Binary systems and stellar mergers in massive star formation

Ian A. Bonnell\textsuperscript{1}\textsuperscript{*} and Matthew R. Bate\textsuperscript{2}

\textsuperscript{1} School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife, KY16 9SS.
\textsuperscript{2} School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL

22 October 2021

ABSTRACT

We present a model for the formation of high-mass close binary systems in the context of forming massive stars through gas accretion in the centres of stellar clusters. A low-mass wide binary evolves under mass accretion towards a high-mass close binary, attaining system masses of order 30-50 M\odot at separations of order 1 AU. The resulting high frequency of binary systems with two massive components is in agreement with observations. These systems are typically highly eccentric and may evolve to have periastron separations less than their stellar radii. Mergers of these binary systems are therefore likely and can lead to the formation of the most massive stars, circumventing the problem of radiation pressure stopping the accretion. The stellar density required to induce binary mergers is \( \approx 10^6 \) stars pc\(^{-3}\), or \( \approx 0.01 \) that required for direct stellar collisions.

Key words: stars: formation – stars: luminosity function, mass function – globular clusters and associations: general.

1 INTRODUCTION

The formation of high-mass stars is a large unknown in modern astronomy. While our understanding of the formation of low-mass stars has improved dramatically over the past decade (Larson 2003), we still do not know whether massive star formation is basically a scaled-up version of low-mass star formation or if it results from a dramatically different process (Stahler, Palla & Ho 2000; Bally & Zinnecker 2005). The basic questions concern how mass is added and how it interacts with the large radiation pressure from the high stellar luminosity once the star reaches masses in excess of 10 M\odot. Models of scaled-up low-mass star formation have repeatedly shown that if the gas contains typical interstellar dust, then the radiation pressure deposits sufficient momentum into the dust (well coupled to the gas) to repel the infalling gas (Yorke & Krügel 1977; Wolfire & Caselli 1987; Beech & Mitalas 1994; Edgar & Clarke 2004).

Potential solutions to this problem include accretion through a disc (Yorke & Sonnhalter 2002), accretion overpowering the radiation pressure (McKee & Tan 2003), and massive star formation through mergers of (dust free) stars (Bonnell, Bate & Zinnecker 1998; Bonnell & Bate 2002). Disc accretion can help in two ways. Firstly, the matter accretes through a small solid angle and is thus less exposed to the radiation pressure. Secondly, as young stars are generally thought to be rapidly rotating, the star can be significantly cooler at the equator than at its poles. Thus, there is less radiation pressure in the equatorial regions to oppose the accretion. Using this last factor in their models as well as a sophisticated treatment of the radiation transfer, Yorke & Sonnhalter (2002) showed that it is possible to accrete up to masses of the order 30 M\odot before the radiation pressure repels the infalling envelope. McKee & Tan (2003) have speculated that a very concentrated centrally condensed core will provide large accretion rates onto a forming massive star which will then overpower the radiation pressure of the growing star. There are two potential limitations to this process. Firstly, such a core, even if centrally condensed and supported by turbulence, is very likely to fragment and form a small stellar cluster (Dobbs, Bonnell & Clark 2005). Secondly, the implied accretion rates are similar to the models of Yorke & Sonnhalter (2002) which show that the infalling envelope is indeed repelled once the star attains masses of order 30 M\odot.

The third potential solution involves the merger of lower-mass stars in a dense stellar cluster (Bonnell et al.1998). While certainly the most exotic of the three, it does have the attraction that any dust will be destroyed in the lower-mass stars and thus there is no problem with...
the radiation pressure from the forming massive star. The obvious difficulties with this model is that it requires very high stellar densities (of order $10^5$ stars pc$^{-3}$) in order for stellar collisions to be sufficiently common to form massive stars in less than $10^5$ years. Although such densities are $10^5$ times higher than generally found in the cores of young stellar clusters, they are not inconceivable as the dynamics of accretion can induce the core of a cluster to contract significantly (Bonnell et al.1998; Bonnell & Bate 2002).

One inescapable feature of massive stars is that they form in rich stellar clusters (Clarke et al. 2000; Lada & Lada 2003). Even apparently isolated massive stars are best explained as being runaways from stellar clusters (de Wit et al.2005; Clarke & Pringle 1992). These systems have a regular field-star IMF and thus we need to put massive star formation into the context of forming many more low-mass stars. Models for the formation of stellar clusters, neglecting any feedback processes, show that the fragmentation of a turbulent molecular cloud can form hundreds of stars and that they follow a field-star like IMF (Bonnell, Bate & Vine 2003). Intriguingly, the initial masses of these stars, even those that end up being high-mass, are all initially close to the Jeans mass of the cloud (Bonnell, Vine & Bate 2004).

The development of high-mass stars in these systems occurs due to subsequent accretion onto the forming cluster, where the stars near the centre of the potential accrete more rapidly and thus attain much higher masses (Bonnell et al.2001a; Bonnell et al.2004). This effect is increased once a significant disparity in masses is achieved. It is this competitive accretion which explains the origin of the IMF while maintaining a low median stellar mass in the cluster (Bonnell et al.2001b; Bonnell et al.2003). Massive star formation in the context of low-mass star formation can thus be explained as being primarily due to the environment of the forming massive star (Bonnell et al.2004), linking the formation of a massive star to the formation of a stellar cluster. However we still need to understand how the mass accretion overcomes the radiation pressure to form the most massive stars.

A further complication to any model of massive star formation is that most massive stars are in binary systems (Mason et al.1998; Preibish et al.1999; Garcia & Mermilliod 2001). These systems are often very close, with separations $\lesssim 1\text{ AU}$, and companions that are also high-mass stars (Garmann, Conti Massey 1980; Bonanos & Stanek 2005). It is these close massive binary systems that motivate the present study. In Section 2 we explain the difficulties of forming close binary systems. In Section 3 we discuss the numerical simulations of cluster formation. Section 4 explains the formation of massive binary systems in stellar clusters and their orbital evolution. The potential for binary mergers is discussed in Section 5. We discuss the implications of these results in § 6 and finally, our conclusions are given in Section 7.

2 THE PROBLEM: FORMING CLOSE BINARY STARS

Forming close binary stars systems is difficult even amongst lower-mass stars. If the binary components form through fragmentation (eg, Boss 1986; Bonnell 1999), then the Jeans radius at the point of fragmentation must be smaller than the binary separation,

$$R_{\text{bin}} > 2R_L \propto T_1^{1/2} \rho^{-1/2}.$$  

This implies a high gas density and thus a low Jeans mass,

$$M_* \approx M_J \propto T_2^{3/2} \rho^{-1/2}.$$  

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

$$R_{\text{bin}} \propto M_* T^{-3}.$$  

such that close systems have very low masses (Boss 1986). For example, if the typical 30 AU binary has solar mass components, then a 1/3 AU binary should have components of 0.01 $M_\odot$ (Bonnell & Bate 1994). Forming close binary stars in situ is therefore difficult as it requires subsequent accretion to reach stellar masses (Bate 2000). An alternative is that the components form at greater separation and then are brought together. Recent simulations of low-mass 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, angular momentum lost to circumbinary discs (e.g. Pringle 1991;Artyomowicz et al.1991) and dynamical interactions with other stars. Can the same processes explain high-mass close binary systems?

2.1 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,

$$L \propto M_{\text{bin}}^{3/2} R_{\text{bin}}^{1/2}.$$  

If the accreted material has zero net angular momentum, as is expected if it infalls spherically symmetric, then $L \approx$ constant, and the binary separation should be a strong function of the mass,

$$R_{\text{bin}} \propto M_{\text{bin}}^{-3}.$$  

If instead, the accreted material has constant specific angular momentum, the same as the initial binary, then the total angular momentum will scale with the mass of the binary, $L \propto M$ and thus the orbital separation will scale with the mass as

$$R_{\text{bin}} \propto M_{\text{bin}}^{-1}.$$  

In a turbulent medium, as expected here, the angular momentum of each parcel of infalling gas is essentially randomly oriented. The net angular momentum will then do a random walk with increasing mass such that

$$L \propto M_{\text{bin}}^{1/2},$$  

and thus

$$R_{\text{bin}} \propto M_{\text{bin}}^{-2}.$$  

Under these basic assumptions, we can see that accretion onto a binary system can significantly decrease its separation at the same time as it increases its mass (Bate & Bonnell 1997; Bate 2000).
3 CALCULATIONS

The numerical simulations discussed here were first reported in Bonnell, Bate & Vine (2003). The simulations used the Smoothed Particle Hydrodynamics (SPH) method (Monaghan 1992). The code has variable smoothing lengths in time and in space and solves for the self-gravity of the gas and stars using a tree-code (Benz et al. 1991). The initial conditions consisted of 1000 $M_{\odot}$ of gas in a 0.5 pc radius uniform density sphere. The cloud also contains significant turbulent motions such that the kinetic energy is equal to the magnitude of the potential energy. The gas is isothermal at 10K which implies an initial Jeans mass of $1 M_{\odot}$. Star formation is modeled by the inclusion of sink-particles (Bate, Bonnell & Price 1995) that interact only through self-gravity and through gas accretion. Sink-particle creation occurs when dense clumps of gas have $\rho \gtrsim 1.5 \times 10^{-15}$ g cm$^{-3}$, are self-gravitating, and are contained in a region such that the SPH smoothing lengths are smaller than the 'sink radius' of 200 AU. This ensures that the initial sink-particles can have masses as low as our resolution limit of 0.1$M_{\odot}$. Gas particles are accreted if they fall within a sink-radius (200 AU) of a sink-particle and are bound to it. In the case of overlapping sink-radii, the gas particle is accreted by the sink-particle to which it is most bound. The gravitational forces between sink-particles is smoothed within 160 AU using the SPH kernel. Thus any binary separation within 160 AU is an overestimate of the true separation. This implies that the frequency of dynamical interactions in the simulation is artificially higher than would be the case if the binary was allowed to evolve to smaller separations. This is offset to some degree by the corresponding decrease in the strength of each interaction due to the gravitational softening. The simulations were carried out on the United Kingdom’s Astrophysical Fluids Facility (UKAFF), a 128 CPU SGI Origin 3000 supercomputer.

3.1 Reconstructing the binary’s orbital parameters

In spite of the fact the gravitational forces are smoothed at distances less than 160 AU, we can still hope to extract information as to what the true binary separations should be. This is possible as the orbital parameters depend solely on the system’s mass, angular momentum and total energy, which are all directly calculable from the simulation. Thus we can estimate what the true binary semi-major axis, $R_{\text{semi}}$, would be in the absence of any gravitational smoothing as

$$R_{\text{semi}} = \frac{J^2}{GM_{\text{bin}}}.$$  (9)

where $J$ is the specific angular momentum, $M$ is the total mass of the binary system and $G$ is the gravitational constant. We can likewise calculate the eccentricity, $e$, of the orbit from

$$e = \sqrt{1 + \frac{2EJ^2}{G^2M_{\text{bin}}^2}},$$  (10)

where $E$ is the total specific energy (energy per unit mass) of the binary system. This term includes the smoothed gravitational potential that corresponds to the smoothed gravitational forces. We can then estimate the semi-major axis of the orbit as well as the periastron separation,

$$R_{\text{peri}} = R_{\text{semi}}(1 - e),$$  (11)

of the binary and determine its evolution. Furthermore, we can compare the periastron separation to the stellar radii to estimate if the binary system would merge to form a more massive star.

4 FORMATION OF HIGH-MASS BINARY STARS

The birth of high-mass stars in the simulation of Bonnell et al.(2003) is due to competitive accretion in a cluster environment. The simulation forms numerous sub-clusters which eventually merge to form one large system. The high-mass stars form in the centres of the dense sub-clusters due to the combined potential that funnels the gas down to the centre of the system there to be accreted by the growing protostellar massive star. The clusters themselves form as small-N groupings and grow by accreting stars and infalling gas. Thus, the system is initially small and 3-body capture occurs readily (Binney & Tremaine 1987). In small-N systems a central binary forms when three initially unbound stars pass so close that there is violent exchange of energy, with one star being ejected at high speed and the other two becoming bound to one another. In larger systems this does not work as the larger velocity dispersion and smoother gravitational potential drastically reduces the probability of having a third star sufficiently close to extract the excess kinetic energy. As the high-mass stars all form in the centre of the individual sub-clusters, they generally have undergone three-body capture early in the cluster’s growth and are therefore in binary systems.

Once the binary has formed, continuing accretion onto it increases the masses of the individual stars. Of equal importance is the effect of the accretion on the binary’s separation. As the infalling gas has no correlation with the binary, its specific angular momentum is uncorrelated with that of the binary’s. Thus, accretion does not significantly increase the binary’s angular momentum and the separation of the binary decreases as mass is added (see also Bate 2000). This process is illustrated in Figure 1 which shows the evolution of the binary mass versus orbital separation for one of the high-mass binary systems formed in the simulation (final masses 17 and 10 $M_{\odot}$). The system originates as a low-mass wide binary and evolves towards higher masses and smaller separations. Once the separations are $\lesssim 160$ AU, the gravitational smoothing stops the binary from evolving to smaller separations.

The early stages of the evolution are well parameterised by $R_{\text{bin}} \propto M_{\text{bin}}^{-2}$ as expected for accretion from a turbulent medium where each gas parcel has randomly oriented angular momentum (see §2.1 above). Unfortunately, the binary’s orbital evolution quickly enters the regime where the gravitational forces are smoothed (160 AU). From this point on, we use the evolution of the energy and angular momentum to determine the evolution of the binary’s orbit.
41 Evolution of the binary parameters

A binary’s orbital parameters depend solely on the angular momentum, energy and mass of the binary system (see §3 above). Thus, as long as we can calculate these quantities, we can extract the binary properties and their evolution. Figure 2 shows the evolution of the binary’s system mass as a function of its semi-major axis and periastron separation, for the same binary as shown in Figure 1. The evolution of the smoothed separation is also shown for comparison. The semi-major axis of the binary is generally much smaller than the smoothed separation. Thus, from separations of order 100 AU at masses of several solar masses, the binary evolves to a semi-major axis of order 1 AU by the time the system has accreted up to 30 \( M_\odot \). This once again roughly agrees with an \( R_{\text{bin}} \propto M_\text{bin}^{-2} \) evolution as expected for accretion from a turbulent medium.

The evolution of the periastron separation is also plotted in Figure 2. From this figure we can see that the binary is generally in a highly eccentric orbit where the periastron separation is an order of magnitude smaller than the semi-major axis, corresponding to an eccentricity of \( e \approx 0.9 \). At one point the periastron separation appears to be larger than the semi-major axis and this denotes a binary system which is unbound. At other points the evolution decreases in system mass indicating an exchange has occurred with a third star, or that this third star temporarily passes closer to the primary. There is obviously some ambiguity in the evolution due to the gravitational smoothing imposed which maintains an artificially large cross section for further dynamical interactions in addition to smoothing out these interactions. Nevertheless, we see that the periastron separation decreases more dramatically than does the semi-major axis and attains separations of order the size of high-mass stars (\( R_{\text{peri}} \lesssim 0.05 \) AU). In fact, at several points, the deduced semi-major axis is smaller than the stellar radii of the stars. Such systems can reasonably be expected to undergo stellar mergers or at the very least, tidal forces which will reduce their semi-major axes to be of order their periastron separations.

5 Binary Systems and Stellar Mergers

The above evolution of one of the high-mass binaries is a typical example of the evolution of the orbital parameters under mass accretion. The distribution of binary separation as a function of mass is shown for all the high-mass binary systems (where at least one star has \( m \geq 5 M_\odot \)) in Figure 3. This figure plots the binary’s semi-major axis against the total binary mass (filled pentagons) and the individual component masses against the periastron separations (open triangles), linked by solid lines for each system. The more massive stars are generally in binaries with semi-major axes less than 10 AU and periastron separations less than 1 AU. In fact, of the 10 stars at the end of the simulation with masses \( m \geq 10 M_\odot \), all ten are in binary systems \( R_{\text{semi}} \leq 100 \) AU and 8 of them have \( R_{\text{semi}} \leq 10 \) AU. For the 18 stars between 5 and 10 \( M_\odot \), the numbers are 7 with \( R_{\text{semi}} \leq 100 \) AU and 5 with \( R_{\text{semi}} \leq 10 \) AU.

In addition to the large fraction of close binary systems amongst the high-mass stars, it is also worth noting that generally both components of the binary are high-mass stars. Both of these properties are in agreement with observations of massive binary systems (Mason et al. 1998; Garcia & Merrmillod 2001; Garmony et al. 1980). Of even greater potential...
Massive binary stars

Figure 3. The binary semi-major axis is plotted against binary mass (filled pentagons) for all the systems containing at least one star with \( m \geq 5 M_\odot \). The periastron separations (open triangles) are also plotted for these systems against the individual component masses, and are joined to their total binary mass and semi-major axis by solid lines. Of note is that some binary systems have only one individual component plotted indicating that the other star has another, closer companion. The dashed line indicates an approximation of the stellar radii and thus periastron separations below this line would force the binary to merge.

The significance is that the periastron separations of the systems are dangerously close to the estimated size of the stellar radii (assuming a main-sequence mass-radius relationship),

\[
R_* \approx R_\odot \left( \frac{M_*}{M_\odot} \right)^{0.8}.
\]  

Thus, many of these systems could be undergoing mergers, while at least one system has \( R_{\rm peri} < R_* \). In fact, this is only an instantaneous picture of the binary systems and as we can see from Figure 2, the evolution is somewhat chaotic and frequently perturbed by passing stars.

In order to quantify the frequency and relevance of binary mergers in high-mass star formation, we have evaluated throughout the simulation when a binary system has a periastron passage closer than half its stellar radii. Using this and the condition that each star can only merge with a more massive star once (only the most massive pre-merger star continues as an independent entity), we have estimated the potential for mass growth via binary mergers. This merger-acquired mass is plotted in Figure 4 against the mass acquired through gas accretion. The final products are plotted as filled pentagons while open squares denote merger products which subsequently merged with a more massive star. The mergers are estimated by calculating the binary properties throughout the simulation and ensuring that each star can only merge once with a more massive star. The solid line denotes equal mass being acquired through mergers and accretion.

Figure 4. The mass gained in binary mergers, based on having periastron separations smaller than one half of the primary’s radius, is plotted against the mass acquired through gas accretion. The final products are plotted as filled pentagons while open squares denote merger products which subsequently merged with a more massive star. The mergers are estimated by calculating the binary properties throughout the simulation and ensuring that each star can only merge once with a more massive star. The solid line denotes equal mass being acquired through mergers and accretion.

The most massive star would increase its mass from \( \approx 30 M_\odot \) to nearly \( 75 M_\odot \) through multiple binary mergers. Thus, in some cases binary mergers could be a significant factor in forming massive stars.

6 DISCUSSION

The potential for binary systems to merge and form the most massive stars is an intriguing solution to the difficulty of overcoming the radiation pressure of the forming high-mass star. A binary system with a semi-major axis of a few AU can be easily perturbed by an encounter with a third star that passes near the binary. This encounter radius is significantly larger than the size-scale for direct collisions and thus drastically reduces the requirement of an ultradense cluster. The encounter time for an interaction at \( R_{\rm enc} \) is given by

\[
\frac{1}{t_{\rm enc}} = 16\sqrt{\pi n v_{\rm disp} R_{\rm enc}^2} \left( 1 + \frac{G M_{\rm bin}}{2 v_{\rm disp}^2 R_{\rm enc}} \right),
\]  

where \( v_{\rm disp} \) is the velocity dispersion and \( n \) is the stellar density. If we consider an eccentric binary of semi-major axis 1 AU, the stellar density \( n \) of order \( 10^6 \) stars pc\(^{-3}\) is required to have another star pass within \( R_{\rm enc} \approx 2 \) AU, of order the apastron separation, in \( t_{\rm enc} \leq 10^6 \) years, assuming \( v_{\rm disp} \) in the range of a few to 10 km s\(^{-1}\). This is still a fairly high density but not drastically so relative to that of the cores of young stellar clusters (McCaughean & Stauffer 1994), especially considering that they could have been much denser in their earlier evolutions (Kroupa, Hurley & Aarseth...
2001; Scally, Binney, & Tremaine 2005). Central stellar densities an order of magnitude higher are deduced in the more massive clusters near the Galactic centre (Figer et al.

An important implication of this work is that the most massive stars are more likely to be single stars, or at least not in a close binary system. This is due to their being merger products and thus the binary system is destroyed in forming this very massive star. Intriguingly, well determined masses for stars in binary systems rarely exceed 50 M⊙ (Bagnuolo et al., 1992; Rauw et al., 2004; Bonanos et al., 2005) with the most massive stars in a binary being a pair of ≈ 70 M⊙ (Rauw et al., 2004; Bonanos et al., 2005). This is in contrast with deduced masses for single stars that can extend to 150 M⊙ and beyond (Davidson & Humphreys 1997; Figer et al., 1998; Eikenberry et al., 2004). This apparent discrepancy can be resolved either by the spectroscopic masses being far in excess of the dynamical masses, or, by the most massive stars having formed from the merger of two massive stars in a close binary system.

7 CONCLUSIONS

The formation of high-mass close binary systems is a natural outcome of forming massive stars through gas accretion in a clustered environment. Competitive accretion in clusters naturally forms closer, more massive binaries out of lower-mass wide systems. These systems can evolve from solar-mass binaries with separations of order 10 AU to masses of 10−30 M⊙ with separations of order 1 AU or less. The frequency of high-mass binary systems formed in a numerical simulation of a forming stellar cluster is 100 per cent for stars with n ≥ 10 M⊙ and 60 per cent for stars with n ≥ 5 M⊙. The high frequency of binary systems and the fact that they generally comprise two high-mass stars is in agreement with observations (Mason et al., 1998; Garcia & Mermilliod 2001; Preibish et al., 1999). The binaries typically have very eccentric orbits such that their periastron separations can be comparable to, or less than, the stellar radii. Mergers of these systems are therefore expected and can be a significant factor in forming the most massive stars. Stellar densities required to perturb such a binary and force it to merge are estimated to be of order 10⁶ stars pc⁻³.

ACKNOWLEDGMENTS

We thank Hans Zinnecker for continually asking about binary systems, the referee Ant Whitworth for comments which improved the text, and the organisers of the Massive Stars in Interacting Binaries meeting in Sacacomie, Que, which prompted this study. The computations reported here were performed using the U.K. Astrophysical Fluids Facility (UKAFF). MRB is grateful for the support of a Philip Leverhulme Prize.

REFERENCES

Artyomowicz, P., Clarke, C. J., Lubow, S. H., & Pringle, J. E., 1991, ApJ, 370, L35
Beech, M., Mitalas, R., 1994, ApJS, 95, 517
Bagnuolo, W. G., Gies, D. R., Wiggs, M. S., 1992, ApJ, 385, 708
Bally, J., Zinnecker, H., 2005, AJ, in press
Bate, M. R., Bonnell, I. A., Price, N. M., 1995, MNRAS, 277, 362
Bate, M. R., Bonnell, I. A., Bromm, V., 2002, MNRAS, 336, 705
Bate, M. R., Bonnell, I. A., 1997, MNRAS, 285, 33
Bate, M. R., 2000, MNRAS, 314, 33
Binney, J., & Tremaine, S., 1987, Galactic Dynamics, Princeton University Press
Bonanos, A. Z., Stanek, K. Z., 2005, ASPC, 332, 257
Bonnell, I. A., Bate, M. R., 1994, MNRAS, 271, 999
Bonnell, I. A., Bate, M. R., 2002, MNRAS, 336, 659
Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E., 2001a, MNRAS, 323, 785
Bonnell, I. A., Bate, M. R., Vine, S. G., 2003, MNRAS, 343, 413
Bonnell, I. A., Bate, M. R., & Zinnecker, H., 1998, MNRAS, 298, 93
Bonnell, I. A., Clarke, C. J., Bate, M. R., Pringle, J. E., 2001, MNRAS, 324, 573
Bonnell, I. A., Vine, S. G., Bate, M. R., 2004, MNRAS, 349, 735
Clarke, C. J., Bonnell, I. A., Hillenbrand, L. A., 2000, in Protostars and Planets IV (eds V. Mannings, A. P. Boss and S. Russell), 151.
Clarke, C. J., Pringle, J. E., 1992, MNRAS, 255, 423
Davidson, K., Humphreys, R. M., 1997, ARA&A, 35, 1
de Wit, W. J., Testi, L., Palla, F., Zinnecker, H., 2005, A&A, in press
Dobbs, C. L., Bonnell, I. A., Clark, P. C., 2005, MNRAS, in press
Edgar, R., Clarke, C., 2004, MNRAS, 349, 678
Figer, D. F., Najjarro, F., Morris, M., et al. 1998, ApJ, 506, 384
Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., McLean, I. S., 1999, ApJ, 525, 750
Garcia, B., Mermilliod, J. C., 2001, A&A, 368, 122
Garmany, C. D., Conti, P. S., Massey, P., 1980, ApJ, 242, 1063
Kroupa, P., Aarseth, S., Hurley, J., 2001, MNRAS, 321, 699
Lada, C. J., Lada, E., 2003, ARA&A, 41, 57
Larson, R. B., 2003, Rep. Prog. Physics, 66, 1651
Mason, B. D., Gies, D. R., Hartkopf, W. I., Bagnuolo, W. G., Brumme, T. T., McAlister, H. A., 1998, AJ, 115, 821
Massey, P., Penny, L. R., Vukovich, J., 2002, ApJ, 565, 982
McCuaig, M. J., Stauffer, J. R., 1994, AJ, 108, 1382
McKee, C. F., Tan, J. C., 2003, ApJ, 585, 850
Monaghan, J. J., 1992, ARA&A, 30, 543
Preibisch, T., Balega, Y., Hofmann, K., Weigelt, G., Zinnecker, H., 1999, NewA, 4, 501
Pringle, J. E., 1991, MNRAS, 248, 754
Rauw, G., et al., 2004, A&A, 420, L9
Rauw, G., Vreux, J.-M., Gosset, E., et al. 1996, A&A, 306, 771
Scally, A., Clarke, C., McCaughrean, M. J., 2005, MNRAS, 358, 742
Stahler, S. W., Palla, F., Ho, P. T. P., 2000, prpl.conf, 327
Wolfire, M. G., Cassinelli, J. P., 1987, ApJ, 319, 850
Yorke, H., Krügel, E., 1977, A&A, 54, 183
Yorke, H., Sonnhalter, C., 2002, ApJ, 569, 846