The Formation of Massive Binary Stars

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Abstract. The formation of massive stars in close binary systems is complicated due to their high radiation pressure, the crowded environment and the expected minimum separation for fragmentation being many times greater than the orbital separation. I discuss how massive star formation can be understood as being due to competitive accretion in stellar clusters. Massive binary systems are then formed due to accretion onto wider low-mass systems. The combination of accretion and dynamical interactions with other stars in the cluster then result in producing a close binary system. Tidal and 3-body captures in dense stellar cores can also play a role in forming massive binary systems while stellar mergers of such close binary systems due to interactions may play an important role in overcoming the radiation pressure.

1. Introduction: The Problem

Although massive stars are commonly found in close binary systems, their formation mechanisms are poorly understood. There are a number of difficulties that need to be overcome in order to explain their formation mechanism. These include the intrinsic difficulty of forming massive stars, and the intrinsic difficulty of forming close binary systems, even amongst low-mass stars.

1.1. Formation of Massive Stars

There are several potential difficulties in forming high-mass stars. Firstly, the timescale of less than $10^6$ years to assemble 10 to more than 100 M$_\odot$ implies large accretion rates. Secondly, their crowded location in the centre of young stellar clusters implies that there was not enough room to fit in the precursor fragment. In order to get the Jeans radius to be smaller than the interstellar separation, the resultant Jeans mass is also correspondingly small (Bonnell, Bate & Zinnecker 1998). Lastly, and most importantly, the radiation pressure from a high-mass star is sufficient to reverse the infall of gas that contains typical dust properties (Wolfire & Casinelli 1987; Beech & Mitalas 1994). There are a number of ways this last problem can be circumvented. The radiation pressure can be overwhelmed by ultra-high accretion rates (McKee & Tan 2003) although how this in practice can occur is unclear. More promising is that accretion occurs preferentially through a disc, combined with a rapidly rotating star that emits most of its radiation towards the poles (Yorke & Sonnhalter 2002). A third (and fairly exotic) solution is that massive stars form due to stellar mergers in the ultradense core of a cluster (Bonnell, Bate & Zinnecker 1998).
1.2. Formation of Close Binary Stars

Forming close binary stars systems is difficult even amongst lower-mass stars. The reason for this is that if the components form through fragmentation (e.g., Boss 1986; Bonnell 1999), then the Jeans radius at the point of fragmentation must be smaller than their separation,

\[ R_{\text{sep}} \gtrsim 2R_J \propto T^{1/2} \rho^{-1/2}. \]  

(1)

As above, this implies a high gas density and thus a low Jeans mass,

\[ M_\ast \approx M_J \propto T^{3/2} \rho^{-1/2}. \]  

(2)

This results in the mass of the stars being directly related to their separation,

\[ R_{\text{sep}} \propto \frac{M_\ast}{T}, \]  

(3)

such that close systems have very low masses. For example, if the typical 30 AU binary has solar mass components, then a 1/3 AU binary should have components of 0.01 \( M_\odot \). Forming close binary stars in situ is therefore difficult as it requires subsequent accretion to reach stellar masses (Bonnell & Bate 1994). An alternative is that the components form at greater separation and then are brought together. Recent simulations of star formation in a cluster environment have shown that close binaries can result from the induced evolution of wider systems (Bate, Bonnell & Bromm 2003a). The binaries evolve due to gas accretion and dynamical interactions with other stars. Can the same processes explain high-mass close binary systems?

2. The Formation of Stellar Clusters

One inescapable feature of massive stars is that they form in rich stellar clusters (Clarke et al. 2000; Lada & Lada 2003). In fact, with the exception of runaway stars, presumably ejected from clusters or binary systems, there is little evidence for young massive stars not to be in the centre of dense stellar systems. Furthermore, the central O stars of young open clusters are generally in close binary systems with comparable mass companions (Mermilliod 2000). It would therefore seem sensible to study the formation of massive stars in the context of the formation of a stellar cluster.

The fragmentation of a molecular cloud to form a stellar cluster has been the subject of several studies (Boss 1996; Klessen et al. 1998; Klessen & Burkert 2000; Bate, Bonnell & Bromm 2003b; Bonnell, Bate & Vine 2003). In recent work, the fragmentation is due to turbulently generated structure in molecular clouds. For example, in Bonnell et al. (2003), the fragmentation of a 1000 \( M_\odot \) cloud occurs as the turbulence generates filamentary structure (see Figure 1). The filaments fragment to form individual stars which fall into local potential wells forming small clusters. These clusters grow by accreting further stars and gas and eventually merge to form a large stellar cluster containing some \( \approx 400 \) stars. This simulation was also noteworthy as it was the first that was sufficiently large to populate a full IMF from low-mass to high-mass stars.
Competitive accretion in stellar clusters occurs as individual stars compete gravitationally for the reservoir of gas. As fragmentation is highly inefficient (e.g., Bate et al. 2003b; Bonnell et al. 2003), there remains a large mass of gas that can dominate the potential. Accretion of this gas can then determine the final stellar masses. Numerical studies have shown that competitive accretion results in a large range of masses, with stars in the centre of the cluster, the deepest part of the potential, accreting more gas due to their location (Bonnell et al. 1997; Bonnell et al. 2001a). Furthermore, competitive accretion can explain the initial mass function as it predicts a two power-law IMF. Low-mass stars accrete the majority of their mass in a gas dominated regime where tidal forces limit their eventual mass, resulting in a shallow IMF (Bonnell et al. 2001b). Higher-mass stars accrete their mass in the stellar dominated cores of the clusters with accretion rates determined by a Bondi-Hoyle process, resulting in a steeper IMF.

Of added importance here is that accretion also increases the local stellar density. Infalling mass that is accreted by individual stars increase the stars’ binding energy forcing the cluster to contract (Bonnell et al. 1998; Bonnell & Bate 2002). In the study of Bonnell & Bate (2002), gas accretion onto a cluster of 1000 stars increases the core stellar density by a factor of over $10^5$. Thus massive stars are expected to form in dense environments (See Figure 2a). This is equivalent to a decrease in stellar separations by a factor of 50. The formation of close massive binaries can occur in an analogous fashion (see below).

### 2.1. Accretion and Massive Stars

The numerical simulations discussed above provides a framework in which to understand the formation of massive stars. In this scenario, the massive stars form due to competitive accretion onto the core of the cluster in which the massive star is forming. The Lagrangian nature of the SPH hydro code used for the simulations allows for the decomposition of the mass accretion history of each star. In this way we have been able to analyse where the mass of the massive stars comes from and thus the potential for accretion to form close binaries amongst the massive stars.

We found that the vast majority of the mass which comprises the massive stars comes from large distances and is accreted onto the star after a stellar
cluster has formed (see Figure 2b). The initial fragment mass which forms the star is of low mass, typical to the mean stellar mass. The infalling gas then has to pass through the cluster to be accreted by the central massive star. We also found that the infalling gas is accompanied by newly formed stars such that the formation of a massive star is a necessary byproduct of the formation of a stellar cluster. It should be noted that these simulations neglect the effect of radiation pressure from the massive stars, or equivalently assume that accretion through a disc (Yorke & Sonnhalter 2002) occurs.

Figure 2. The stellar density is plotted against radius in the 400 star cluster in the left panel. Stars with \( m > 10 \, M_\odot \) are plotted as solid circles while those more massive than 2 \( M_\odot \) are plotted as squares. The right panel shows that the majority of the final stellar mass comes from outside the central binary and even outside the forming cluster of stars (Bonnell et al. 2004).

3. Binary Formation and Evolution

The numerical simulations detailed above form a significant number of binary systems amongst the massive stars. The binary systems generally form through three-body capture in the cores of the clusters. During the earlier stages of the cluster formation, the small number of stars contained in each subcluster allows for significant interactions and a relatively low velocity dispersion such that three-body capture is common and few of the eventual higher-mass stars are not in binary or multiple systems.

3.1. Accretion and Binary Evolution

Accretion onto binary systems has the potential of forming close systems out of wider systems at the same time as forming higher-mass components. In order to see this, let us consider the angular momentum of a binary system,

\[
J \propto M^{3/2} R^{1/2}.
\]  

(4)

If the accreted material has zero net angular momentum as is expected if it infalls spherically, then this implies that the binary separation should be a strong
function of the mass,

\[ R \propto M^{-3}. \]  

(5)

If instead, the accreted material has constant specific angular momentum, the same as the initial binary, then \( J \propto M \) and

\[ R \propto M^{-1}. \]  

(6)

Figure 3. The evolution of a massive binary’s mass versus its separation due to the combined effect of accretion and stellar interactions. The gravitational softening is set at 180 AU, such that all separations below this value are upper limits. The panel on the right plots the final distribution of binary masses (in units of 1000 M\(_\odot\)), as a function of their separation in units of AU (Bonnell & Bate 2002). We see that the separation decreases for the more massive systems which have undergone the most accretion.

Thus we can see that a large decrease in the orbital separation can occur when significant mass accretion forms a high-mass binary system. Unfortunately, in most of the simulations reported above, the gravitational potentials were smoothed in order to minimise computational expense. Still, we can see that the accretion is having a significant effect on the binary’s evolution. Figure 3a plots the evolution of a binary’s separation versus its mass due to gas accretion. We see that the separation decreases dramatically as the mass increases. Even though the separation is limited by the gravitational smoothing of 180 AU, we can estimate that the separation decreases with system mass as

\[ R \propto M^{-2} \]  

(7)

such that an increase in mass from typical stellar masses of 1 M\(_\odot\) to high-masses of 50 M\(_\odot\) would decrease a binary’s separation from 1000 AU to 0.4 AU. Thus, forming close systems from accretion is feasible (Figure 3b).

3.2. Dynamics and Binary Evolution

A secondary effect of the accretion in clusters is to increase the stellar density. This occurs in an analogous manner to the evolution of a binary system undergoing accretion depending on the amount of momentum imparted with the mass.
Figure 4. The dynamical hardening of a massive binary due to accretion and stellar interactions is shown in the top panel. The binary’s separation decreases steadily due to accretion but can suddenly decrease due to the passage of a third star. Occasionally this hardening forces the binary to merge, forming a higher-mass star with the perturbing star now becoming the companion. The mass (upper curve) of the primary is plotted in the bottom panel as well as the number of stars (Lower curve) in its vicinity. Jumps in the mass indicate stellar mergers (Bonnell & Bate 2002).

to the accreting stars (Bonnell et al.1998). As discussed above, simulations of accreting clusters show increases in stellar densities of order $10^5$. This has two important effects. Firstly, it increases the probability of stars passing close to a binary and thus hardening it by removing some of the binary’s orbital angular momentum. This effect has been noted to be relevant for the formation of close low-mass binaries (Bate et al.2003a). In terms of forming massive close binaries, the simulations show that the massive stars always form in the centre of the clusters where the potential well is deepest, It is also here that the stellar density is highest (Figure 2a) and thus binary hardening through stellar interactions is most likely even more important in the case of high-mass systems.

Binary hardening is limited by the size of the stars. In extreme circumstances, the hardening will force the binary to merge to form a higher mass system. This was seen to occur in the simulations of accretion onto a large stellar cluster (Bonnell & Bate 2002). Figure 4 plots the evolution of a massive binary system due to the presence of additional stars in the cluster core. The binary’s separation evolves due to ongoing accretion and due to the perturbation of other stars in the core. Accretion leads to a steady smooth decline in the binary separation while close interactions lead to a rapid decrease in the separation and sometimes to direct mergers. At this point, the third star, gen-
Figure 5. The interactions between two $3 \, M_\odot$ stars (top) which results in a tidal capture while the interaction between a $10$ and a $3 \, M_\odot$ stars results in the tidal disruption of the $3 \, M_\odot$ star (Davies et al. 2004).

Generally already bound due to the accretion and stellar dynamics in the cluster core, becomes the binary companion to a more massive primary.

Two other binary formation processes can occur in dense stellar clusters. One is the aforementioned tidal capture when unbound stars pass within a few stellar radii of each other (Fabian, Pringle & Rees 1975; Bonnell et al. 1998). The second process is disc capture of passing stars (Clarke & Pringle 1991; Hall, Clarke & Pringle 1996). These processes require the presence of a circumstellar disc which can be due to either direct infall, or due to the tidal disruption of a low-mass star (Davies et al. 2004). In Davies et al. (2004), we investigate the stellar collisions expected in a merger scenario and find that while two high-mass stars are capable of tidal capture, a high-mass interacting with a pre-main sequence low mass star results in a tidal disruption of the low mass star. This material will form an inner disc which can then act to aid in the capture of any successive stellar interactions (Figure 5).
4. Conclusions

The formation of close massive binary stars can be understood in the context of the formation of a stellar cluster and the subsequent competitive accretion which produces the initial mass function. Massive stars form in the cores of the cluster where three-body capture forms binary systems. These binaries evolve from wide low-mass systems to close high-mass systems due to the effects of gas accretion and stellar interactions and binary hardening. Binary mergers due to such hardening may be important in overcoming the effects of radiation pressure. The expected results of such processes are close systems with comparable mass companions. The mass ratios should be fairly high due to mass accretion favouring equal mass ratios and due to any exchanges from stellar interactions.

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