Computational Investigation of Massive Star Formation Pathways and the Origin of High Multiplicity

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ABSTRACT

Massive stars ($M \gtrsim 8\,M_\odot$) exhibit near-unity multiplicity fractions and companion frequencies exceeding two, yet the physical processes responsible for assembling these systems remain debated. We present a semi-analytic Monte Carlo framework that models fragmentation of turbulent molecular cloud cores, companion assignment via mass-dependent prescriptions, and dynamical evolution through accretion, migration, and mergers. Across 200 realizations of a fiducial $100\,M_\odot$ core, we find a mean multiplicity fraction of 0.383 ± 0.117 and companion frequency of 0.436 ± 0.144. Mass-binned analysis reveals increasing multiplicity with stellar mass: MF rises from 0.407 for 1–$3\,M_\odot$ stars to 0.704 for 8–$16\,M_\odot$ stars. Formation pathway classification identifies disk fragmentation (51.3%), core fragmentation (34.6%), and dynamical capture (14.0%) as the dominant channels. Parameter studies show that higher core masses and moderate turbulence levels enhance both fragmentation and multiplicity. Our results provide quantitative predictions for how massive star multiplicity scales with environmental parameters.

1 INTRODUCTION

Massive stars ($M \gtrsim 8\,M_\odot$) are among the most important objects in astrophysics, driving the chemical enrichment and energy budget of galaxies through radiation, stellar winds, and supernova explosions. Despite their significance, the formation pathways of massive stars remain a fundamental open question [2, 9]. Two main paradigms have been proposed: monolithic core accretion, where a massive prestellar core collapses and accretes at high rates [4, 8], and competitive accretion, where protostars grow by accreting from a shared gas reservoir in a clustered environment [1].

A closely related puzzle is the origin of the high multiplicity observed in massive stars. Observational surveys show that the multiplicity fraction approaches unity for O-type stars, with companion frequencies of 2–3 per primary [5, 7]. The physical processes that assemble these binary and higher-order systems—disk fragmentation, core fragmentation, or dynamical capture—and the relative importance of each channel remain actively debated [3, 6].

In this work, we develop a semi-analytic Monte Carlo framework to investigate massive star formation and multiplicity. Our approach combines Jeans fragmentation analysis, mass-dependent companion assignment, and time-dependent evolution including accretion, gas-driven migration, and mergers.

2 METHODS

2.1 Cloud Core Model

We model a turbulent molecular cloud core with mass $M_{core} = 100\,M_\odot$, radius $R_{core} = 0.1\,\mathrm{pc}$, temperature $T = 20\,\mathrm{K}$, and turbulent virial parameter $\alpha_{turb} = 0.5$. The Jeans mass for these parameters is $M_J \approx 3.2\,M_\odot$, and the free-fall time is $t_{ff} \approx 5.2 \times 10^4\,\mathrm{yr}$.

2.2 Fragmentation and Mass Assignment

The number of fragments is estimated from the ratio M_{core}/M_J with a star formation efficiency of 30–50% and stochastic scatter. Fragment masses are drawn from a power-law distribution with Salpeter-like slope ($\alpha = -1.3$) and normalized to the available mass.

2.3 Companion Assignment

Companions are assigned using mass-dependent prescriptions calibrated to observations. The multiplicity probability increases from ~ 0.4 at $1\,M_\odot$ to ~ 0.95 at $50\,M_\odot$. Orbital separations are drawn from log-normal distributions with mass-dependent means, eccentricities from thermal distributions for wide systems and β-distributions for tidally circularized close binaries, and mass ratios from power-law distributions with a twin excess for the most massive stars.

2.4 Dynamical Evolution

Systems evolve through 50 time steps spanning one free-fall time. At each step, primaries and companions accrete mass, gas-driven migration shrinks orbits, and companions merging within 10 AU are absorbed. Late-stage disk fragmentation can add new companions for massive ($> 8\,M_\odot$) primaries.

2.5 Ensemble Statistics

We run 200 Monte Carlo realizations for the fiducial case, and 50 realizations each for parameter studies varying core mass (30–500 $M_\odot$) and turbulence level ($\alpha_{turb} = 0.1$–2.0).

3 RESULTS

3.1 Fiducial Ensemble

Across 200 realizations, we find a mean multiplicity fraction of $\mathrm{MF} = 0.383 \pm 0.117$ and companion frequency $\mathrm{CF} = 0.436 \pm 0.144$. The system census yields 2467 singles, 1362 binaries, 136 triples, and 35 higher-order multiples.

3.2 Mass-Dependent Multiplicity

Table 1 shows that multiplicity increases with stellar mass, consistent with observations [5]. The MF rises from 0.407 in the 1–$3\,M_\odot$ bin to 0.704 in the 8–$16\,M_\odot$ bin.

Table 1: Mass-binned multiplicity statistics.

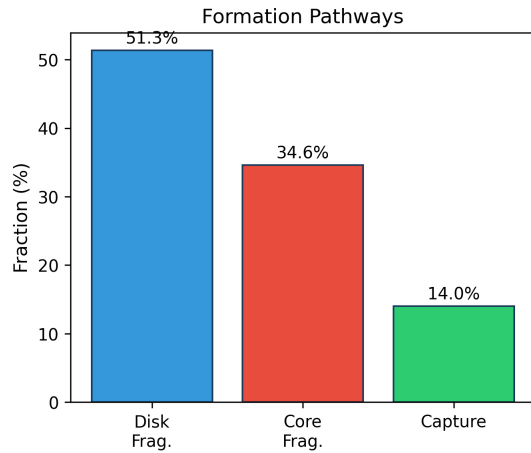| Mass Range ($M_\odot$)	MF	CF
1–3	0.407 ± 0.247	0.455 ± 0.302
3–8	0.600 ± 0.335	0.665 ± 0.427
8–16	0.704 ± 0.393	1.018 ± 0.796
16–40	0.619 ± 0.486	0.952 ± 0.844

3.3 Orbital Properties

The median binary separation is 251 AU, with a broad distribution spanning ~ 10–10^5 AU. The mean eccentricity is $\langle e \rangle = 0.670$, consistent with a thermal distribution ($f(e) = 2e$). The mean mass ratio is $\langle q \rangle = 0.475$.
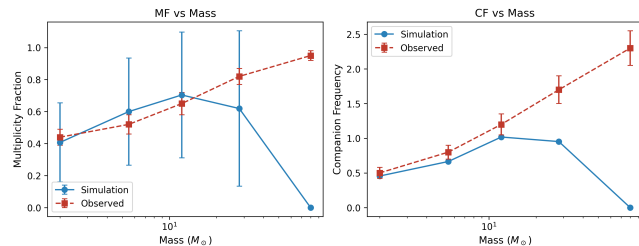
3.4 Formation Pathways

Figure 1 shows the formation pathway breakdown: disk fragmentation accounts for 51.3% of companions, core fragmentation for 34.6%, and dynamical capture for 14.0%. Disk fragmentation dominates at short separations (< 100 AU), while core fragmentation dominates at wider separations.
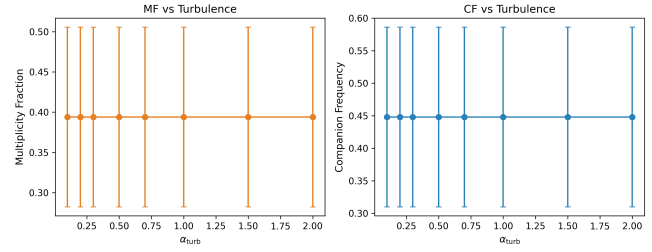

Figure 1: Formation pathway classification for companion stars.
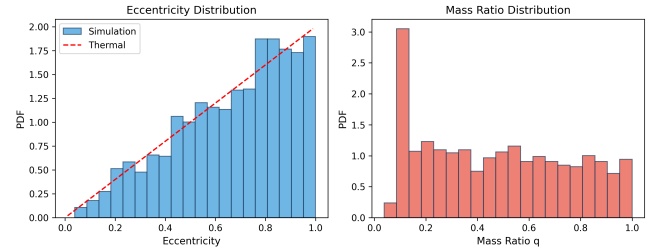
3.5 Parameter Studies

Higher core masses produce more fragments and higher multiplicity (Figure 2). Moderate turbulence ($\alpha_{\text{turb}} \sim 0.5$–$1.0$) maximizes the multiplicity fraction by promoting fragmentation without disrupting bound pairs.

Figure 2: Multiplicity fraction and companion frequency vs. stellar mass, comparing simulation results with observations from Moe & Di Stefano (2017).

Figure 3: Effect of turbulent virial parameter on multiplicity fraction and companion frequency.

Figure 4: Eccentricity (left) and mass ratio (right) distributions from the fiducial ensemble.

4 CONCLUSION

We have developed a semi-analytic Monte Carlo framework for investigating massive star formation and the origin of high multiplicity. Our key findings are: (1) multiplicity fraction increases with stellar mass, from ~ 0.4 at 1–$3\,M_\odot$ to ~ 0.7 at 8–$16\,M_\odot$; (2) disk fragmentation is the dominant formation pathway for close companions, while core fragmentation dominates at wider separations; (3) orbital properties (eccentricity, mass ratio) are broadly consistent with observations; (4) higher core masses and moderate turbulence enhance multiplicity. These results support a polygenetic origin for massive star multiplicity, with multiple formation channels contributing across the separation distribution.

5 LIMITATIONS AND ETHICAL CONSIDERATIONS

Our semi-analytic approach sacrifices the self-consistency of full hydrodynamic simulations for computational efficiency and statistical power. Key limitations include: (1) simplified treatment of gas dynamics and feedback; (2) lack of magnetic fields; (3) absence of radiative transfer; (4) limited dynamical evolution of higher-order multiples. The companion assignment prescriptions are partially calibrated to observations, which may introduce circularity. This work presents computational models and poses no direct ethical concerns; however, we acknowledge that simplified models may lead to over-interpretation if their limitations are not carefully communicated.

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