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MASSIVE BINARY SYSTEMS AS GAMMA-RAY BURST PROGENITORS

JELENA PETROVIĆ[1,2]

[1] *Sterrenkundig Instituut, Utrecht Universiteit, 3384 CC Utrecht, The Netherlands*

[2] *Department of Astrophysics, Radboud University, 6525 ED Nijmegen, The Netherlands*
E–mail: petrovic@astro.ru.nl

Abstract. The collapsar model for gamma-ray bursts requires three essential ingredients: a massive core, removal of the hydrogen envelope, and enough angular momentum in the core. We study current massive star evolution models of solar metallicity to determine which massive star physics is capable of producing these ingredients. In particular, we investigate the role of hydrodynamic and magnetic internal angular momentum transport and binary mass and angular momentum transfer. We follow the evolution of rotating binary systems that include rotational processes for both stars. Neglecting magnetic fields, we show that the cores of massive single stars can maintain a high specific angular momentum ($j{\sim}10^{17}$ cm^2 s^{-1}) when evolved with the assumption that mean molecular weight gradients suppress rotational mixing processes. In binary systems that undergo mass transfer during core hydrogen burning the mass receiving star accretes large amounts of high angular momentum material, leading to a spin-up of the core. We find, however, that this merely compensates for the tidal angular momentum loss due to spin-orbit coupling, which leads to synchronous rotation before the mass transfer event. Therefore the resulting cores do not rotate faster than in single stars. We also present models that include magnetic fields generated by differential rotation and we consider the internal angular momentum transport by magnetic torques. We find that the magnetic coupling of core and envelope after the accreting star ends core hydrogen burning leads to slower rotation ($j{\sim}10^{15-16}$ cm^2 s^{-1}) than in the non-magnetic case. We conclude that our binary models without magnetic fields can reproduce stellar cores with a high enough specific angular momentum ($j{\geq}3{\cdot}10^{16}$ cm^2 s^{-1}) to produce a collapsar and a GRB. If magnetic torques are included, however, GRBs at near solar metallicity need to be produced in rather exotic binary channels, or current dynamo model overestimates the magnetic torques.

1. INTRODUCTION

The most widely used model for GRB production in the context of black hole formation in a massive star is the so called collapsar model (Woosley, 1993a). A collapsar is a massive (M=35-40M$_{\odot}$, Fryer 1999) rotating star whose core collapses to form a black hole (Woosley, 1993b; MacFadyen and Woosley, 1999). If the collapsing core has enough angular momentum ($j{\geq}3{\cdot}10^{16}$ cm^2 s^{-1}, MacFadyen and Woosley 1999) an accretion disk is formed around the black hole. The accretion of the rest of the core at accretion rates up to $0.1\,\mathrm{M}_\odot\ \mathrm{s}^{-1}$ by the newly-formed black hole is thought to be capable of producing a collimated highly relativistic outflow. This releases large amounts of energy ($\sim 10^{51}$ erg s^{-1}) some of which is deposited in the low density rotation axis of the star. In case the star has no hydrogen envelope, i.e., has a light crossing time which is less or comparable to the duration of the central accretion (about 10s), a GRB accompanied by a Type Ib/c supernova may be produced. The collapsar models for gamma-ray bursts thus needs three essential ingredients: a massive core, loss of the hydrogen envelope, and sufficient angular momentum to form an accretion disk.

A star evolving in a binary system and accreting matter from the companion, increases its surface angular momentum. If this angular momentum can be transported efficiently through the stellar interior, the star may evolve into a red supergiant that has a rapidly spinning core with sufficient specific angular momentum to produce a collapsar.

2. ROTATING BINARY SYSTEMS WITHOUT MAGNETIC FIELD

To check if accretion can add enough angular momentum to the core, we modeled the evolution of a rotating binary system with initial masses of $M_{1,\mathrm{in}}$=$56\,\mathrm{M}_\odot$ and $M_{2,\mathrm{in}}$=$33\,\mathrm{M}_\odot$ and an initial orbital period of p_in=6 days. The binary system quickly synchronizes during the main sequence evolution. Due to this synchronization, both stars lose angular momentum and their initial surface rotational velocities are 92 km s^{-1} for the primary and 64 km s^{-1} for the secondary which is much slower than the typical values for single stars of these masses (200 km s^{-1}, Heger et al., 2000). This means that stars in binary systems lose a significant amount of angular momentum due to synchronization. The angular momentum loss increases with the initial orbital period.

Fig. 1 shows specific angular momentum profiles of the secondary at different points of its evolution. The specific angular momentum of the secondary increases significantly due to fast Case A mass transfer (Fig. 1, dotted line). After this, the secondary loses angular momentum due to stellar wind mass loss, but also gains certain amount through slow Case A and Case AB mass transfer (Fig. 1, dashed and dot-dashed line). The result is that the core has a larger specific angular momentum when central helium burning starts than at the beginning of hydrogen core burning. After core hydrogen exhaustion, the secondary evolves into a red supergiant, the core contracts and the envelope expands. This leads to a spin-up of the core and a spin-down of the envelope. The specific angular momentum of the core at $3\,\mathrm{M}_\odot$ is $\sim 5.5{\cdot}10^{16}$ cm^2 s^{-1} (Fig. 1, three dot-dashed line). The envelope is convective and slowly rotating ($\sim$0.02 km s^{-1}). The core is rigidly rotating with maximum rotational velocity of $\sim$100 km s^{-1}. The core and the envelope are separated by layers that have a high μ-gradient. Angular momentum is not efficiently transported through these layers, so the core is not slowed down by the slow rotation of the envelope. When a third of the central helium supply is exhausted, the core (at $3\,\mathrm{M}_\odot$) has a specific angular momentum of $\sim 5{\cdot}10^{16}$ cm^2 s^{-1}. If we assume that the angular momentum

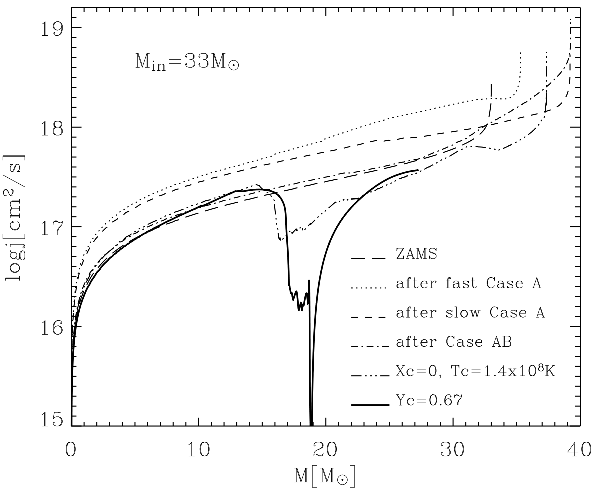

Figure 1: Specific angular momentum profiles of the secondary star on the hydrogen ZAMS (long dashed line), after fast (dotted line) and slow (short dashed line) Case A mass transfer, after Case AB mass transfer (dash-dotted line), when helium ignites in the core (three dots-dashed line) and when the central helium abundance is 67% (solid line).

of the core decreases further during helium core burning with the same rate, specific angular momentum of the core at the moment of helium exhaustion is expected to be $\sim 4{\cdot}10^{16}$ cm^2 s^{-1}. Since there is no significant angular momentum loss from the core during core carbon burning, we can conclude that this star has enough angular momentum to produce a collapsar and, in the case that the hydrogen envelope is lost during red supergiant phase, a gamma-ray burst.

3. ROTATING BINARY SYSTEMS WITH MAGNETIC FIELD

We model the evolution of the same binary system including angular momentum transport by magnetic torques, using the improved dynamo model of (Spruit, 2002).

Fig. 2 shows specific angular momentum profiles of the secondary at different phases of evolution. The specific angular momentum of the secondary increases significantly due to the fast Case A mass transfer (Fig. 2, dotted line). Angular momentum is transported more efficiently through the stellar interior compared to the non-magnetic model, since the incurred magnetic torques are a few orders of magnitude more efficient in angular momentum transport than the rotational instabilities. Comparing the specific angular momentum of the non-magnetic (Fig. 1) and magnetic model (Fig. 2), we notice that during fast Case A the angular momentum of the magnetic star increases more than that of the corresponding non-magnetic star ($2{\cdot}10^{17}$ cm^2 s^{-1} for magnetic and $1.25{\cdot}10^{17}$ cm^2 s^{-1} for non-magnetic star, $\sim 10^4$ yrs after fast Case A, at $3\,M_\odot$).

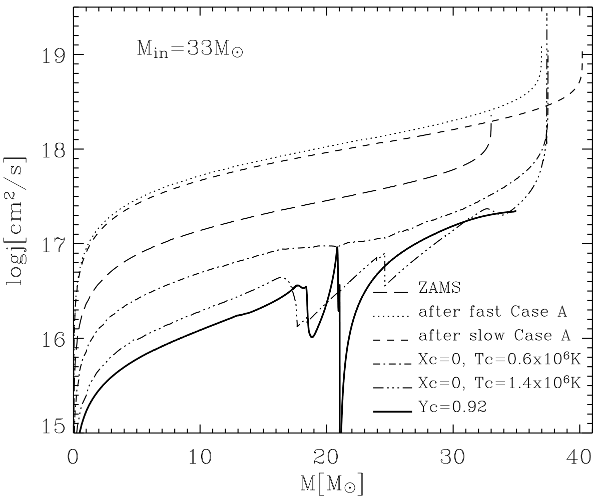

Figure 2: Specific angular momentum profiles of the secondary star with magnetic fields on the hydrogen ZAMS (long dashed line), after fast (dotted line) and slow (short dashed line) Case A mass transfer, when all hydrogen is exhausted in the center (dot-dashed line), when helium ignites (three dots-dashed line) and and when the central helium abundance is 92% (solid line).

The accretion stops when the secondary still has almost 50% of the hydrogen to burn in the core. Angular momentum is efficiently transported from the stellar core to the surface and the μ-gradient can not stop it as in the case of the non-magnetic star. During further main sequence evolution, the stellar core loses significant angular momentum and when hydrogen core burning stops, the specific angular momentum at $3\,M_\odot$ is $2{\cdot}10^{16}$ cm^2 s^{-1}. Before helium ignites in the core, the specific angular momentum decreases to $6{\cdot}10^{15}$ cm^2 s^{-1}.

4. CONCLUSIONS

We conclude that our binary models without magnetic field can reproduce stellar cores with a high enough specific angular momentum ($j{\geq}3{\cdot}10^{16}$ cm^2 s^{-1}) to produce a collapsar and a GRB.

However, if the magnetic field is taken into consideration, GRBs at near solar metallicity need to be produced in rather exotic binary channels, or the magnetic effects are overestimated in our current models.

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