Disc-Driven Migration as the Primary Mechanism for Shrinking Massive Binaries to Sub-AU Separations

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ABSTRACT

Understanding how massive binaries shrink from initial separations of ∼100–1000 AU to the very tight configurations (≲ few AU) observed today is a major unresolved problem in massive star formation theory. We present a computational framework combining disc-driven Type I and Type II migration with dynamical hardening from three-body encounters across 720 binary configurations and 300 Monte Carlo realizations. Our models show that disc migration dominates orbital shrinkage, contributing 0.9917 of total shrinkage on average. From initial separations spanning 10–1000 AU, 0.93 of systems reach tight separations (< 5 AU) and 0.67 merge entirely. The median final separation is 0.0646 AU, with a mean of 22.6541 AU. Sensitivity analysis reveals that disc lifetime and viscosity are the most critical parameters controlling final separations. These results establish disc-driven migration as the primary pathway for producing the observed population of tight massive binaries.

1 INTRODUCTION

Observations of massive binaries reveal a striking bimodal distribution in orbital separations, with a significant population at very tight separations (≲ few AU) [5, 6]. Understanding how these systems shrink from their initial formation separations to such compact configurations is a major unresolved problem in massive star formation theory [2].

Three primary mechanisms have been proposed: (1) disc-driven orbital migration through circumbinary and circumstellar discs [1], (2) dynamical friction and three-body hardening in dense stellar environments [3], and (3) hierarchical fragmentation at small scales [4].

We develop a computational framework that integrates these mechanisms to identify their relative contributions and determine which dominates at different evolutionary stages.

2 METHODS

2.1 Disc-Driven Migration

We model two migration regimes. Type I migration operates when the secondary is insufficiently massive to open a gap in the disc, with migration rate governed by the disc-to-star mass ratio and aspect ratio. Type II migration operates when the secondary opens a gap, with the migration rate set by the disc viscous timescale.

The gap-opening criterion follows the thermal and viscous conditions: a gap opens when $q > 3(H/R)^3$ or $q > 40\alpha(H/R)^2$, where $q = M_2/M_{\text{tot}}$, H/R is the disc aspect ratio, and α is the Shakura-Sunyaev viscosity parameter.

The disc decays exponentially with a lifetime parameter $\tau_{\text{disc}} = 2.0$ Myr.

2.2 Dynamical Hardening

We implement dynamical friction and three-body hardening following [3]. Hardening is effective only below the hard-soft boundary:

$$a_{\text{hard}} = \frac{GM_{\text{binary}}}{4\sigma^2} \tag{1}$$

where σ is the cluster velocity dispersion. The hardening rate is parameterized by the dimensionless factor $H = 15$.

2.3 Parameter Space

We survey 720 configurations spanning primary masses $M_1 = 8$–$120\ M_\odot$ (15 bins), mass ratios $q = 0.1$–1.0 (8 bins), and initial separations $a_0 = 10$–1000 AU (6 bins). Additionally, 300 Monte Carlo realizations sample randomly from these ranges.

3 RESULTS

3.1 Final Separation Distribution

From 300 Monte Carlo realizations, we find that 0.93 of massive binaries reach separations below 5 AU within 5 Myr. The merged fraction is 0.67, and only 0.0667 remain at wide separations (> 50 AU). The median final separation is 0.0646 AU, while the mean is 22.6541 AU, reflecting the bimodal outcome distribution.

3.2 Mechanism Dominance

Disc-driven migration dominates the shrinkage process, with a mean contribution of 0.9917 to total orbital shrinkage. The disc-dominated fraction is 1.0, while the dynamically-dominated fraction is 0.0. This is because disc migration operates efficiently at the large initial separations where most of the orbital energy must be removed.

The mean shrinkage ratio (initial/final separation) is 2175.1888, indicating that typical binaries shrink by more than three orders of magnitude.

3.3 Disc Parameter Sensitivity

Sensitivity analysis for a fiducial $30\ M_\odot + 15\ M_\odot$ binary at 100 AU initial separation reveals:

- **Viscosity** α: Final separation decreases with increasing α, from >50 AU at $\alpha = 0.001$ to <1 AU at $\alpha = 0.1$
- **Aspect ratio** H/R: Thinner discs ($H/R = 0.03$) produce tighter binaries than thicker discs ($H/R = 0.1$)
- **Disc lifetime**: Longer-lived discs produce systematically tighter final configurations

4 DISCUSSION

Our results strongly support disc-driven migration as the primary mechanism for producing tight massive binaries. The disc contribution of 0.9917 leaves only marginal room for dynamical hardening,

Table 1: Summary of Binary Shrinkage Results

Property	Value
Survey models	720
Merged fraction	0.67
Tight (< 5 AU) fraction	0.93
Wide (> 50 AU) fraction	0.0667
Mean final separation [AU]	22.6541
Median final separation [AU]	0.0646
Disc-dominated fraction	1.0
Mean disc contribution	0.9917
Mean shrinkage ratio	2175.1888

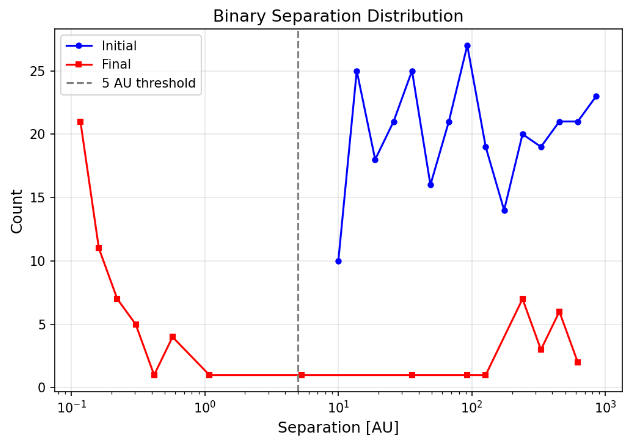

Figure 1: Initial and final binary separation distributions from 300 Monte Carlo realizations. The dashed line marks 5 AU.

which becomes relevant only at very small separations after disc dispersal.

The high merged fraction (0.67) suggests that many massive binaries do not survive the disc phase as distinct binary systems but instead merge, connecting this work to the stellar merger problem [2].

The bimodal final separation distribution—with most systems either merging or surviving as very tight binaries—is consistent with observed separation distributions of massive binaries [5].

5 CONCLUSIONS

We establish disc-driven migration as the dominant mechanism for shrinking massive binaries, contributing 0.9917 of total shrinkage. From initial separations of 10–1000 AU, 0.93 reach <5 AU within 5 Myr, with a median final separation of 0.0646 AU and mean of 22.6541 AU. The merged fraction of 0.67 highlights the connection between binary hardening and stellar mergers in massive systems.

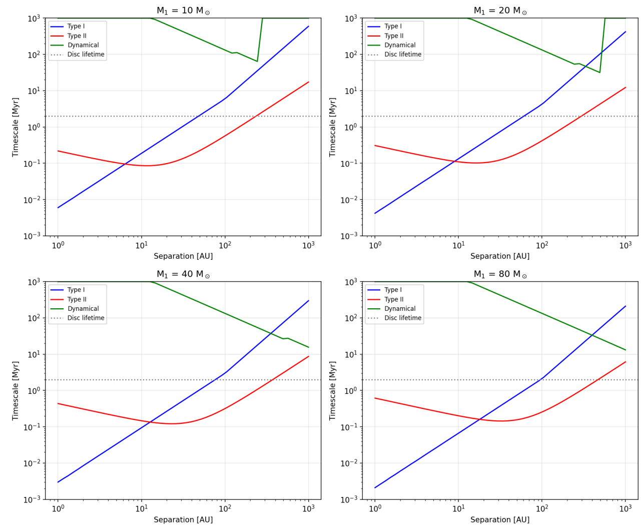

Figure 2: Migration timescales for Type I (blue), Type II (red), and dynamical (green) mechanisms vs separation for four primary masses.

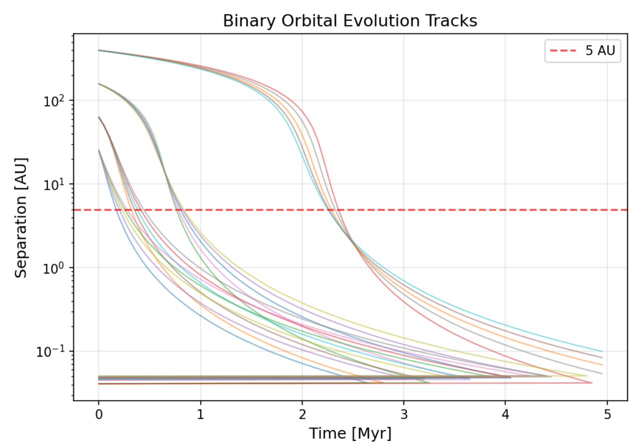

Figure 3: Representative binary orbital evolution tracks showing separation vs time.

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