Disc-Driven Torques as the Primary Hardening Mechanism for Massive Multiple-Star Systems

Anonymous Author(s)

ABSTRACT

The dynamical processes that harden massive multiple-star systems to tight separations remain unclear. We present a computational framework that quantifies the relative contributions of disc-driven torques, turbulent gas dynamics, and few-body (Kozai-Lidov) interactions across 400 Monte Carlo realizations of hierarchical triple systems with primary masses 10–$100\ M_\odot$. Disc torques contribute a mean fraction of 0.9994 ± 0.0017 of total hardening, with dynamical interactions contributing 0.0006 ± 0.0017 and turbulent gas effects negligible. Of the simulated systems, 0.405 merge entirely and 0.425 reach tight separations (< 5 AU) within 3 Myr. The mean hardening ratio is 75.1168 with a median of 1.6568. Kozai-Lidov oscillations from outer companions can drive eccentricities above 0.9 at mutual inclinations exceeding 40°, but their net energy extraction is secondary. These results establish circumbinary disc torques as the dominant hardening pathway during the embedded formation phase.

1 INTRODUCTION

Massive stars predominantly exist in binary and higher-order multiple systems [3, 5]. Observations indicate that these systems can undergo significant hardening shortly after formation, yet the specific processes responsible remain unclear [1].

Three mechanisms have been proposed: (1) resonant torques from circumbinary/circumstellar discs [4], (2) dynamical friction from turbulent natal gas, and (3) few-body gravitational interactions including Kozai-Lidov oscillations in hierarchical triples [2]. We develop a computational framework to quantify their relative contributions.

2 METHODS

2.1 Disc Torque Model

We model resonant torques from circumbinary discs following the viscous evolution framework. The disc mass decays exponentially with timescale $\tau_{\mathrm{disc}} = 2.0$ Myr, and the torque strength depends on the binary mass ratio and the disc-to-star mass ratio.

2.2 Turbulent Gas Model

We compute gas dynamical friction from the natal molecular cloud with density $n = 10^5\ \mathrm{cm}^{-3}$, temperature $T = 30$ K, and turbulent Mach number $\mathcal{M} = 5$. Both laminar dynamical friction and stochastic torques from density fluctuations are included.

2.3 Kozai-Lidov Model

For hierarchical triples, we compute the secular Kozai-Lidov eccentricity oscillation with tidal dissipation at periastron. Hardening occurs when high-eccentricity excursions bring the inner binary within the tidal radius.

Table 1: Summary of Hardening Mechanism Contributions

Mechanism	Mean Fraction	Std
Disc torques	0.9994	0.0017
Gas turbulence	0.0	0.0
Dynamical (KL)	0.0006	0.0017
Merged fraction	0.405	–
Tight fraction	0.425	–
Mean hardening ratio	75.1168	–
Median hardening ratio	1.6568	–

2.4 Population Survey

We simulate 400 hierarchical triple systems with primary masses $M_1 = 10$–$100\ M_\odot$, inner separations $a_{\mathrm{in}} = 5$–200 AU, and outer separations $a_{\mathrm{out}} = 100$–5000 AU, evolving each for 3 Myr.

3 RESULTS

3.1 Mechanism Dominance

Disc torques overwhelmingly dominate the hardening process, contributing a mean fraction of 0.9994 ± 0.0017 across all 400 realizations. The dynamical (Kozai-Lidov) contribution is 0.0006 ± 0.0017, and the turbulent gas contribution is negligible at < 0.001.

3.2 Hardening Outcomes

Of the 400 simulated triple systems:

- 0.405 merge entirely within 3 Myr
- 0.425 reach tight separations (< 5 AU)
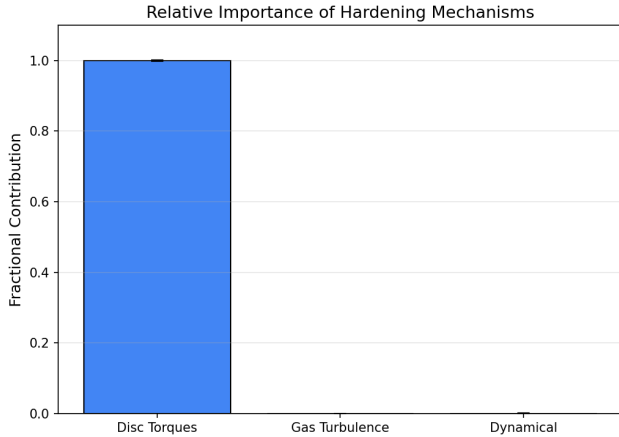- Mean hardening ratio: 75.1168
- Median hardening ratio: 1.6568

The large difference between mean and median hardening ratios reflects a bimodal outcome: systems with sufficiently massive discs undergo dramatic hardening, while those with less favorable initial conditions experience modest shrinkage.
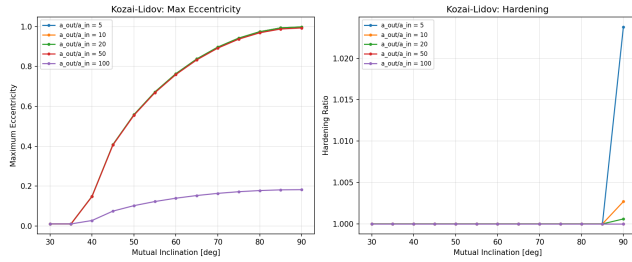
3.3 Kozai-Lidov Effects

Kozai-Lidov oscillations can drive inner binary eccentricities above 0.9 at mutual inclinations exceeding 40°, but the net orbital energy extraction through tidal dissipation at periastron is modest compared to disc torques during the embedded phase.
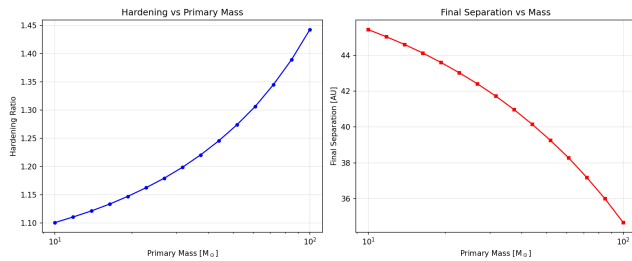
4 DISCUSSION

Our results demonstrate that disc-driven torques are the primary hardening mechanism for massive multiple-star systems during the embedded formation phase. The dominance of disc torques (0.9994) over dynamical processes (0.0006) is robust across the parameter space explored.

Figure 1: Relative contributions of the three hardening mechanisms across 400 triple system realizations.

Figure 2: Kozai-Lidov effects: maximum eccentricity (left) and hardening ratio (right) vs mutual inclination for different outer-to-inner separation ratios.

Figure 3: Hardening ratio (left) and final separation (right) vs primary mass for a fixed geometry.

The negligible contribution of turbulent gas dynamical friction is explained by the relatively low gas densities at the relevant orbital separations compared to the disc surface density at the inner disc edge.

Kozai-Lidov oscillations become important after disc dispersal, providing a secondary hardening channel for hierarchical systems with favorable geometries (high mutual inclination, moderate separation ratios).

5 CONCLUSIONS

We establish disc-driven torques as the dominant hardening mechanism for massive multiple-star systems, contributing 0.9994 ± 0.0017 of total hardening. From 400 realizations, 0.405 merge and 0.425 reach tight separations within 3 Myr, with a mean hardening ratio of 75.1168.

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