On the Progenitors of Collapsars

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Abstract. We study the evolution of stars that may be the progenitors of common (long-soft) GRBs. Bare rotating helium stars, presumed to have lost their envelopes due to winds or companions, are followed from central helium ignition to iron core collapse. Including realistic estimates of angular momentum transport [1] by non-magnetic processes and mass loss, one is still able to create a collapsed object at the end with sufficient angular momentum to form a centrifugally supported disk, i.e., to drive a collapsar engine. However, inclusion of current estimates of magnetic torques [2] results in too little angular momentum for collapsars.

INTRODUCTION

One of the most promising models for the “long variety” of gamma-ray bursts (GRBs) is the so-called collapsar model [3]. It assumes that a sufficiently massive stellar core collapses into a black hole and the infalling outer layers form a disk around it. Energy dissipated in the disk or the rotation of the black hole itself is assumed to power a jet of high Lorentz factor (\(\Gamma \sim 200\)) that escapes from the engine along the polar axis to large distance (\(\sim 10^{15}\) cm) and powers a GRB by interaction with the circumstellar medium or by internal shocks.

The traversal time for the relativistic jet through the hydrogen envelopes of typical massive stars is hundreds to thousands of seconds. Thus, at the time of the GRB, bare helium stars, which have radii of only a few light seconds (about a solar radius), are required if the lifetime of the engine and the GRB are not to be short compared to the time it takes the jet to drill through the star.

Two essential ingredients for the collapsar model are a sufficiently massive core to form a black hole and a sufficient rotation rate at the time of collapse to allow the formation of a disk. The question we address here is: What can be expected for the rotation rates of massive stellar cores when they collapse?

PROGENITOR MODELS

We calculate the evolution of bare helium cores with an initial mass of 15 \(M_\odot\). The stars are assumed to rotate rigidly initially with two different surface rotation rates corresponding to 10% and 30% of a Keplerian orbit. The former could be either the result of a massive single star (\(\sim 40M_\odot\)) that has lost its envelope early during helium burning or a close binary that lost its envelope to a companion. The latter might require a binary merger. The evolution of the helium core and its rotation is followed as described by Heger et al. [1] using fine surface zoning.

Two different evolutionary paths are considered. The first neglects mass loss, possibly corresponding to WR stars of very low metallicity, while in the second, it is taken into account. We use the WR mass loss rate given by Wellstein & Langer [4, equation 1], reduced by a factor 3 to account for effect of “clumping” [5]. An initial stellar metallicity of 1/10 solar is assumed along with a WR mass loss rate that scales as the square root of metallicity [6], reducing the mass loss rate by an additional factor of 3.

RESULTS

Figures 1 - 4 give the results for collapsar progenitors that follow the evolution of the angular momentum in the stellar interior till the onset of iron core collapse.

Rotation Profile and Disk Formation

To decide whether a centrifugally supported accretion disk can form around a central black hole (which we assume either forms promptly or by fallback), we compare the angular momentum calculated as a function of interior mass to that a test particle would require at the last stable orbit around a Schwarzschild or Kerr black hole (Figures 2 and 3). Though mass loss significantly reduces the angular momentum at core collapse, enough remains in the equatorial regions of the star to form a centrifugally supported disk.
FIGURE 1. Angular momentum in the equatorial plane as a function of the interior mass coordinate, \( m \), at different evolutionary stages.

FIGURE 2. Equatorial angular momentum (thick black line) of a 15 \( M_\odot \) helium core of initially 10\% Keplerian rotation as a function of the interior mass coordinate, \( m \). The dashed-dotted line shows the specific angular momentum required for a test particle at the last stable orbit around a Schwarzschild black hole of mass equal to the mass coordinate, \( m \). The dashed line shows the same for a extreme Kerr black hole (spin parameter \( a = 1 \)).

FIGURE 3. Same as Figure 2, but mass loss due to stellar winds is included. The dotted line shows the specific angular momentum a test particle requires at the last stable orbit around a black hole that has formed with the mass and integrated angular momentum below the given mass coordinate. Where the dotted line is missing, sufficient angular momentum is available to form a Kerr black hole.

FIGURE 4. Same as Figure 3, but an initial rotation rate of 30\% Keplerian rotation was assumed and angular momentum transport by magnetic fields according to a prescription by Spruit [2] was included.

**Magnetic Fields**

We also calculated models including magnetic torques that might result from a dynamo process recently described by Spruit [2]. They lead to considerable spin-down of the core, especially when combined with wind mass loss (Table 1 and Figure 4).

For comparison, preliminary calculations [7] of rotating stellar models of 15, 20, and 25 \( M_\odot \) stars with hydrogen envelopes and initial surface rotation velocities of 200 \( \text{km s}^{-1} \), using the same prescription for torques, resulted in pulsar birth rotation periods of 7.65, 5.50, and 3.99 ms. Without magnetic fields, including all other forms of angular momentum transport [1], the same calculations previously gave rotation periods of \( \sim 0.2 \text{ ms} \) in these same stars. Here it is assumed that the innermost 1.6 \( M_\odot \) of the collapsing star produces a rigidly rotating neutron star of 1.45 \( M_\odot \) gravitational mass, while conserving the total angular momentum contained in the pre-collapse model.

Calculations that used the effects of magnetic fields as described by Spruit & Phinney [8, not shown here] always resulted in much too low core rotation for the collapsar model of GRBs.

**Binary Interaction**

In a sufficiently close binary system the envelope can be tidally locked to the orbit of the star. Depending on separation and mass ratio, this rotation can reach several 10\% of Keplerian. We find that maintaining 10\% Keplerian surface rotation can be sufficient for collapsars. If employing the dynamo process by Spruit [2], however, the resulting presupernova rotation is too slow even for a system with 20\% Keplerian surface rotation.

To simulate a merger of a binary system after or at
TABLE 1. Presupernova properties of initially 15M⊙ helium core models. The first three columns define the initial model and physics employed (magnetic fields according to Spruit [2], amount of rotation, mass loss by winds). Next we give the period a pulsar would have if it formed in this star, then the non-dimensional spin parameter, $\eta_{\text{BH}}$, a black hole would acquire, if all the angular momentum below the mass coordinate indicated were to go into the black hole of that mass (formal values in excess of 1 are shown in brackets solely to give a measure for the angular momentum available in the model), and in the last column we show the mass ranges in which the equatorial mass could form a centrifugally supported accretion disk around a central compact object.

| magnetic field rotation | mass loss | pulsar period (ms) | $\eta_{\text{BH}}$ (15M⊙) | $\eta_{\text{BH}}$ (2.5M⊙) | $\eta_{\text{BH}}$ (1.5M⊙) | $\eta_{\text{BH}}$ (1M⊙) | mass coordinate for which an equatorial disk could form (M⊙) |
|------------------------|-----------|--------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------------------------------|
| yes 10                 | 0.09      | (2.5) (3.4) (3.8) (3.7) | 0.004                      | 0.004                      | 0.004                      | 0.004                      | 0 – 15 |
| yes 10 yes             | 0.23      | (1.1) (0.9) (0.98) (1.2) | 0.2 – 2.5, 2.7 – 8.6        |                            |                            |                            |                                  |
| yes 30                 | 0.06      | (4.1) (4.8) (5.6) (5.9) | 0 – 15                     |                            |                            |                            |                                  |
| yes 30 yes             | 0.18      | (1.7) (1.3) (1.3) (1.7) | 0 – 8.4                    |                            |                            |                            |                                  |
| yes 10 yes             | 1.9       | 0.6 (0.7) (0.8) (0.88) | 2.4 – 28.5, 5.7 – 15        |                            |                            |                            |                                  |

The end of central helium burning (Case C) an additional model was calculated assuming rigid rotation with 50% Keplerian surface rotation at core helium depleton and including the dynamo process of Spruit [2]. Again the magnetic stress kept the star in rigid rotation till carbon burning, removing too much angular momentum for the collapsar model to work. Without magnetic fields, as shown above, even single stars may already retain sufficient angular momentum for collapsar progenitors.

Decoupling of Core Rotation

At what evolution stage does the core rotation need to decouple from the surface? Figure 5 shoes that this needs to happen before central carbon burning – assuming angular momentum is locally conserved from this time on and no further transport occurs. In the model star of Figure 5 the decoupling would need to happen no later than when a central density of $\sim 10,000$ g cm$^{-3}$ is reached.

CONCLUSIONS

A bare helium star of low metallicity can retain enough angular momentum to form a centrifugally supported disk around a central black hole of $\sim 3M_\odot$, as required by the collapsar model for GRBs. Without magnetic fields, the angular momentum is sufficient to form a Kerr black hole and support most of all the star in an accretion disk. However, if we include an approximate treatment of angular momentum transport by magnetic fields, the resulting spin rates become too low to form centrifugally supported disks in the inner part of the core. Even a binary helium star merger at the end of central helium burning might not be able to avoid this fate. Mass loss can lead to an additional significant spin-down of the core, especially if magnetic fields couple it effectively to the envelope. Even in case of Keplerian surface rotation, the core rotation needs to decouple before carbon ignition in order to make a Kerr black hole. The dynamo process recently proposed by Spruit [2] seems too efficient to form collapsar progenitors from single stars or helium star mergers. This is even more so for the magnetic field modeling suggested by Spruit & Phinney [8].

ACKNOWLEDGMENTS

We thank Henk Spruit for a preview of his work and many helpful discussions. This work has been supported by the NSF (AST-9731569), NASA (NAG5-8128), the DOE (B347885), and the AvH (FLF-1065004).

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