to date, at least six LGRB/SNe pairs. The very low occurrence rate of LGRB/SN per CCSN calls for progenitor properties that are rarely encountered in star formation/evolution.

Two LGRB central-engine models are currently favored. They suggest the key components for a successful LGRB/SN are a compact progenitor with a short light-crossing time of $\sim$1 s and fast rotation at the time of collapse. One is the collapsar model (Woosley 1993), in which a fast-rotating progenitor fails to explode in its early post-bounce phase and instead forms a black hole, while the in-falling envelope eventually forms a Keplerian disk feeding the hole on an accretion timescale comparable to that of the LGRB. The other model involves a proto-magnetar (Wheeler *et al.* 2000), in which the LGRB is born after a successful SN explosion, either by the neutrino or the magneto-rotational mechanism, although the latter seems more likely given the rapid rotation required for the magnetar (Dessart *et al.* 2008).

The only stellar-evolutionary models for LGRB progenitors that are evolved until the onset of core collapse are those of Woosley & Heger (2006). We thus focus on their model set for our investigation on the dynamics of the CCSN engine and the potential formation of a black hole in the collapsar context. In this work, we use the open-source, spherically symmetric, general relativistic, Eulerian hydrodynamics code `GR1D` (O'Connor & Ott 2010). Rotation is included through a centrifugal-acceleration term in the momentum equation.

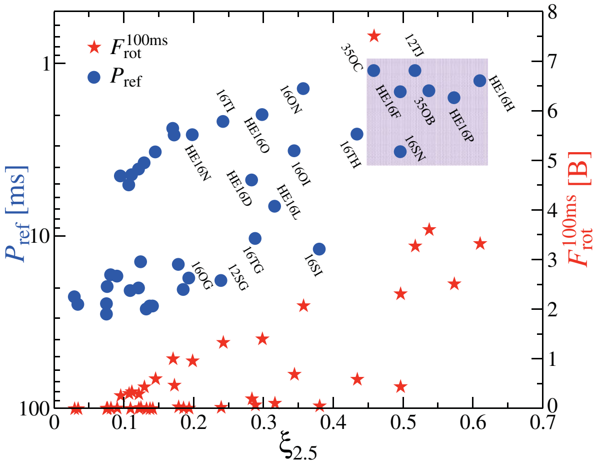

Figure 1. Reference proto-neutron star spin period, P_{ref}, taken at the onset of explosion (left axis, blue dots) and the free energy stored in differential rotation 100 ms after bounce $F^{\mathrm{rot}}_{100\,\mathrm{ms}}$ (right axis, red stars) vs. bounce compactness $\xi_{2.5}$. Most models have a low bounce compactness and are unlikely to form a black hole. Models with a high bounce compactness (dark shaded box) systematically have short spin periods and a large budget of free energy stored in the differential rotation. Comparing the reference spin periods of this figure to Metzger *et al.* (2011), one would predict that none of these models form black holes.

2. Results

Our simulations first demonstrate that most of the Woosley & Heger (2006) models have a small bounce compactness $\xi_{2.5}$, where $\xi_M = (M/2.5\,M_\odot)/(R_M/10^8\,\mathrm{cm})$ (Fig. 1). O'Connor & Ott (2011) argue that a bounce compactness of ~0.45 represents a threshold value for the neutrino mechanism since above it an unrealistic neutrino-heating efficiency is required to prevent black hole formation. The progenitors in Fig. 1 that are below this threshold value are, in terms of compactness, similar to garden variety, low-mass, non-rotating, progenitors and do not seem to have any more reason to form a black hole than, e.g., the RSG progenitors expected to produce SNe II-Plateau. However, if we assume that the magneto-rotational instability is able to generate large scale magnetic fields on short timescales, the fast rotating progenitors in Fig. 1 ($P_{\mathrm{ref}} \lesssim 10\,\mathrm{ms}$) may be ideal progenitors of a proto-magnetar-powered LGRB.

There are seven models in Woosley & Heger (2006) that have bounce compactnesses larger than the threshold value of O'Connor & Ott (2011); they are highlighted with a shaded box in Fig. 1. If these progenitors were non-rotating one might expect a failed supernova and black hole formation, however each of the progenitors has significant rotation ($P_{\mathrm{ref}} \lesssim 3\,\mathrm{ms}$) and most have a significant amount of free energy in differential rotation, which can be tapped by the magneto-rotational instability. Dessart et *al.* (2008) evolved the 35OC model with magnetic fields in 2D and found a strong magneto-rotational explosion. This leads us to predict that the other models in this category will have a similar fate. If these models explode, they may also make excellent candidates for progenitors of the proto-magnetar-powered LGRB.

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