Rapidly Rotating Core-Collapse Supernova Progenitors from Binary Stellar Evolution

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Introduction

Rapidly rotating core-collapse supernovae are key to the formation of exotic compact objects such as magnetars and are potential sources of strong gravitational wave emission. Binary interaction offers one of the most promising pathways to spin up massive stars and endow them with high angular momentum at the point of collapse.

In this study, we employ the stellar evolution code MESA to explore how binary mass and orbital period affect angular momentum transfer in low-metallicity, massive binary systems.

We evolve the systems through the mass transfer phase up to detachment, and subsequently follow the separate evolution of both donor and accretor stars until core collapse.

Method

We use Modules for Experiments in Stellar Astrophysics (MESA)[2] to simulate binary stellar evolution. The binary systems have initial orbital periods of 8–20 days, mass ratio q=0.5, donor star masses of 20–65$M_{\odot}$, and metallicity Z=0.001, with initial rotation synchronized by tidal locking. Our setup follow Renzo & Götberg (2021)[3] and Wang & Pan (2024)[4], but upgraded to MESA version r24.03.1.

Core-collapse supernova (CCSN) progenitors are constructed in two steps[4]: we first evolve the binary system until detachment, and then evolve the accretor star individually until core collapse. In addition, we conduct CCSN progenitors from single-star evolution for comparison. The rotation speeds of single-star progenitors are set to $0.1\omega_c$, $0.5\,\omega_c$ and the value corresponding to a 10-day spin period, where ω_c is the critical rotation rate of the star.

Result

Binary evolution Stage

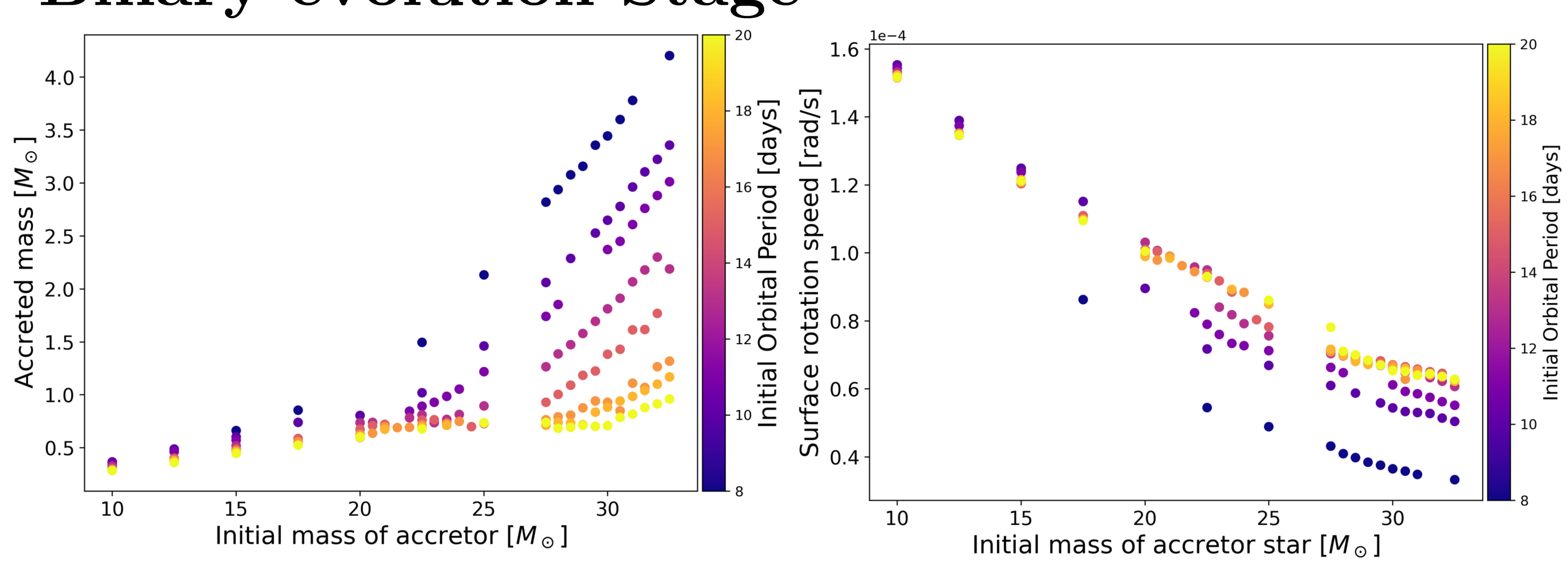

Figure 1. Accreted mass (left) and surface rotational speed (right) as functions of the initial accretor mass. Color indicates the initial orbital period.

Fig 1. shows that accretors in systems with higher initial masses tend to accrete more material via Roche lobe overflow (RLOF) and achieve higher surface rotational speeds. Systems with shorter initial orbital periods (shorter orbital separation) also tend to accrete more mass.

Abundance Evolution Before Core Collapse

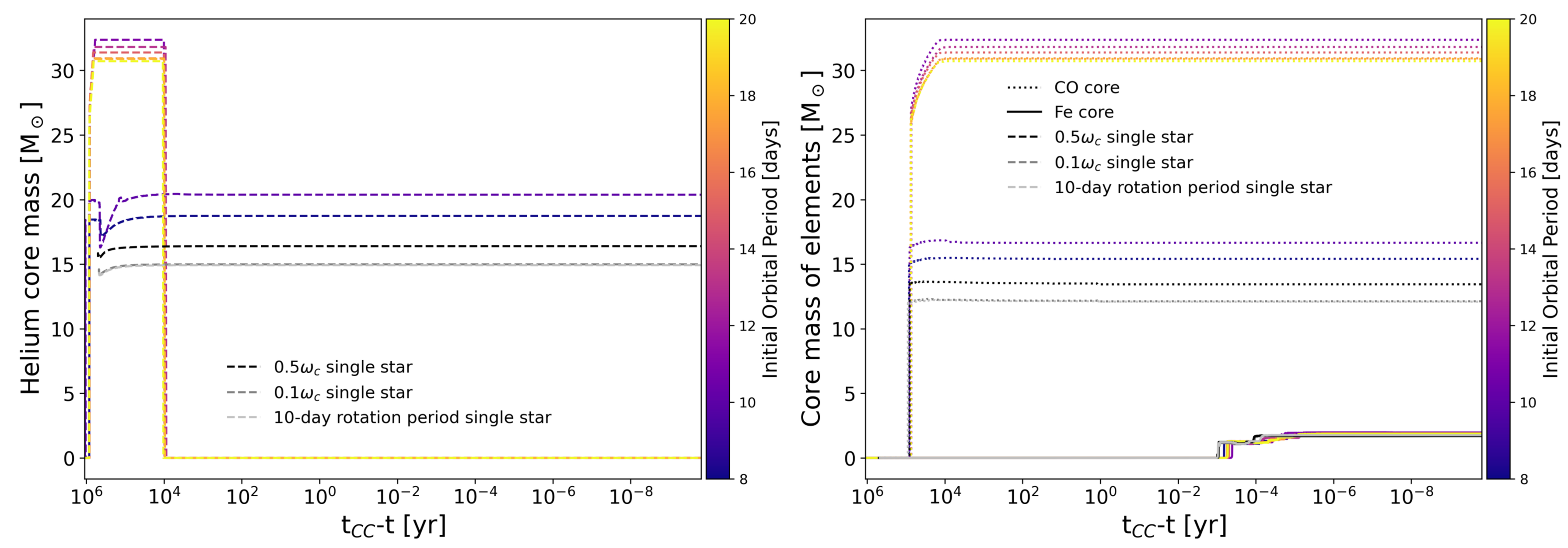

Figure 2. He core mass (left) and CO and Fe core masses (right) as functions of time before core-collapse ($t_{CC} - t$). Color indicates the initial orbital period.

Fig 2. shows the abundance evolution of 30$M_{\odot}$ stars. In shorter-period models, the evolutions of the helium and CO core masses are similar to those of single-star models, but with higher core masses. These differences are related to variations in the internal convection zones during helium burning, as shown in Fig. 3.

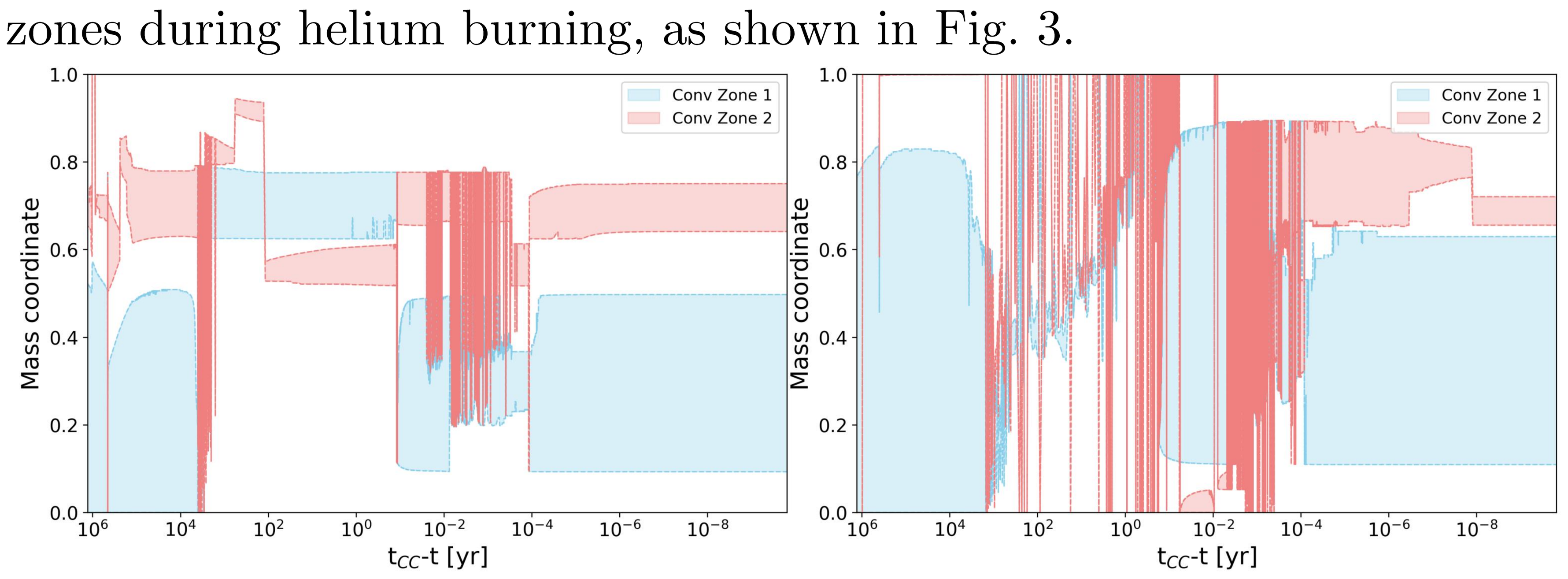

Figure 3. Kippenhahn diagrams showing the convective regions (shaded) in the accretor stars for 30$M_{\odot}$ accretors in binaries with P = 10 day (left) and 17 day (right). The x-axis indicates time before core-collapse ($t_{CC} - t$) and the y-axis shows the normalized mass coordinate. Blue and red shaded regions denote the largest and second-largest convective zones (by mass), respectively.

Around Core Collapse

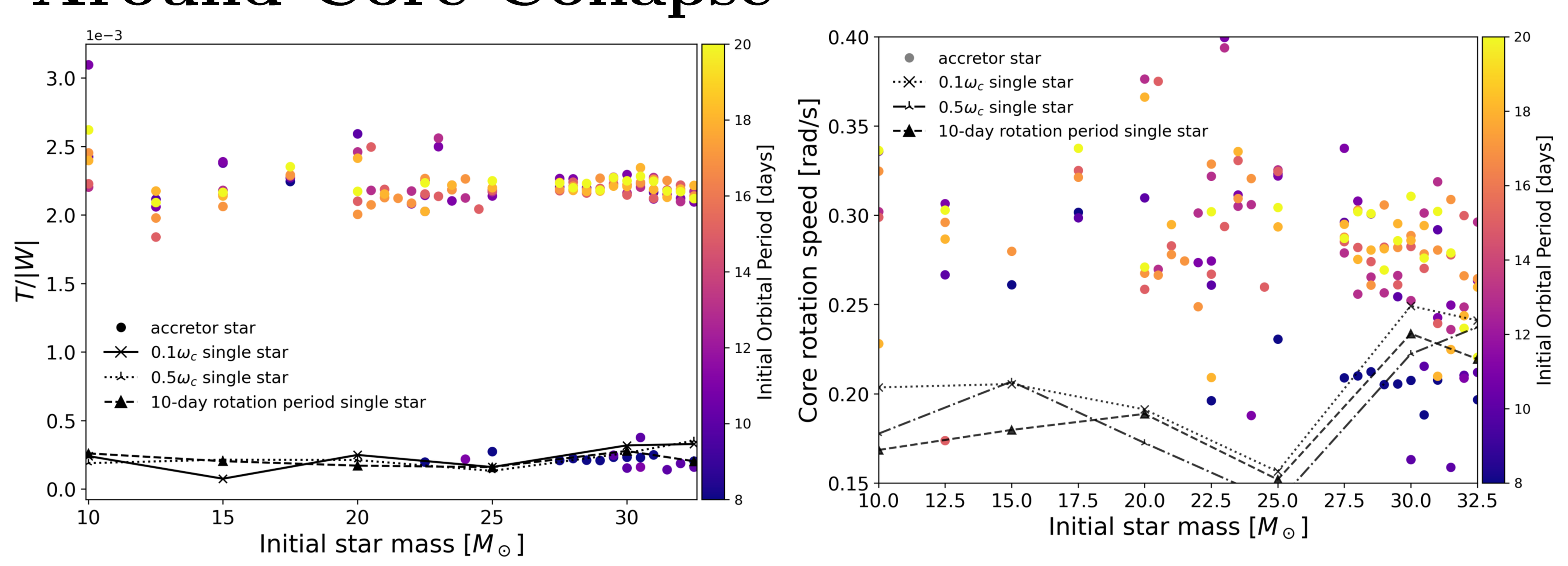

Figure 4. Ratio of rotational energy to gravitational potential energy ($T/|W|$) (left) and core rotation speed (right) at the time when the central density reaches $10^9 g/cm^3$, plotted as functions of initial stellar mass. Color indicates the initial orbital period.

Fig 4. shows that accretor stars evolved from binary systems tend to have higher $T/|W|$ ratios and core rotational speeds near core collapse compared to single-star models.

Conclusion

During the mass transfer phase, accretors in low-period, high-mass binary systems tend to accrete more mass.

In high-mass, short-period systems, the evolution of the He and CO cores of the accretor star resembles that of a single star, but with higher core masses. In contrast, long-period models tend to produce stars without a He core but with a more massive CO core. In these longer-period systems, convection extends through nearly the entire star, allowing its interior to remain approximately chemically homogeneous, thereby enabling complete helium burning.

We observe that stars evolved through binary systems tend to have higher $T/|W|$ ratios and faster core rotation speeds. A high $T/|W|$ indicates a greater likelihood of strong gravitational wave emission.[5] As a result, accretor stars in binary systems tend to have higher core rotation rates and distinct internal structures, which may aid in identifying the progenitors of rapidly rotating compact objects.

Our future work will conduct multi-dimensional CCSN simulations to further investigate the multi-messenger signals from these binary CCSN progenitors..

References

[1] Song & Liu 2023, *ApJ*, 528, 368
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[4] Wang & Pan 2024, *ApJ*, 964, 23
[5] Richers et al. 2017, Phys. Rev. D, 95, 063019