Numerical evidence for the formation and ejection of the Pistol star from the Quintuplet cluster

Taotao Yang[1], Eirini Chrysovergi[1], Marc Seegers[1]

[1] Leiden Observatory, Leiden University, P.O. Box 9513, Leiden, 2300 RA, South Holland, The Netherlands .

Contributing authors: tyang@strw.leidenuniv.nl; chrysovergi@strw.leidenuniv.nl; seegers@strw.leidenuniv.nl;

Abstract

The Pistol star is one of the most massive stars in the Milky Way, with estimated mass between $\mathbf{100-200}\ \boldsymbol{M_\odot}$. Located close to the Galactic Center adjacent to the Quintuplet cluster, high-resolution infrared observations of the Pistol star's nebula have revealed observational evidence for its ejection from the cluster. In this article, we perform scattering simulations of three equal-mass binaries with each star at $\mathbf{50}\ \boldsymbol{M_\odot}$ to demonstrate the ejection scenario and constrain the formation history of the Pistol star. The results indicate that successive hierarchical collisions in the presence of already massive stars would efficiently assemble stars exceeding $\mathbf{90}\ \boldsymbol{M_\odot}$, followed by its ejection with velocities easily reaching $\mathbf{70\ km/s}$. The simulations yield results consistent with Pistol star's observed velocity of $\mathbf{60-95\ km/s}$.

1 Introduction

Massive stars in our Universe play a major role in shaping their environments through intense radiative feedback, stellar winds, and mergers. However, their formation mechanisms are still poorly understood. Conventional models assume isolated stellar evolution and fail to account for stars reaching masses of $\sim 100\ M_\odot$. Star clusters provide rich environments for stellar collisions and mergers to enable rapid assembly of massive stars.

The Pistol star, with $\sim 100\ M_\odot$ and luminosities reaching $10^{6.6} L_\odot$ [1] is located close to the Galactic Center [2] adjacent to a young (4 Myr), massive ($\sim 10000\ M_\odot$) dense star cluster, the Quintuplet cluster [3]. High-resolution observations provided

evidence for the Pistol star's ejection from the cluster, with estimated velocities at $60 - 95$ km/s [2].

We test this scenario by conducting scattering simulations of three equal-mass binaries, sampling through a 19-dimensional parameter space. We classify quantitatively the massive remnants exceeding 90 $M_\odot$ with resulting cross-sections and velocity distributions.

2 Results

We observe that $2,955\,(\sim 3\%)$ out of $100,000$ scattering simulations produce ionized outcomes through hierarchical collisions with remnant masses $> 90\ M_\odot$ as shown in Fig. 1. We notice that remnants of 100 $M_\odot$ order of magnitude cluster at $1 - 8$ km/s, while remnants of 180 $M_\odot$ reach 100 km/s, matching Pistol star observations at $60 - 95$ km/s. Furthermore, the spin range is between $3 \times 10^{-7}\mathrm{s}^{-1}$ to $3 \times 10^{-6}\mathrm{s}^{-1}$, corresponding to periods of 1-10 days, echoing spin ranges of Main Sequence stars ([4]). Further shown in Fig. 2, we observe a cross-sections of ejection σ that increase monotonically with impact parameter ρ, eccentricity e, separation s, and velocity ν_{mag} before plateauing.

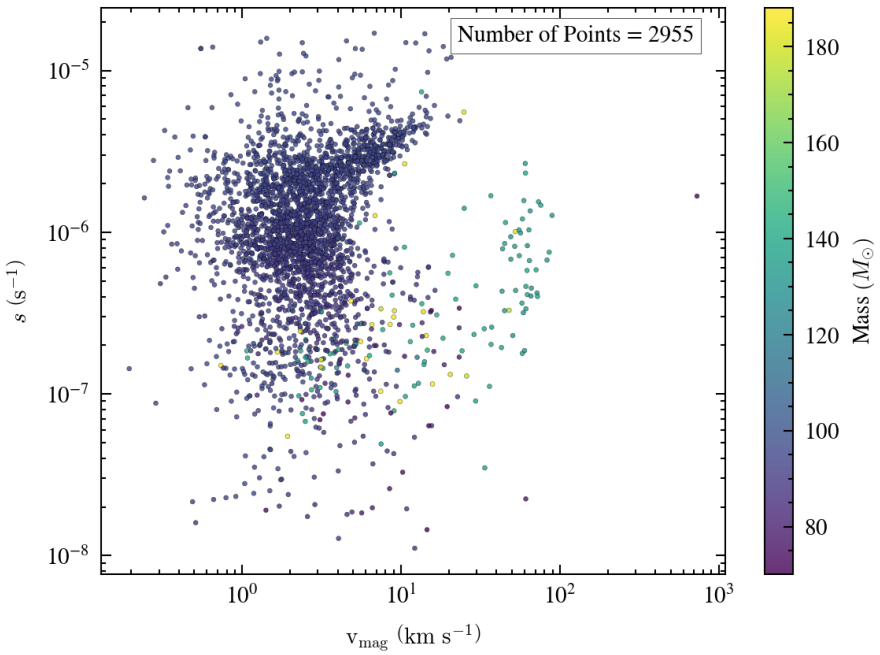


Fig. 1 Mass of stars in ionized outcome, with successive hierarchical collisions mapped against their spins s and velocities ν_{mag}. Figure records 2,955 cases out of 100,000 simulations, where hierarchical collisions have lead to ionized outcomes.

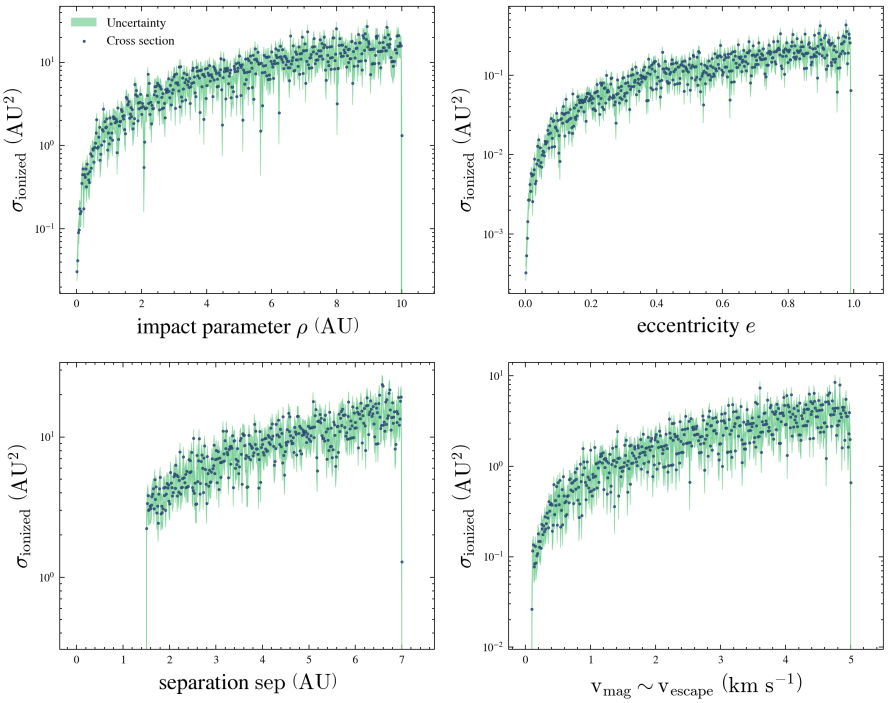


Fig. 2 Cross-section σ of ejection against sampled parameters including impact parameter ρ, eccentricity e, separation s, and velocity $\nu_{\rm mag}$. Plot shows wide flybys with $\rho \gtrsim 2$ AU dominate.

3 Methods

We perform scattering simulations of three binaries of equal, 50 $M_\odot$ masses. These encounters are modeled using the Astrophysics Multipurpose Software Environment (`AMUSE`) [5–9], following the general scattering formalism of Hut and Bahcall [10]. We design a software package to quantitatively understand the probability of hierarchical collisions that produce ionized remnants with mass > 90 $M_\odot$ that are ejected from the system.

3.1 Initial conditions

The initial conditions are set by the three interacting binaries of equal 50 $M_\odot$, parameterized with intrinsic parameters including eccentricity e, separation s (AU), true anomaly f, impact parameter ρ (AU), velocity $\nu_{\rm mag}$, and impact orientations ϕ, θ, ψ. For simplicity, we assume that one of the binaries resides at origin with zero velocity. Effectively, we initialized a system with geometry as shown in Fig. 3 with parameter space Θ given in Eq. (1).

$$\vec{\Theta} = \left[\vec{e},\ \vec{s},\ \vec{\nu}_{\rm mag},\ \vec{\rho},\ \vec{\theta},\ \vec{\phi},\ \vec{\psi},\ \vec{f},\ \vec{m}\right] \tag{1}$$

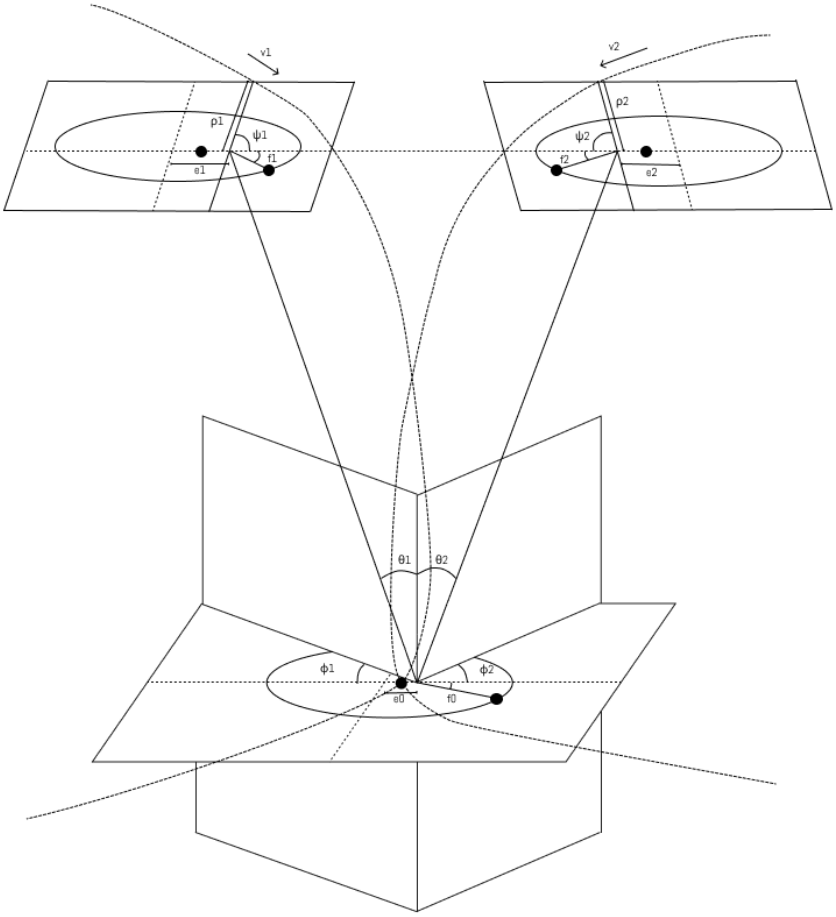


Fig. 3 Initial configuration of our three binary encounter. Each binary have its own eccentricity, separation and true anomaly f. We control the impact through the impact orientation ϕ, θ, ψ, as well the impact parameter ρ, expressed in AU. We control the velocity of the incoming binaries which, in our simulation, express in dimensionless escape velocities. For all the stars in this configuration, we assume an equal mass of 50 $M_{\odot}$ and an initial distance of 100 AU.

3.2 Simulations

We perform the simulations by first evolving the six-body system with stellar evolution code `SeBa` over 3.5 Myrs, a timescale comparable to the estimated age of the Quintuplet cluster. We couple the stellar evolution with a fourth order Hermite gravitational integrator, `ph4`. We resolve the collisions adopting `fi`, a second-order integrator that enables Smoothed Particle Hydrodynamics (SPH) for handling close encounters of this six-body system. The stars are presented as uniform spheres with 1000 SPH particles and the close encounters are processed via SPH for a duration of 0.1 yrs, allowing sufficient time for close encounters. Through this selection we ensure

that we can simulate efficiently large deformations, shocks or mass stripping in a fully Lagrangian approach. Upon collisions, the properties of the remnant are calculated and updated for the simulation.

An important feature of our implementation is that we allow hierarchical collisions to occur. More precisely, we set a stopping condition, where we check every 50 yrs to classify the current state of the system into outcomes that signal the end of the simulations: (1) a desired ionization outcome with remnant mass of $>$ 90 $M_{\odot}$; (2) systems consisting of single ionized stars; or (3) compact bound systems with sufficiently large mutual separations. In principle, the above outcomes signify that either the desired result is achieved or further collisions will not happen in our system. A schematic overview of our work flow can be seen in Fig. 4. We also parallelize the simulation over multiple CPU cores to allow for rapid calculations.

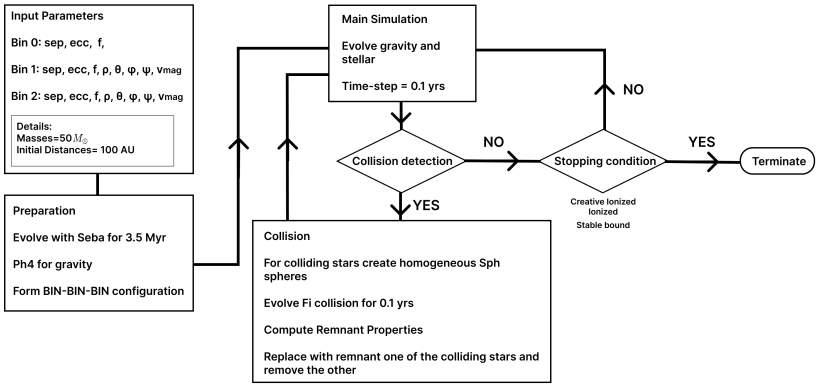


Fig. 4 Simulation flowchart resolving triple-binary encounter evolution. Simulation processes take input parameters and evolve with `SeBa`, `ph4`, and `fi`. When reaching stopping conditions, the simulation terminates and we record the results. We implement parallelism on CPU to run multiple simulations simultaneously.

3.3 Cross-sections

We estimate the differential cross-section of an ionized outcome, by the effective impact area that led to that specific, desired, result. In general, the cross-section σ is given by the impact parameter ρ and its probability $P(\rho)$, dependent on the generated parameter we pass into the simulation:

$$\sigma = \int_0^{\rho_{max}} 2\pi P(\rho) d\rho \tag{2}$$

To estimate the corresponding cross-section, we sample the 19-dimensional parameter space according to the ranges listed in Tab. 1. We employ Latin Hypercube sampling to ensure stratified coverage across all dimensions, improving convergence and reducing clustering compared to uniform sampling [11, 12].

Variable	Binaries	Ranges	Description
s	0, 1, 2	$(0, 7]$	Orbital separation
e	0, 1, 2	$[0, 1)$	Initial eccentricities
f	0, 1, 2	$[0, 2\pi)$	Projected true anomaly
$\nu_{\rm mag}$	1, 2	$[0, \infty)$	Incoming velocity
ρ	1, 2	$[0, \infty)$	Impact parameter
ϕ	1, 2	$[0, 2\pi)$	Impact orientation
θ	1, 2	$[0, \pi/2]$	Impact orientation
ψ	1, 2	$[0, 2\pi)$	Impact orientation

Table 1 Sampled parameters for simulations.

Adopting the formalism in Eq. (2), we constrain the cross-section and project it to our parameters of interest. In Fig. 2, we show a clear correlation for the cross-section probability over parameter ρ, e, s, and $\nu_{\rm mag}$.

4 Discussion

With our simulations, we provided numerical evidence for the formation and ejection of the Pistol star from the young, massive Quintuplet cluster. Mergers of $\sim 50 M_\odot$ stars lead to creative collisions. This result favors the hypothesis that massive stars are products of hierarchical collisions [13]. Additionally, this scenario contradicts the conventional stellar evolution, where stars reach their mass through a slow timescale at the order of magnitude of $\sim$ Myrs based on nuclear fusion in their stellar interior. Instead, massive stars are able to acquire their mass through successive mergers due to close encounters.

We assume pre-existing massive stars within a cluster, supported by the mass of the Quintuplet cluster ($\sim 10,000\ M_\odot$) [3]. Therefore, massive stars of $\sim 50\ M_\odot$ could have already formed through potential mergers of smaller $\sim 10\ M_\odot$ stars in the cluster. We initialize the simulation with these stars in tight binaries to reflect the importance of the binary separation and the presence of bound systems for our desired, ionization outcome. We choose the initial distances of the incoming binaries at 100 AU, a value ~ 10 times higher than the separation range, to ensure that the gravitational interaction of our initial setup is minimal. This way, the incoming binaries are approaching from an effectively large distance. By adopting a translation to escape velocities, we control whether the interaction was gravitationally focused ($\ll \nu_{\rm esc}$), marginally bound ($\sim \nu_{\rm esc}$), or effectively hyperbolic ($> \nu_{\rm esc}$).

From the cross-section results, we notice a preference for wide flybys ($\rho \gtrsim 2\,{\rm AU}$) over head-on collisions. This is reflected in the geometric selection: larger impact parameters sample more of the interaction volume while maintaining sufficient pericenter proximity for mergers. More eccentric binaries further enhance this coverage

through closer encounters and velocity spikes [14]. In addition, the separation shows that wider binaries are easier to collide and get ejected, although our initial range was already biased for that. Last but not least, the velocity figure shows that high relative velocities allow encounters to sample a larger effective cross-section area, leading to more creative ionized outcomes. Overall, the $\sim 3\%$ success rate indicates such events are plausible within young clusters similar to the Quintuplet cluster.

In our simulations, we recorded the final achieved mass, velocity, and spin of the creative ionized stars. We compare these numerical results with the observational evidence. We illustrate that the remnants of hierarchical collisions fall into two general cases: (1) stars with $\sim 100\ M_\odot$ remain clustered at $1-8$ km/s; (2) more massive stars with $\sim 160\ M_\odot$ reflecting high $\nu_{\rm eject}$. An outlier case of $\sim 90\ M_\odot$ star is discovered with $\nu_{\rm mag} \sim 1,000$ km/s. Although this outlier case remains puzzling, its presence is statistically marginal comparing to the other events.

Consequently, we acknowledge the limitation in mass parameter sampling. More precisely, by fixing the mass of triple-binary systems to be identical, we have introduced a special case for dynamic interactions. Additionally, by treating the stars as uniform spheres with 1,000 SPH particles, we are at risk of oversimplifying the hydrodynamic interactions between stars in terms of resolution and mass exchange for massive remnants. We implement these limitations as a compromise for achieving efficient calculations over large samples. However, we have demonstrated that hierarchical collisions are more likely to contribute to the massive star formation than its conventional stellar evolution mechanism.

5 Conclusion

We performed numerous scattering simulations with equal-mass six-body systems to quantitatively support Pistol star formation through hierarchical collisions in the Quintuplet cluster. These results demonstrate Pistol star as ionized outcome of hierarchical collisions, with mass consistently surpassing $90\ M_\odot$, consistent with observational evidence [2]. It is therefore shown that dense stellar clusters allow for rapid formation of high mass stars through collisions over conventional stellar evolution. We estimate a $\sim 3\%$ probability of equal-mass triple-binary to generate remnants resembling the characteristics of Pistol star. Future improvements should focus on adapting the existing simulation run to allow for arbitrary input of configurations of binary and trinary systems, thus scaling the parameter space to even higher dimensions to explore novel outcomes of these potential interactions.

Declarations

Code availability. Source code listing, example datasets, and documentations are available on GitHub at https://github.com/yourusername/strw-amuse-project.

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