The contribution of binary star formation on core-fragmentation scales on protostellar multiplicity

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ABSTRACT

Context. Observations of young multiple star systems find a bimodal distribution in companion frequency and separation. The origin of these peaks have often been attributed to binary formation via core and disc-fragmentation. However, theory and simulations suggests that young stellar systems that form via core-fragmentation undergo significant orbital evolution.

Aims. Using simulations of star formation in giant molecular clouds we investigate the influence of environment on multiple star formation pathways and the contribution of core-fragmentation is on the formation of close (<100 AU) binaries.

Methods. Simulations are run with the adaptive mesh refinement code RAMSES with sufficient resolution to resolve core-fragmentation beyond 400 AU and dynamical evolution down to 16 AU, but without the possibility of resolving disc-fragmentation. The evolution of the resulting stellar systems is followed over millions of years.

Results. We find that star formation in lower gas density environments is more clustered, but despite this, the fractions of systems that form via dynamical capture and core-fragmentation are broadly consistent at ∼40% and ∼60% respectively. In all gas density environments, we find the typical scale at which systems form via core-fragmentation is 10²⁻³⁻⁵ AU. After formation, we find that systems that form via core-fragmentation have slightly lower inspiral rates (∼ 10⁻¹⁻⁵ AU/yr measured over first 10000 yr) compared to dynamical capture (∼ 10⁻¹⁻³⁻⁻⁵ AU/yr). We then compared the simulation with conditions most similar to the Perseus star forming region to determine whether the bimodal distribution observed by Tobin et al. (2016b) can be replicated. We find that it can be replicated, but it is sensitive to the evolutionary state of the simulation.

Conclusions. Our results indicate that a significant number of binary star systems with separations <100 AU can be produced via non-disc-fragmentation pathways due to efficient inspiral, suggesting disc-fragmentation is not the dominant formation pathway for low-mass close binaries in nature.

Key words. Star Formation – Binary stars; Simulations – MHD

1. Introduction

Around half of all stars exist in binary or multiple star systems (Moe & Di Stefano 2017), and many are born with a companion (Chen et al. 2013). Models of star and planet formation must account for this multiplicity.

The main proposed pathways for binary star formation are:

1. Disc-fragmentation (a ≤ 100 AU): can occur in massive, gravitationally unstable (i.e. Toomre Q parameter < 1) protostellar discs, if the gravitationally unstable regions are able to efficiently cool (Gammie 2001). This has been modelled in simulations (Takaishi et al. 2021), and with high angular resolution imaging, it is possible to see what could be the outcome of disc-fragmentation observationally (Tobin et al. 2016a). Bate (2019) investigated the dependency of metalliclicity on fragmentation and find in their models that 15 – 20% of systems formed via this pathway.

2. Core-fragmentation (100 AU ≤ a ≤ 10000 AU): occurs in turbulent protostellar cores. Simulations of core-fragmentation into binaries have often displayed significant orbital migration from their initial separation (Ostriker 1999, Wurster et al. 2018, Lee et al. 2019, Kuruwita et al. 2020, Saiki & Machida 2020), and separations can shrink due to the ejection of tertiary companions (Armitage & Clarke 1997) down to <100 AU. Observations of wide binaries with mis-aligned discs have also been attributed to formation via core-fragmentation (Lee et al. 2017).

3. Dynamical Capture: In dense stellar environments it is possible for stars that are marginally unbound to become bound or vice versa (Parker & Meyer 2014). There is observational evidence to support that primordial wide binaries formed in clusters can disintegrate (Elliott & Bayo 2016). There is also evidence suggesting a third of multiple stars did not form together and instead became bound via dynamical interactions (Murillo et al. 2016).

Observations of the companion frequency distribution of protostars have found a bimodal distribution (Tobin et al. 2016b 2022). For the Perseus molecular cloud, Tobin et al. (2016b) finds a peak at approximately 75 AU and 3000 AU. The authors suggested that the peak at 75 AU is caused by disc-fragmentation, while the peak at 3000 AU is likely caused by fragmentation of protostellar cores. They hypothesise that core-fragmentation is a dominant mechanism for system with separations >200 AU. However, the authors also hypothesise that the lack of binaries with separations >1000 AU may be due to rapid in-spiralling to lower separations.

Surveys of circumstellar disc sizes find the average radius to be ≤75 au (Cox et al. 2017, Ansdel et al. 2018) for low-mass young stars and the very large and massive discs that could fragment to form stars are uncommon. While there is evidence that
disc-fragmentation can form close binaries, it is unlikely to be the sole source of binaries with separations of ~10s of au.

In this work we investigate the contributions of core-fragmentation and dynamical capture to the origin of the observed bimodal separation distribution. We run multiple simulations of star formation from giant molecular clouds with different initial masses, to investigate how the environment may influence formation pathways for multiple star systems, and orbital evolution of these systems.

In Section 2 we cover the RAMSES code and the simulation set up. In Section 3 we look at the formation and evolution of the multiple star systems that form, including a comparison with observations. In Section 4 we discuss the overall results of this work and the implications. In Section 5 we discuss some of the limitations of this paper and suggestions for future work.

2. Method

2.1. Simulation set-up

We use a locally developed version of the publicly available magnetohydrodynamics (MHD) Adaptive mesh refinement (AMR) code Ramses (Teyssier 2002), which is described in Haugbølle et al. (2018). The simulation setup is a 4 pc box with an isothermal equation of state and solenoidal turbulent driving resulting in a typical velocity dispersion of 2 km s$^{-1}$, with periodic boundary conditions. Six simulations were run with initial gas masses of 1500, 3000, 3750, 4500, 6000 and 12000 $M_\odot$. The box contains a magnetic field of 7.2 $\mu$G, initially aligned with z-axis, corresponding to an alfvenic Mach number of 5. The simulations ran until a star formation efficiency (SFE) of at least 0.05 was reached. The SFE is defined as the fraction of the initial gas mass that is accreted onto sink particles. The refinement strategy is based on the overdensity. We refine the root grid when the density reaches a threshold density such that the Jeans length is resolved by 14.4 cells, and then refine the grid every time the density increases by a factor of four, keeping the minimum number of cells per Jeans length constant on all levels, except the highest level of refinement. Sink particles are allowed to form on the highest level of refinement from gas that has reached a density corresponding to resolving the Jeans length with at least 2 cells. The maximum resolution is 50 AU, and the density threshold for sink formation is $1.7 \times 10^5$ cm$^{-3}$. Details of each simulation are summarised in Table 1.

| $M_{gas}$ | $T_{end}$ (T$_5$) | SFE | $M_*$ ($M_{*,5}$) | $N_*$ ($N_{*,5}$) |
|---|---|---|---|---|
| $M_\odot$ | Myr | $\%$ | $M_\odot$ | |
| 1500 | 26.8 (26.8) | 5 | 75 (75) | 86 (86) |
| 3000 | 25.0 (23.8) | 13 | 393 (150) | 413 (191) |
| 3750 | 23.7 (23.5) | 7 | 252 (187) | 411 (313) |
| 4500 | 23.5 (23.2) | 8 | 341 (225) | 506 (394) |
| 6000 | 23.0 (22.8) | 8 | 461 (300) | 895 (624) |
| 12000 | 22.5 (22.4) | 8 | 923 (600) | 2474 (1795) |

Table 1: Columns show the initial gas mass ($M_{gas}$), simulation duration ($T_{end}$), final star formation efficiency (SFE), final total mass in sink particles ($M_*$) and final number of sink particles produced ($N_*$). The values in parenthesis are the corresponding column value at SFE=0.05.

This sink particle prescription is similar to others used in different MHD codes (Bate et al. 1995; Krumholz et al. 2004; Federrath et al. 2010; Gong & Ostriker 2013). When a sink particle forms, it initially has no mass, but mass is accreted from cells within the accretion radius ($r_{acc}$). In our simulations $r_{acc} = 4$ cells. The accretion rate, $\dot{m}$, in the time step is dependant on the gas density, distance of the gas to the sink
Fig. 2: Projections of the density over the entire computational domain from the formation of the first sink (Left column) to SFE = 0.05 (Right column), for each simulation. The sink particles are annotated with blue particles. The colour bars are logarithmically centred on the mean gas density of the initial gas distribution.
Fig. 3: Illustrates the three formation pathways that a system with a new sink ID is classified into: Top: If a sink is formed and is gravitationally bound to another star at birth, this is bound core-fragmentation, Middle: If a sink is formed and is gravitationally unbound at birth, but later becomes bound to the sink it was most bound to at birth, this is unbound core-fragmentation, and Bottom: If a sink is formed and is gravitationally unbound at birth, and later becomes bound to a sink that is not the sink it was most bound to at birth, this is dynamical capture.

3. Results and discussion

The evolution of the total accreted mass, number of stars, and SFE of all simulations are shown in Figure 1 and values are summarised in Table 1. Figure 1 shows that simulations with higher initial gas mass have a higher star formation rate (Padoan & Nordlund 2011; Padoan et al. 2012; Federrath & Klessen 2012) and also a higher rate of stars formed (Haugbølle et al. 2018) in accordance with theory. The high mass simulations also begin to produce sink particles earlier than the lower mass simulations, with the first sinks in the 12000 $M_\odot$ simulation forming around 22 Myr, while the 1500 $M_\odot$ simulation begins forming its first sinks around 23 Myr, as shown in Table 1.

Projections of the density for each simulation is shown in Figure 2. Each row is a simulation and each column shows a projection for SFE=0%, 1.7%, 3.3%, and 5% respectively. The colour bars are centred logarithmically on the initial mean gas density of each simulation (defined as $M_{gas}/4pc^3$), and have the same range. This was chosen to visualise degrees of gas concentration between simulations. The sink particles are annotated by blue dots. From the projections we see that most sink particles reside in regions of high column density, which, in particular at early times, is close to their region of birth.
Fig. 4: Separation vs SFE of all systems formed in each simulation. The markers indicate the formation pathway of the system if it contains a new sink id. Blue boxes: Bound core-fragmentation, purple triangles: unbound core-fragmentation, red circles: dynamical capture.
3.1. Identifying multiple star systems and their formation pathways

As the sink particles accrete and interact, multiple star systems form and disintegrate. Multiple star systems were identified by:

1. Finding the sink particle pairs that are below a separation threshold and gravitationally bound (where the \( E_{\text{potential}} + E_{\text{kinetic}} = E_{\text{total}} < 0 \)). For our work, the maximum separation is set to 10,000 AU.
2. Sort pairs from lowest to highest separation.
3. A new ‘particle’ is saved with the position being the centre of mass of the bound sink particle pair and mass that is the total mass of the particle pair.

This process is carried out iteratively, until all bound systems with up to six components are identified. Six components is chosen as the maximum number of stars in a system, because higher multiples systems tend to be short-lived with very weakly bound outer companions in a highly dynamical environment, such as close to the hub-like clusters in the simulations. Sextuples are also the largest systems identified in the observations by Tobin et al. (2016b). When comparing with observations we change the approach for identifying multiple systems, since three dimensional distance and energies are not available for observations. This is discussed in Section 8.5.

When iterating, to avoid double counting sink particles that are already in a bound systems, only systems are used to calculate pairs. These are either an actual sink particle if it is single, or one of the systems that was created to collapse a bound pair.

As highlighted in Section 2.1.1 with given the numerical resolution in our models, we can only capture core-fragmentation. However, some sink particles can form isolated and unbound, but later become bound to another star. We use the birth conditions of a sink particle found in a binary/multiple to determine the pathway in which the system formed. We chronologically check bound systems, and if a new sink particle ID is found, we determine the system’s formation pathway using the following criteria:

1. **Bound core-fragmentation**: If a sink is form bound to another sink or system of sinks, then it was formed via bound core-fragmentation.
2. **Unbound core-fragmentation**: If a sink is formed unbound, but the sink or systems of sinks it was most bound to at birth is in the current multiple system, then it was formed via unbound core-fragmentation.
3. **Dynamical capture**: If a sink is formed unbound, and the sink or system of sinks it was most bound to at birth is not in the current multiple system, then it was formed via dynamical capture.

These formation pathways are illustrated in Figure 3. For systems with more than two stars, the formation pathways is determined by the newest sink particle ID i.e. the most recently formed star. This classification only rely on the energetics of the sink particles, and not that of the gas. Therefore, some of the systems found to be formed by unbound core-fragmentation may in reality be bound, when making a detailed account of the gas distribution. We have chosen not to do this, since it would entail relating different volume elements to different sink systems, which is not easily done in a unique manner, and beyond the scope of this article.

In Figure 4, we plot the separations of all multiple systems for each simulation. For binaries, this is the true separation, but for higher order multiples, this may be the separation between stars and the centre of mass of an inner system, or two centres of masses, depending on the system configuration. If a new sink particle ID is found in a system, we also annotate its formation pathways with a marker at the initial separation of the system. In Figure 5 the blue boxes indicate systems that formed via bound core-fragmentation, the purple triangles indicate systems that formed via unbound core-fragmentation, and the red circles indicate systems that formed via dynamical capture. We see that all formation pathways occur throughout the simulations. We also see in each panel that many systems experience rapid orbital shrinkage, where the final separations of the systems is more than an order of magnitude smaller than the initial separation.

In Figure 5 we plot the fractions of systems that form via the different pathways for each simulation. The fractions are broadly consistent over all simulations. The fraction of systems formed via bound core-fragmentation varies between 35−45%, unbound core-fragmentation varies between 10−25%, and dynamical capture varies between 35−50%.

When looking at only the systems that are born unbound, in the lowest mass simulations, more than a third of these systems follow the unbound core-fragmentation pathway. This drops to 20% in the highest mass simulations. The inverse correlation between whether a star that is born unbound and later becomes bound to the star it was most bound to, or another star, may be due to the increasing stellar density with gas mass. In higher stellar density environments the likelihood of dynamical capture would increase.

Overall, the fractions of systems formed via core-fragmentation (bound and unbound) is slightly higher in the lower mass simulations. This may be because the lower mass simulations require a larger over density in order for protostellar cores to collapse, and this results in more systems forming via the core-fragmentation pathways. This implies that star formation in lower mass GMC is more clustered than in higher mass one.
3.2. Measuring clustering with two point correlation function

In this section we measure three-dimensional two point correlation functions (TPCF) to gain an insight into how clustered the sink particles distributions are in each simulation. A TPCF quantifies clustering by measuring all possible separations between points (for N stars, the number of separations is \(N(N-1)/2\)) and binning the separations into logarithmic separation bins \(r\). This is calculated for the observed data points \(P_{DD}(r)\) and for randomly generated points that are uniformly distributed \(P_{RR}(r)\). These two distributions are normalised using the number of data points and randomly generated stars to obtain:

\[
DD(r) = \frac{P_{DD}(r)}{N_D(N_D - 1)}, \quad RR(r) = \frac{P_{RR}(r)}{N_R(N_R - 1)},
\]

where \(N_D\) and \(N_R\) is the number of data points and randomly generated points respectively. The basic TPCF (Peebles 1980) is derived by dividing the normalised distribution of the data \(DD(r)\) by the normalised distribution of the random points \(RR(r)\), i.e.:

\[
1 + \omega(r) = \frac{DD(r)}{RR(r)}
\]

If the data is clustered, the resulting TPCF will have values \(\gg 1\) in smaller separations and typically has a power law function as a function of separation with a negative slope.

In order to calculate a TPCF an underlying distribution must be derived, for comparison. Given the periodic boundary conditions of our simulation, the largest separation two sinks can have is \(\sqrt{3(L/2)^2} \sim 3.5\,\text{pc}\) which is equivalent to \(\sim 7 \times 10^3\,\text{au}\). With this largest separation and the smoothing length of 16.6 au, 10 separation bins spaced logarithmically between \(10 - 10^6\,\text{au}\) were selected to calculate the TPCF. In order to derive the underlying distribution, \(5 \times 10^5\) positions were randomly generated within the simulation domain, and separations were calculated. The large number of randomly generated positions was necessary in order to populate the smallest separation bin. 100 instances of \(5 \times 10^5\) randomly generated positions was performed, and the final underlying distribution \(P_{RR}(r)\) was taken to be the mean of these 100 instances, and the error is the standard deviation in a separation bin over the 100 instances.

For the simulations, the distribution \(P_{DD}(r)\) is derived by calculating all separations between stars and binning the separations. The error of this distribution is taken to be the Poisson noise, because of the low number of stars per separation in the simulation, i.e. \(\sigma_{P_{DD}}(r) = \sqrt{N}\).

The TPCFs for all simulations at SFE = 0.05 is shown in Figure 6. The error bars for the TCFP is derived by summing the relative errors of DD\((r)\) and RR\((r)\). After calculating the TPCF a power-law is fit to the function, with a steeper slope indicating stronger clustering. At SFE = 0.05, the lower mass simulations show stronger clustering, however, this is only at one snapshot in time.

To understand how the clustering evolves over the course of the simulations, TPCFs were calculated for every time step over each simulations, and power-law fits were derived. In Figure 7 we plot the median gradient of the power-law for each simulation smoothed over a window of SFE 0.05%, and the shaded region shows the standard deviation. Initially the gradient is not well constrained due to the low number of sink particles. After SFE \(\approx 0.02\), the \(M_{gas} = 1500\,M_\odot\) simulation consistently has stronger clustering over the course of the simulations, while the higher mass simulations typically have shallower gradients. This is consistent with the hypothesis that the lower mass simulations produces more multiple star systems via core-fragmentation pathways due to stronger clustering.

Observationally, the two-point correlation functions in the nearby Taurus, \(\rho\) Oph, and Orion regions are found to be a power law with exponents in the range \(-2 < \beta < -1\) (Gomez et al. 1993; Larson 1995; Gomez & Lada 1998), which compares well to our results, given that exponent should be increased by one when projecting from three to two dimensions.

3.3. System formation scales

The star forming environment may affect the initial separation of systems formed via core-fragmentation pathways, which might give insight into a fragmentation scale. In Figure 8 we plot the histogram of the initial separations of the systems formed via the three different formation pathways for each simulation pathway. For the core-fragmentation pathways, the histograms are stacked in the left column, while the initial separation of dynamical capture is shown on the right column of Figure 8.
We fit Gaussian distributions to the sum of the histograms for systems formed via bound and unbound core-fragmentation to characterise a typical bound core-fragmentation scale. The means and widths of these distributions are plotted against GMC mass in Figure 9. If we assume that the cores on average can be described as critical mass Bonnor-Ebert spheres, the external pressure on the cores will increase with increasing cloud mass, leading to the core fragmentation scale depending inversely proportional to the square root of the cloud mass, indicated by the dashed line in the figure. The typical fragmentation scale over all simulations appears to be around $10^{-3.5}$ AU which is consistent with observations that find a peak of around $\sim 3000$ AU in the separation distribution of protostars (Pokhrel et al. 2018).

When looking at the initial separations of systems formed via dynamical capture (shown on the right column of Figure 8), we see that for all GMC masses the histogram grows with larger initial separations. For simulation 12000 $M_\odot$ the initial separation histogram plateaus beyond 1000 AU. This plateau is likely due to the higher stellar density which creates a situation where it is more likely for stars to capture other stars at smaller separations first before capturing stars at larger separations.

3.4. Orbital evolution of the different pathways

Simulations of binary star formation via protostellar core-fragmentation often show that the binaries undergo significant orbital migration. There are two classes of mechanisms that can efficiently provide migration. Dynamical friction (Chandrasekhar 1943; Ostriker 1999), slow-down due to accretion of material with lower angular momentum, and the initial high-eccentricity configuration of newly-formed cores is a combination of reasons why naturally binaries with separations below $\sim 1000$ AU suffer rapid inspiral. Prestellar cores form in general along filaments, which are kinematically cold in the direction transverse to the filament. Therefore, binaries formed through core fragmentation will initially have an angular momentum, much lower than what is required for circular motion and launch on highly eccentric orbits. This low angular momentum leads...
to rapid inspiral of the young binary system. Systems formed
via dynamical capture were likely to be marginally unbound
and became bound. When these systems first form, their angu-
lar momentum is high, and thus, these systems are not expected
to undergo fast orbital evolution. On the other hand, dynami-
cal capture provides for the possibility of three-body interaction,
which can lead to interaction and hardening of the binary sys-
tems (Reipurth 2000).

To investigate inspiral, we measure the rate of change of the
semi-major axis in the 1000 and 10,000 yr after the first perias-
tron of a system. The semi-major axis is calculated at all time
steps using:

$$a = \frac{G M_{\text{tot}}}{2\epsilon_{\text{orb}}}$$  (3)

where $M_{\text{tot}}$ is the total mass of the system, and $\epsilon_{\text{orb}}$ is the mass
specific orbital energy of the system, $\epsilon_{\text{orb}}$ is calculated by sum-
ming the specific kinetic and potential energies of the system.

The median inspiral rate for systems of different formation
pathways is plotted against simulated mass in Figure 10. The
error bars indicate the standard deviation of the measured inspiral
rates. For both baselines, the inspiral rates are not a
function of the GMC mass.

Most of the inspiral rates are generally higher (10^{-2.5} AU yr^{-1})
compared to the 10,000 yr baseline (10^{-0.75} AU yr^{-1}). This
variation is not surprising because we expect the inspiral
process, while bound core-fragmentation systems reach
a steady orbit sooner.

Overall, we see that many systems experience significant or-
bital evolution within the early stages of their lifetime.

### 3.5. Comparison with observations

We now aim to compare the multiplicity statistics produced from
these simulations with observations of protostellar multiplicity.
In particular we compare our results with that of (Tobin et al.
2016b) of the Perseus star forming region. Tobin et al. (2016b)
observed protostars in this region and measured how the com-
panion frequency (CF) evolved with separation of the compo-
ents. The companion frequency (CF) as defined by (Reipurth &
Zinnecker 1993) is the average number of companions a star
has and is given by:

$$CF = \frac{B + 2T + 3Q + ...}{S + B + T + Q + ...}$$  (4)

where $B, T, Q, ...$ are the number of single, binary, triple, quadru-
ple, and higher order system respectively.

Fig. 9: Mean fragmentation scale as a function of the GMC mass.
The curve shows the peak of Gaussian distributions fitted to the
(stacked) histogram of initial separations of systems formed
via core-fragmentation pathways plotted in Figure 3. The error-
bars is the width of the Gaussian distributions, and not the error
on the peaks. The dashed line show the theoretical prediction
from assuming that cores on average can be described as critical
Bonnor-Ebert spheres.

Fig. 10: Shows the median inspiral rate of systems formed via the
different formation pathways (see Figure 3) measured over the
1000 yr (Top) and 10,000 yr (Bottom) after the first periastron of
the system vs initial gas mass of each simulation. The error bars
show the standard deviation of the measured inspiral rates.)
Tobin et al. (2016b) observed a bimodal distribution in the CF versus separation, with peaks at ~75 AU and ~3000 AU for Class 0 and I objects. The peak at 75 AU was attributed to binaries formed via disc-fragmentation while the peak at 3000 AU was attributed to systems formed via core-fragmentation. However, we have shown in the previous sections that multiple systems that formed on core-fragmentation scales often experience significant orbital evolution, down to separations ~ 75 AU. We aim to determine what the contribution of core-fragmentation is to the observed bimodal distribution.

3.6. The Perseus star forming region and finding the best simulation for comparison

The Perseus star forming region consists of multiple star forming clusters. Arce et al. (2010) present a comprehensive analysis of the mass, volume, turbulence, and star forming efficiency of various star forming regions in Perseus. From Arce et al. (2010) the estimated current mass, including gas mass, mass in outflows, and young stellar objects, in the L1448, NGC1333, B1-Ridge, B1, IC348, and B5 star forming regions is approximately 3220 M⊙. The estimated total volume of all star forming regions is 53.5 pc³, which is slightly smaller than the 4³ = 64 pc³ volume of the simulations. Based on these mass and volume estimates, the Mgas = 3000 M⊙ or 3750 M⊙ simulations are best for the comparison.

To further refine which simulation is best for comparison, we calculate which simulation produces a similar number of sink particles with luminosities that would be observable by the observations of Tobin et al. (2016b).

The bimodal distribution found by Tobin et al. (2016b) is only prominent in Class 0 and I objects, and it is not seen in Class II objects. Therefore, for this comparison, we aim to target sink particles that would be classified as Class 0/I. Accretion in protostars is generally higher in the early protostellar stages than in the later stages, so an accretion limit of 10⁻⁷ M⊙ yr⁻¹ is applied to select sinks that are likely to be in the Class 0/I stages. Observationally, Class I objects have observed accretion rates from ~10⁻⁷ to 10⁻⁶ M⊙ yr⁻¹, however Class II are not observed to have accretion rates above 10⁻⁶ M⊙ yr⁻¹ (Fiorellino et al. 2021). With the selected accretion limit we may miss some Class I objects with low accretion rate, but avoid selecting Class II objects.

The number of Class 0/I objects observed by Tobin et al. (2016b) was 92 stars, with luminosities between 0.1 and 55 L⊙. In Tobin et al. (2016b), the upper limit of the Perseus observations is stated to be approximated 120 L⊙. In order to find the best simulation for comparison with these observations, we calculated the number of sink particles in a simulation that would be observable based on both the highest luminosity object (55 L⊙), and the theoretical maximum luminosity (120 L⊙). We assume that the luminosity is dominated by the accretion luminosity. To calculate the accretion luminosity we use:

\[ L_{\text{acc}} = f_{\text{acc}} \frac{GM}{R_*} \]  

(5)

where \( M \) is the mass accretion rate for the sink particle, \( R_* \) is the radius of the protostar, and \( f_{\text{acc}} \) is the fraction of potential energy from accretion that is converted to radiation. For these calculations we take \( R_* = 2R_\odot \) for all protostars and \( f_{\text{acc}} = 0.5 \) (i.e. 50% of potential energy is converted to radiation). The evolution of the number of visible stars over time is shown in Figure 11. We see that for all simulations, before SFE ~ 0.005 essentially all sink particles are visible. However at later times, the total number of sink particles and visible sink particles diverges. This is because older sink particles may have stopped accreting or have very low accretion rates, but newer sinks are forming which have higher accretion rates. In all simulations a steady state in the number of visible sinks is established after SFE ~ 0.01. Based on the steady state visible star numbers and the number of objects observed by Tobin et al. (2016b) (i.e. 92 stars),
Observations capture the star formation evolution at a particular time, while simulations evolve over time. To make an appropriate comparison with observation, we need to find the best time of the simulations to compare with observations. To do this, we estimate a characteristic star formation efficiency of the observed star forming regions in Perseus.

Arce et al. (2010) provide right ascension and declination boundaries for the L1448, NGC1333, B1-Ridge, B1, IC348, and B5 star forming regions and observational estimates for the star formation efficiency in these regions. Based on the boundaries of these regions, we find how many of the Class 0 and I objects from Tobin et al. (2016b) are in each region. We find that 12 stars are in L1448, 39 stars are in NGC1333, 4 stars are in B1-Ridge, 10 stars are in B1, 13 are in IC348, 2 are in B5, and 12 are unclassified. We re-classified the unclassified stars based on which star forming region they are closest to on the sky, and this adds 11 stars to B1-Ridge and 1 star to B1.

We then calculate a weighted average of the star formation efficiency based on the number of stars in each region and the observed SFE. Based on Arce et al. (2010), the SFE of each region is 1.5% for L1448, 4.9% for NGC1333, 2.4% for B1-Ridge, 2.1% for B1, 9% for IC348 and 0.4% for B5. From this, the characteristic SFE we retrieve is ~4.2%.

3.7. Data processing to make CF vs Separation histogram.

In order to accurately carrying out a comparison with observations, we must process our data in the same way the observations were processed. While the true sink particle separations and separations between centres of mass for sub-systems was used to find bound systems previously, to be consistent with Tobin et al. (2022), we also calculate the separations between mid-points of components and sub-systems. Please refer to Figure 1 of Tobin et al. (2022) for details on measuring separations in a multiple star system.

For some of the comparisons with observations, we save a projected mid-point-separation, e.g., save the true separations projected onto the yx-plane. We also vary whether accretion and luminosity limits are applied to be consistent with Tobin et al. (2016b), and whether to count unbound pairs (pairs with projected separation < 10,000 AU). The various analysis settings are summarised in Table 2. After all the multiple systems are found based on the settings and limitations applied, we then process systems to determine how the companion frequency evolves with projected separation.

We create 12 separation bins logarithmically spaced from 10^3 – 10^4 AU, in the same fashion of Tobin et al. (2016a) and Tobin et al. (2022). Within each bin, if a multiple system has components with separations smaller than the lower bound of the bin, it is considered a single star, and if there are components with projected separations larger than the upper bound then that system is separated into smaller systems.

It is not appropriate to compare the observations with a single time step in the simulations because accretion rates and luminosity can vary between time steps. Therefore, the CF versus separation histogram was integrated over an SFE ±0.1% window, and the median value in each bin is used to produce the resulting histogram.

For comparison with observations, we retrieved the observations for Perseus from Tobin et al. (2022). We removed objects that were not Class 0/1 and processed the data to create our own histogram. We use the entire data set to produce the dashed histogram shown in Figure 12. To approximate the correction for unbound pairs observed by Tobin et al. (2022), we recalculate the histogram only for separation with boundness likelihoods > 0.68 (Refer to Table 4 of Tobin et al. (2022)). This produces the solid line histogram shown in Figure 12. The error-bars are calculated using the binomial statistics described by equation 3 in Tobin et al. (2022).

The results for SFE = 4.2% is shown in Figure 12. For the 3D-Full settings, the true CF distribution of all bound system appears to be relatively uniform at CF=0.1. However, the CF drops significantly in the last separation bin, indicating that there are fewer true bound systems at these large separations. When observational limits are imposed in 3D-Limits, we observe an overall reduction in CF in all bins. We also see a bimodal distribution appear with peaks at ~ 150 AU and ~ 2000 AU. When projected onto 2D in 2D-Bound, the peak at ~ 150 AU is still seen, but larger peak is smeared out. Projecting separations into 2D will affect larger separations that smaller separations, therefore it is expected that CF histogram would be more affect at larger separations. When unbound pairs are counted in the 2D-Unbound analysis we see that the CF increases significantly above projected separations of > 100 AU.

3.7.1. YSO density and contamination from chance alignments

Tobin et al. (2022) correct their observations for possible chance alignments. The likelihood of a chance alignment is dependant on the observed young stellar object (YSO) density. Based on our 2D-Bound and 2D-Unbound analysis, Tobin et al. (2022) appear to have to sufficiently filtered out chance alignments which may contaminate their results.

Our simulation produced significantly more unbound pairs than Tobin et al. (2016a), and we hypothesise that the chosen simulation has a significantly higher stellar density that Perseus. To investigate this we calculate the YSO density distribution for our simulation at different stages of evolution.

The YSO density is calculated using the same method described by Tobin et al. (2022). The YSO density around the sink particle is calculated using:

\[
\Sigma_{YSO} = \frac{10}{\pi r^2} \quad (6)
\]

| Name         | Projection into 2D | Bound Check | M and \( L_{\text{acc}} \) Limits |
|--------------|--------------------|-------------|---------------------------------|
| 3D-Full      | False              | True        | False                           |
| 3D-Limits    | False              | True        | True                            |
| 2D-Bound     | True               | True        | True                            |
| 2D-Unbound   | True               | True        | True                            |

Table 2: Settings used for CF vs. separation histogram. Name: of set up, Projection into 2D: projects mid-point separation onto the xy-plane, Bound Check: only counts gravitationally bound pairs, Limits: only counts ‘visible’ stars based on accretion and luminosity limits (see Section 3.6).
Fig. 12: The median companion frequency vs. separation at star formation efficiency of 4.2\%, integrated over a SFE \pm 0.1\% window, for the \textit{M}_{\text{gas}} = 3750 \text{M}_\odot simulation. The solid histograms in each panel shows the resulting CF vs. Separation histogram for the different settings summarised in Table 2. For settings with the luminosity limits, the blue and orange show the results with an upper limit of 55 and 120 \text{L}_\odot respectively. The black dashed histogram shows the observed distribution found by [Tobin et al. (2022)] for all class 0/I objects, and the solid black line is the histogram derived from pairs with boundness likelihood \geq 0.68. The error-bars are calculated using the binomial statistics described by equation 3 in Tobin et al. (2022).

where \( r_{11} \) is the separation to the eleventh nearest visible neighbour.

We measure the YSO density at SFE = 0.5\%, 1\%, 2\%, 3\%, 4\%, and 5\%. The resulting cumulative distributions are plotted in Figure 13 against the observed YSO density of Perseus for the Class 0/I objects. At SFE > 0.5\%, the YSO density measured in the simulations is larger than Perseus. In the simulations, we observe that the maximum YSO density increases up to SFE=2\% and then decreases. This may reflect that initial burst of star formation in clusters, and then the later dispersal of these clusters.

The higher YSO density in the simulations contributes to the significantly higher CF measured with the 2D-Unbound set-up in Figure 12. The median YSO density for both Perseus and our simulation at SFE=4\% is approximately 100\,pc\(^{-2}\), however the simulation has an extended tail at higher densities. The highest YSO density measured among the Perseus objects is \(10^{2.8}\,\text{pc}^{-2}\), while the highest YSO density in the simulation at SFE=4\% is \(10^{3.8}\,\text{pc}^{-2}\), an order of magnitude greater. Therefore around some objects we may expect up to 10 times more unbound pairs, contributing to the significant excess in companion frequency seen in Figure 12.

Despite the significant increase in CF when counting unbound pairs, a peak in CF is still visible in this set-up at \(\sim 200\) AU.

3.7.2. Finding best fit using two-sample KS test

While we find a bimodal distribution at the calculated characteristic SFE, we aim to determine if there is another time in the simulation where a stronger bimodal distribution is found. We carry out a two-sample Kolmogorov–Smirnov (KS) test (Massey 1951) because it is a non-parametric comparison of the shape of two distributions. While we show the result of the bimodal distribution found in Perseus, we are not concerned by the values of
In order to calculate the KS statistic, we:

1. Order all the separations within systems observed in Perseus, and then calculate a cumulative distribution function (CDF). This distribution is normalised by dividing the CDF by the sum of all values (such that the bounds are 0 and 1).
2. For each time in the simulation, we used the 2D-Bound analysis to find the visible stars. All separations in all bound systems are sorted to produce a normalised CDF for the simulated systems.
3. Calculate the KS statistic, which is the largest vertical separation between the two normalised CDFs. We used the scipy package, which has the scipy.stats.ks_2samp function to calculate the values.

We calculate the KS statistic between SFE=0.01 and 0.05, we also calculate a corresponding critical value, below which, the two distribution are significantly similar. The critical value is found using:

$$\text{KS}_{\text{crit}} = \sqrt{-\ln\left(\frac{\alpha}{2}\right) \times \left(1 + \frac{n}{2m}\right)}$$

(7)

where \(m\) and \(n\) are the number of values in each of the two samples (i.e. the number of separations, which is 39 for Perseus), and \(\alpha\) is derived from the confidence level. We use \(\alpha = 0.99\), therefore if the KS statistic is below the calculated critical value, the two samples are consistent to a confidence level of 99%. We calculate KS statistics for the number for visible stars using limits in 2D-Bound analysis, for both luminosity limits.

We smoothed the KS statistic and critical value over a window of SFE=0.01%. The median value is plotted with an opaque line, and the shaded regions show the 16th and 84th percentile of the integrated values. The critical KS statistic (calculated with Equation (7)) is shown by the black line.

Based on the KS test, the time when we produce a distribution that is most consistent with the Perseus observation is at approximately SFE= 4.1% for both \(L_{\text{max}} = 55\,L_\odot\) and \(120\,L_\odot\).
ulation are generally higher than observations, and in order to reduce the overall CF value, more single stars are needed.

If our simulations resolved disc-fragmentation we expected a higher CF at lower separations and this may shift the inner peak to lower separations.

4. Discussion

4.1. Star formation environment on formation pathways

The classical formation pathways of binary star formation considered mostly disc and core-fragmentation, and dynamical capture was thought to not occur often (Tohline 2002). However, simulations of clustered star formation and observations of young stars may suggest that flybys may occur frequently. Flybys by unbound stars has been proposed as the trigger of the excitation of spiral arms observed in some circumstellar discs (Pérez et al. 2016; Cuello et al. 2019), and potentially trigger accretion bursts (Borchert et al. 2022). Pfalzner & Govind (2021) used N-body simulations of the stellar dynamics in young clusters and determined that stellar flybys are probably more common that initially expected in low mass clusters, and 10%-15% of discs should show evidence of this. Pfalzner & Govind (2021) suggest that while the overall stellar density is lower in low mass star forming regions, the distribution of stars is more clustered, which can aid stellar interactions in the central regions. In our work, we also confirm that star formation is more clustered in lower density environments.

With the evidence that stellar flybys are not uncommon, it is not unreasonable to suggest that some flyby events may turn into dynamical capture events. Our work finds that for stars that are born unbound but later become bound, in higher density environments, they are more like to follow the dynamical capture pathways. Murillo et al. (2016) using SED fitting, inclination effects, and outflows, measure how coeval young multiple star systems in Perseus were. They find that approximately a third of the objects were non-coeval, suggesting these systems did not necessarily form together. This fraction is consistent with our M_gas = 3750 M_⊙ simulation which also found around a third of systems followed the dynamical capture formation pathway (see Figure 5). Our simulations also suggested that the fraction of systems that form via dynamical capture increases in higher density environments.

Fig. 15: Same as Figure 12 but for SFE=4.1%
While we find that the star forming environment may influence the formation pathways of multiples, it does not seem to significantly affect the subsequent orbital evolution. It is difficult to observe evidence of orbital evolution in wide binaries ($a > 1000$ AU) due to the long orbital periods for individual systems. However, observations of OB associations find that the velocity dispersion increases with age \cite{Ramirez-Tannus2021}. This relationship between velocity dispersion and age is suggested to be caused by the hardening of binaries, supporting orbital migration forming close binaries. However, this velocity dispersion evolution is observed on the order of Myr, and not simulations of binary star formation from core-fragmentation frequently produce binaries that experience significant orbital evolution very early \cite{Ostriker1999, Wurster2018, Saiki2020, Lee2019, Kuruwita2020}.

The multiple star systems formed in the simulations of this paper also show significant early orbital evolution (see Figure\textsuperscript{10}). Curiously, we find that systems that formed via dynamical capture experienced faster inspiral rates, when measured over the first 10,000 yr of evolution since first periastron. This was a surprise because we hypothesised that these systems would inspiral slowly. However, many of these systems may have experienced an interaction which quickly hardens previously unbound pairs.

\section{Reproducing observations}

In Section\textsuperscript{3.5} we investigated whether our simulations reproduced the bimodal CF versus separation distributions observed in protostars in Perseus \cite{Tobin2016}, this bimodal distribution has also been observed in Orion \cite{Tobin2022}, and Encalada et al. (2021) appear to resolve the inner peak in Ophiuchus. The valley between the two peaks has also been observed in Class I objects in various star forming regions across the sky by Connelley et al. (2008). Because this bimodal distribution has been observed in multiple regions it is expected to be a long lived feature.

The origin of the two peaks has been attributed to disc-fragmentation producing close binaries, and core-fragmentation producing wide binaries. However, as shown throughout this paper, binaries that are formed on core-fragmentation scales often experience significant orbital evolution early in their formation. We calculated CF versus separation distribution of multiple stars systems, looking at the true distribution, as well as applying observational limits. We successfully produce bimodal distributions at the calculated characteristic SFE of the observed objects in Perseus (4.2\%), and later find a better match to the \cite{Tobin2016} observations at SFE = 4.1\%.

As stated previously, this observed bimodal distribution may be long lived and it is not clear if the evolutionary state of a star forming cloud would affect when this distribution is observed. Multiple star systems form throughout all of the simulations as shown in Figure\textsuperscript{8}, therefore we expect to constantly observe systems forming at large separations (> 1000 AU) and in-spiralling to smaller separations. The derived best-fit is close to the derived characteristic SFE, and it is not clear if this is coincidental.

While the best fit between simulations and observations occurs near when the SFE of the simulation matched observations, when we look at the calculated KS statistic against the critical value in Figure\textsuperscript{13} we see that significant fits appear throughout the evolution of the simulations. Looking at the evolution of the KS statistic, bimodal distributions with similar shapes to that observed in Perseus appear and disappear at different stages. There is an extended period where significant fits are found between SFE ∼3.9–4.3\%, which spans ∼52 kyr in simulation time. This bimodal distribution will be visible for approximately 10\% of the simulation run time. This makes it clear that the feature in our simulation is not spurious, but is a robust feature.

Overall, we can reproduce the observed bimodal distribution in protostellar CF using multiple star systems formed on core-fragmentation scales only due to orbital migration. This is not to say that disc-fragmentation does not occur, but that a significant fraction of closer binaries (<100 AU) can form via non-disc-fragmentation pathways.

\section{Limitations and caveats}

\subsection{Numerical resolution}

On the highest level of refinement, the resolution of our simulations is 50 AU, which means typical circumstellar disc sizes (∼75 AU; \cite{Cox2017, Ansdell2018}) are only resolved over a couple of cells. However, this work only investigates star formation from molecular cloud fragmentation, therefore, resolving discs is not crucial to this work.

Discs are an important part of the mechanism that determines how mass much is accreted onto stars, and what is ejected via outflows, and this is discussed in the next section.

The sink particle motion is calculated using an leap-frog integrator, and the smoothing length is a third of a cell length on the highest resolution, i.e. 16.6 AU. The sink particle motion is calculated using the gravitational potential from both other sink particles and the gas potential. The integrator can accurately calculate the N-body particles until the separation is near the softening length. However, the gravitational potential contribution from the gas can be less resolved as the two sink particle approach separations near the softening length.

Overall, the numerical resolution is limited near and sink particles, and may not accurately simulate orbital evolution when the separations are comparable to the softening length. The work in this paper has primarily focused on resolving the bimodal distribution observed in protostars, with the inner peak at projected separations of 75 AU. With our simulation set up, we are able to sufficiently resolve this inner peak.

\subsection{Non-ideal MHD effects and resolving outflows}

Our simulations compute the ideal-magnetohydrodynamic equations. For molecular clouds, the typical fractional ionisation (abundance of electron) is $10^{-6} - 10^{-8}$. With this ionisation fraction, ambipolar diffusion is present to help dissipate magnetic field flux to allow protostellar cores to collapse. While we do not explicitly include ambipolar diffusion in the computation of the MHD, Šenebelle et al. (2019) argue that the numerical diffusion naturally present in hydrodynamic simulation is sufficient to reproduce the effect of ambipolar diffusion. Other non-ideal effects are not dominant in the molecular cloud regime, however, \cite{Wurster2019} investigated full non-ideal MHD with clustered star formation with smoothed particle hydrodynamical simulations and find there is less magnetic breaking leading to discs forming more easily. With our resolution, we do not resolve discs, therefore, we do not expect the inclusion of other non-ideal effects to affect our results.

Magnetic fields are responsible for launching jets and outflows which return mass and momentum to the surrounding protostellar environment. With the resolution of 50 AU, jets are not self-consistently produced while weak outflows can be produced.
with larger discs. Not resolving outflows will not affect the motion of the sink particles significantly, but outflows regulate what fraction of mass if accreted onto star and what is lost via outflows. As described in Section 2.1, we assume a mass accretion fraction of 50%. The fraction of mass that is accreted is not well constrained and various disc wind models give accretion fractions from 40-90% (Seifried et al. 2012; Fendt & Sheikhnezami 2013). Observations of T-Tauri stars find mass accretion fractions of 50-99% (Nisini et al. 2018), and observations of Herbig-Haro objects find fractions of ~90% (Ellerbroek et al. 2013).

The accretion fraction used in our simulations may be on the lower end of typical accretion fractions but it is still consistent with models and observation.

5.3. Radiation feedback

An isothermal equation of state is used in our simulations, therefore the internal energy remains constant throughout the simulations. This equation of state is satisfactory for our simulations because with our resolution we do not enter the regime where adiabatic heating of protostellar cores occurs ($\sim 3.8 \times 10^{-13} \text{ g cm}^{-3}$; Masunaga & Inutsuka 2000)). This is because the density threshold for sink particle formation does not exceed $1.3 \times 10^{-14} \text{ g cm}^{-3}$.

While an isothermal equation of state is justified in this work for the resolution at which we simulate hydrodynamics, the sink particles are used as proxies for stars, which would be able to produce radiation feedback. Radiation pressure from star formation can inject energy back into the star forming environment, however, radiative MHD simulations carried out by Rosen & Krumholz (2020) find that magnetic fields are dominant over radiation pressure feedback, even in massive stars. Observations also suggest that gas temperature may not have a strong impact on fragmentation and rather, mass and density are key factors in fragmentation (Murillo et al. 2018).

Radiation feedback from the protostars is also found to suppress disc-fragmentation (Offner 2011). However, in this work we are only concerned with multiple star formation on core-fragmentation scales.

6. Summary and Conclusion

We find that systems that form on core fragmentation scales undergo significant orbital evolution. The density of the star forming environment may influence the formation pathways, with star formation in low density environments being more clumped leading to a higher fraction of systems forming via core-fragmentation pathways rather than dynamical capture.

We are also able to reproduce the bimodal distribution observed in Perseus (Tobin et al. 2016b). This is possible due to orbital migration from large separations to < 100 AU, suggesting that disc-fragmentation is not a dominant formation pathways for binaries of close separations.

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