The earliest phases of massive starbirth
ASP Conference Series, Vol. XXX, 2001
P. Crowther, ed.

Multiplicity of Massive Stars - a Clue to their Origin?

Hans Zinnecker

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam

Matthew R. Bate

School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL

Abstract. The coagulation theory of massive star formation predicts that the most massive stars form in the central densest part of a protocluster by stellar collisions and tidal mergers. A further prediction is a high frequency of tight binary systems among massive stars due to tidal capture and the combination of tidal disruption followed by a star-disc encounter (failed stellar mergers). Recent new observations have indeed confirmed this prediction (many short-period SB2 systems among O-stars in young clusters!).

1. Introduction

Among the key reference on the formation of massive stars, we would like to recommend the following: Kahn (1974), Yorke & Krügel (1977), Wolfire & Cassinelli (1987), Nakano (1989), Beech & Mitalas (1994), Bernasconi & Maeder (1996), Jijina & Adams (1996), Bonnell, Bate, & Zinnecker (1998), Garay & Lizano (1999), Stahler, Palla, & Ho (2000), Henning & Stecklum (2001), Larson (2002). There is also an unpublished discussion by Yorke & Zinnecker in the Proc. of the Orion Ringberg Symposium (1997).

We would also like to cite the reviews of Garmany (1994) and Hunter (1995) on massive stars in OB associations and star clusters. The reference that is most relevant to the present paper on the multiplicity of massive stars is the study of Garcia & Mermilliod (2001) on the frequency of short-period spectroscopic binaries among the O-stars in young clusters, and to a lesser extent the data from Preibisch, Weigelt, & Zinnecker (2001) on visual binaries among OB stars found by speckle masking observations.

The outline of this presentation is as follows: first we review the recent data on the multiplicity of massive stars and then, in the second part, we infer some theoretical implications of the data. In particular we focus on stellar encounters of intermediate mass stars in dense young clusters (Bonnell, Bate, & Zinnecker 1998) and discuss the possibility of tidal capture – failed stellar mergers, as it were. In doing so, we highlight the fundamental role of gravitational focussing to form short-period massive binaries with periods of the order of 1 week. We present some results of recent numerical simulations regarding stellar encounters performed by Matthew Bate. We speculate on the physics of stellar collisions and the production of hard X-rays from them which might be detectable despite the dusty curtain behind which massive star formation takes place (perhaps by collisions of lower mass stars).

2. Review of the Binary Star Observations

We begin by providing a definition of "multiplicity". We refer to Reipurth & Zinnecker (1993) who among other possibilities propose the "companion star fraction" for the statistics of multiple systems. This definition is

$$csf = (B + 2T + 3Q)/(S + B + T + Q)$$

with S denoting the number of single stars, B the number of binaries, T the numter of triples, and Q the number of quadruples. Now we evaluate the csf for a given situation, say for a Trapezium system where star S1 is single, S2 is double, S3 is triple, and S4 is a hierarchical quadruple. In this case, csf = 1.5. This means that there are 1.5 companions on average which is a lot. For comparison, for low-mass pre-Main Sequence stars in the Orion Nebula cluster, we have csf = 0.5, i.e. a factor of 3 smaller than for our fiducial Trapezium system above.

2.1. Multiplicity of OB stars in the Orion nebula cluster etc

The multiplicity of 13 bright OB stars in the Orion nebula cluster has been investigated by Preibisch et al. (1999), using infrared speckle interferometry observations obtained at the Russian 6 m telescope. The speckle images have revealed 8 visual companions in total. Considering both, the visual and the spectroscopic companions of the 13 target stars, the total number of companions is at least 14. Extrapolation for unresolved systems suggests that there are at least 1.5 companions per primary star (i.e. csf = 1.5). This number is clearly higher than the mean number of about 0.5 companions per primary star for the low-mass stars in the Orion Nebula cluster (Prosser et al. 1994; Petr et al. 1998) as well as in the field population (Duquennoy & Mayor 1991). The earlier spectral types seem to have a higher companion star fraction than the later types, the dividing line being B3. All this may be a hint that the binary formation process is different for high-mass stars compared to that of lower-mass stars. We note in passing that the famous massive star theta-1 Ori C (mass 40 $M_\odot$), which is the exciting star of the Orion Nebula, is itself a binary system, with a companion at a projected separation of 33 mas or 16 AU and an estimated mass of about 5 $M_\odot$ (Weigelt et al. 1999). Orbital motion in theta-1 Ori C has meanwhile also been detected (Weigelt, pers. communication). An example where a complete orbit of a massive binary has been resolved is 15 Mon in the NGC 2264 cluster, and component masses of 35 and 24 $M_\odot$ have been derived (Gies et al. 1997).

The binary astrometric/spectroscopic binary frequency of early-type stars (B0-B3 vs. B4-B9) in the Sco OB2 association has been discussed by Brown (2001), with companion star fractions at face value of 0.8 and 0.4, respectively.

That binaries are common among O-stars in clusters and associations was also found in another, optical speckle survey of bright O-stars (Mason et al. 1998). However, they are much rarer among field O-stars and especially among runaway O-stars (ibid.).

2.2. Spectroscopic binaries among O stars in young clusters

A surprising new result is the statistics of close spectroscopic binaries among massive stars in young clusters, presented by Mermilliod & Garcia (2001) at the IAU Symp. 200 (see also Garcia & Mermilliod 2001). What they found are two very exciting results: first the spectroscopic binary frequency is extremely high, of the order of 80% in clusters rich in O-stars, i.e. 5 or more O-star members. The prime example they cite is NGC 6231 where 11 out of 14 O-stars are double. Second, they find that all except one of these double systems have similar orbital periods of the order of 5 days! These are very tight binaries indeed, with separations of order 0.2 AU only. In addition, they find that clusters poor in O-stars (say 1 or 2 only) usually feature Trapezium type systems, like in Orion. We propose that these findings must contain clues as to the formation process of massive binaries.

3. Implied Binary Formation Theory

3.1. Stellar encounters in very dense clusters

For the coagulation and tidal capture process to work, the star-star collision timescale

$$\frac{1}{t_{\rm coll}} = 16\sqrt{\pi} n v_{\rm disp} R_*^2 \left(1 + \frac{v_{\rm esc}^2}{v_{\rm disp}^2}\right)$$

in a dense cluster must be sufficiently short, i.e. of the order of or less than the cluster formation time (10^5 years or so).

This is possible if the stellar number density is of the order of 10^8 stars/pc^3, the velocity dispersion of the protocluster of the order of 10 km/s, and the cross section for collisions of the order of 10,000 times the geometrical cross section due to gravitational focussing. The geometrical radius of the intermediate- to high-mass stars that we are using here is of the order of 20 solar radii.

The situation that we envisage is one which might have occurred in a protocluster with parameters similar to the Orion Trapezium cluster, but initially with a stellar number density inside the core radius a factor of 1000 times higher as the core radius shrinks by a factor of 10, due to the gentle revirialisation of accreting protostars a la Bonnell, Bate, & Zinnecker (1998). Then the new core radius is 0.02 pc, 10 times smaller than the present one in the Trapezium Cluster (0.2 pc, McCaughrean, & Stauffer 1994). With 500 $M_\odot$ inside a virial radius of 0.02 pc, we obtain a velocity dispersion of 10 km/s. For these parameters, the cross-section for star-star collisions is enhanced by a factor $(v_{esc}/v_{disp})^2$ where v_{esc} is the escape speed from the star ($\sim$ 1000 km/s) and v_{disp} is the relative speed of the approaching stars at infinity, i.e. the velocity dispersion of the stars in the cluster.

We emphasise the fundamental role of gravitational focussing for this process of massive binary star formation. In essence, to form a massive binary star the impact parameter must be such that due to gravitational focussing of the initially hyperbolic (unbound) orbital motion, a grazing encounter has to occur during which tidal interaction can dissipate enough kinetic energy of the relative motion to result in an elliptical (bound) orbit. This process is called tidal capture.

If the separation near peri-astron is of the order of 2 stellar radii, tidal capture occurs, while if the separation is less than 1 stellar radius a collisional merger occurs. If the peri-astron separation is larger than 3 stellar radii, the stars continue on their hyperbolic path because not enough energy is dissipated for them to become bound. Thus the condition to form a massive binary is to start with an impact parameter of the order of 200 stellar radii, which after gravitational focussing will lead to a grazing encounter with a peri-astron passage at 2 stellar radii.

3.2. Recent results from numerical simulations

Recently, as a follow-up to the original suggestion that massive stars may form via mergers of lower mass stars (Bonnell, Bate, & Zinnecker 1998), Matthew Bate performed smoothed particle hydrodynamics (SPH) simulations of stellar collisions and close encounters. The stellar models consisted of 1-, 3-, and 5-$M_\odot$ pre-main-sequence stars with ages of 2×10^5 years and a zero-age main-sequence 10-$M_\odot$ star (since the pre-main-sequence lifetime of a 10-$M_\odot$ is shorter than 2×10^5 years). The stellar models were provided by Chris Tout.

Several of these collisions are illustrated in Figures 1 and 2. The aims of these calculations were to determine the radii within which two stars merge or form a binary due to tidal capture, to determine the mass lost in such encounters, and to examine the structure of the post-collision objects.

In order for a significant number of collisions to occur within $\sim$ 1 Myr, stellar densities of $\sim 10^8$ stars/pc^3 are required (Bonnell, Bate, & Zinnecker 1998). The associated stellar velocity dispersion is $\approx 10 - 15$ km/s. At these velocities, the SPH simulations show that most encounters where the energy dissipation is sufficient to form a binary result in mergers (i.e. in order to dissipate the required amount of kinetic energy the distance at which stars must pass is a significant fraction of their combined radii). Furthermore, even if a tidal-capture binary is formed, its main effect is to increase the cross-section of the system for the next encounter. This is because the binary is so close that an encounter with a third object results in a chaotic interplay that almost certainly results in a merger, possibly of all three objects. Thus, it is clear that most encounters will result in mergers and that the formation tidial-capture binaries will increase the merger rate. However, it is not yet clear how many tidal-capture binaries there are in existence at any one time in a dense cluster. This is currently being investigated by using the results of the SPH collisions to construct a model of how the dense core of a cluster evolves with time.

Something that may greatly increase the number of close O-star binaries is the formation of discs around massive stars during encounters. The SPH encounter simulations show that a low-mass pre-main-sequence star $\lesssim 3\ M_\odot$ that has a close encounter with a massive zero-age main-sequence star (e.g. 10 $M_\odot$) is tidally disrupted, forming a disc around the massive star. The radius of this disc can easily be an order of magnitude larger than the radius of the massive star. If another star passes through this disc it may result in enough dissipation to form a binary with the massive star. Thus, a sequence of tidal disruption followed by star-disc capture may result in much wider binaries than tidal capture alone. This may increase the survival rate of O-star binaries since the lower ratio of stellar sizes to orbit size makes subsequent encounters more likely to result in hardening of the existing binary or exchange to form a new binary rather than a merger of all three of the objects. Again, more work is required in order to be able to determine the companion star fraction that results from such a model.

4. Physics of stellar collisions

What happens if two stars of $10\,M_\odot$ collide head-on with each other? One can calculate that a kinetic energy $E_{kin} = 10^{50}$ erg will be released in such a collision, assuming it occurs with relative velocity of 1000 km/s. The collisional heat input will lead to a large puffed-up stellar object, with a higher cross-section for the next collision. The object will shrink on a Kelvin-Helmholtz timescale (of the order of $t_{KH} = 10^4$ years), which then corresponds to a luminosity $L = E_{kin} \,/\, t_{KH} = 10^5\,L_\odot$.

What happens to the angular momentum in a non-head-on star-star collision? The numerical simulations suggest that the star is not disrupted, rather the excess of angular momentum leads to a flattened object as the merger product. If several random collisions occur in the build-up of a massive stars, one would expect a random walk of angular momentum vector. However, the net result is still a rapidly rotating object. What is not clear is how quickly this object is able to spin down. As the puffed up object relaxes, a small disc may form around the star allowing angular momentum to be transported from the star to the disc. Alternately, if the collision results in a convection zone, the star may be braked by a magnetic wind. It is worth noting that a similar problem of rapid rotation rates applies to the collision model for the formation of blue-stragglers in star clusters (Leonard & Livio 1995; Lombardi et al. 1996; Sills et al. 1997).

Both the grazing encounters that seem to be best for forming close binaries by tidal capture and the star-disc capture mechanism imply high eccentricity orbits, at least initially. The closest of these may be circularised due to subsequent tidal interaction. The rest, especially those formed by star-disc capture should remain eccentric. Thus, our binary formation mechanism predicts SBs with high eccentricity, a prediction that can be tested.

Is there a reason why in massive binaries there is a preference for equal mass components? We note that equal mass components have the largest cross section for tidal capture (the highest dissipation of kinetic energy). Another reason could be stellar dynamics which favours exchange reactions where a lighter companion is replaced by a heavier one.

5. Future observational challenges

We end by listing a few questions which need answers. At present we don't have these answers, but there is hope that the answers will come in sooner or later.

1. IRc2-I behind the Orion Nebula cluster is probably the nearest high-mass star in the making (e.g. Gezari et al. 1998). Is there a hidden, deeply embedded cluster of lower mass stars around that massive protostar or not?

2. Ultra-compact HII regions are very dense gas and dust condensations. Are there compact embedded clusters in there where stellar collisions and mergers are going on? And what is going on inside the hyper-compact HII regions?
3. Hard X-rays have been detected by Chandra in ultra-compact HII regions, as reported at this workshop. Is this kind of hard X-ray emission indicative of a high-velocity stellar collision deep inside a compact heavily embedded protocluster?
4. There seem to be at least a few isolated O-stars. Are these truly isolated O-stars, not formed in a cluster or have these objects been ejected from their parent cluster? Radial velocity and proper motion studies are needed to measure space motions. An interesting case is the young embedded cluster S255 where two B0 stars are seen outside the cluster, at the same projected distance and in almost opposite directions (Zinnecker, McCaughrean, & Wilking 1993; Kroupa 2001).
5. The most massive stars in the Galaxy appear to exceed a mass of $100\,M_{\odot}$, e.g. HD93129A in Carina (Taresch et al. 1997). This $120\,M_{\odot}$ object is a single star, but perhaps it was initially a very close binary of two $60\,M_{\odot}$ stars! Can the upper limit of stellar mass be boosted by the tidal merging of the two tight stellar components (Zinnecker 1986)?

6. Conclusions

Recent spectroscopic observations have shown that many massive stars live in very tight binary systems, as predicted by the coalescence scenario for the origin of massive stars. However, this is no proof yet that the accretion scenario is ruled out, but it puts up a tough challenge (e.g. close binary formation by gravitational instability and fragmentation of a massive accretion disk). The next step is to search for radial velocity variations in the youngest obscured massive stars detectable by high-resolution infrared spectroscopy, in order to check whether these stars are really born as very close massive binaries or whether they reach such a configuration not at birth but subsequently through gravitational N-body dynamics in a dense protocluster.

Acknowledgments. H. Zinnecker would like to thank the SOC for inviting him to this exciting workshop, and in particular Bo Reipurth being session chairman introducing his talk. H. Zinnecker would also like to thank Bo Reipurth and his wife for offering their extraordinary house and hospitality to him and his daughter during their stay in Boulder.

References

Bernasconi, P. A. & Maeder, A. 1996, A&A, 307, 829

Bonnell, I. A., Bate, M. R., & Zinnecker, H. 1998, MNRAS, 298, 93

Bosch, G. et al. 2001, astro-ph/0110345, accepted for A&A

Brown, A. G. A. 2001, AN, 322, 43

Duquennoy, A. & Mayor, M. 1991, A&A, 248, 485

Garay, G. & Lizano, S. 1999, PASP, 111, 1049

Garcia, B. & Mermilliod, J. C. 2001, A&A, 368, 122

Garmany, C. D. 1994, PASP, 106, 25

Gezari, D. Y., Backman, D. E., & Werner, M. W. 1998, ApJ, 509, 283

Gies, D. R. et al. 1997, ApJ, 475, L49

Henning, Th. & Stecklum, B. 2001 in ASP Conf. Ser., Modes of Star Formation and the Origin of Field Populations, ed. E. K. Grebel & W. Brandner, in press

Hunter, D. A. 1995, RMxAC, 3, 1

Jijina, J. & Adams, F. C. 1996, ApJ, 462, 874

Kahn, F. D. 1974, A&A, 37, 149

Kroupa, P. 2001 in IAU Symposium 200, The Formation of Binary Stars, ed. H. Zinnecker & R. D. Mathieu (ASP), 199

Larson, R. B. 2002, MNRAS, in press

Leonard, P. J. T., Livio, M., 1995, ApJ, 447, L121

Lombardi, J. C., Jr., Rasio, F. A., Shapiro, S. L., 1996, ApJ, 468, 767

Mason, B. D. et al. 1998, AJ, 115, 821

Massey, P., Penny, R. P., & Vukovich, J. 2001, astro-ph/0110088

McCaughrean, M. J. & Stauffer, J. R. 1994, AJ, 108, 1382

Nakano, T. 1989, ApJ, 345, 464

Petr, M. G. et al. 1998, ApJ, 500, 852

Preibisch, Th. et al. 1999, NewA, 4, 531

Preibisch, Th., Weigelt, G., & Zinnecker, H. 2001 in IAU Symposium 200, The Formation of Binary Stars, ed. H. Zinnecker & R. D. Mathieu (ASP), 69

Prosser, C. F. et al. 1994, ApJ, 421, 571

Sills, A., Lombardi, J. C., Jr., Bailyn, C. D., Demarque, P. D., Rasio, F. A., Shapiro, S. L., 1997, ApJ, 487, 290

Stahler, S. W., Palla, F., & Ho, P. T. P. 2000 in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: University of Arizona Press), 327

Taresch, G. et al.1997, A&A, 321, 531

Weigelt, G. et al. 1999, A&A, 347, L15

Wolfire, M. G. & Cassinelli, J. P. 1987, ApJ, 319, 850

Yorke H. W. & Krügel E. 1977, A&A, 54, 183

Yorke H. W. & Zinnecker, H. 1997, Ringberg Orion Symp.

Zinnecker, H. 1986 in IAU Symposium 116 Luminous Stars and Associations in Galaxies, ed. C. W. H. de Loore, A. J. Wiilis, & P. Laskarides (ASP), 271

Zinnecker, H., McCaughrean, M. J., & Wilking, B. A. 1993 in Protostars and Planets III, ed. M. Matthews (Tucson: University of Arizona Press), 429

Discussion

1) Achim Tieftrunk:
Since grazing collisions are in a narrow regime between total misses and collisions, would the number of binary or multiple O/B stars not be very low rather than very high as indicated by the detections of spectroscopic binaries or speckle masking binaries? Grazing collisions forming a bound binary should be extremely rare, no?

2) Hans Zinnecker:
Due to the high velocity dispersion the tidal capture cross section is smaller than the cross section for collisions that lead to mergers. However, the process of tidal disruption of low-mass stars followed by star-disc encounters would tip the balance strongly in favour of binary formation rather than mergers. More detailed studies are required before we can make an accurate prediction.

3) Andre Maeder:
There is a lot of angular momentum available in grazing collisions. Even if there is a lot of dissipation, should not the final massive stars resulting from coalescence be all close to the critical rotational velocities?

4) Hans Zinnecker:
The products of non-head-on collisions do rotate at close to break up and are noticeably flattened. Therefore, massive stars should be fast rotators, at least initially. However, it is possible that they spin down due to magnetic braking or due to the formation of a disc as they relax thermally. It is unclear how efficient these mechanisms are.

Note added in proof: Bosch et al. (2001) conclude that the measured velocity dispersion among massive stars in the R136 cluster in the LMC is dominated by spectroscopic binaries (velocity amplitude $\sim 35\,\mathrm{km/s}$); see also Massey, Penny, & Vukowich (2001) who recently discovered four very massive SB2 in R136.

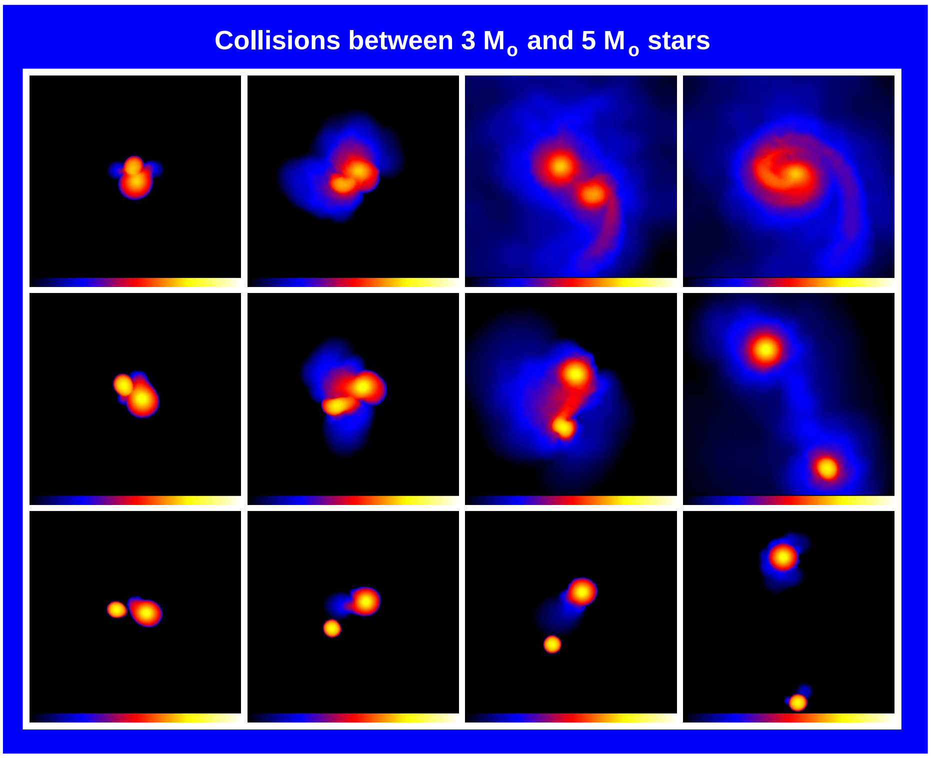

Figure 1. Encounters between 3-M$_\odot$ and 5-M$_\odot$ pre-main-sequence stars. The stars have radii of 7.95 and 12.9 solar radii, respectively. Three encounters are shown: a collision with $r_{\rm min} = 8.6$ solar radii resulting in a merger (top), a grazing encounter with $r_{\rm min} = 21.5$ resulting in a binary (middle), and a detached encounter with $r_{\rm min} = 25.8$ resulting in a tidal-capture binary (bottom). All encounters have zero relative velocity at infinity (i.e. parabolic encounters). This is a good approximation since the relative velocity at closest approach is much greater than the expected velocity dispersion in the cluster ($\sim 10\,{\rm km/s}$).

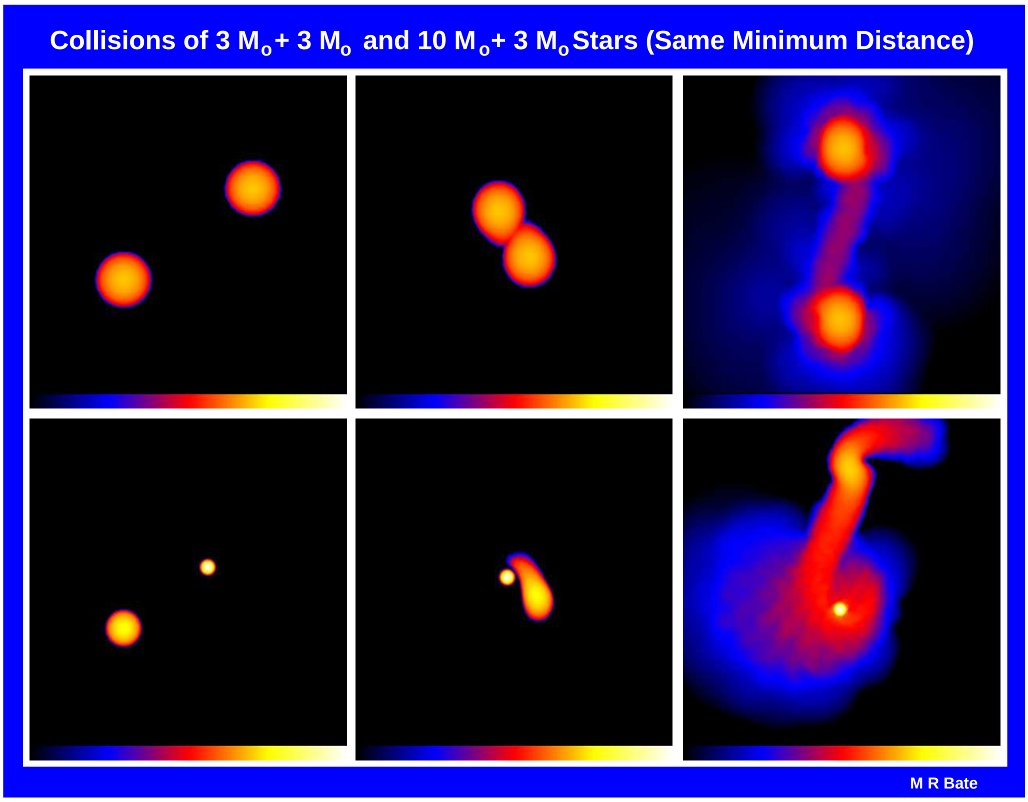

Figure 2. Top: A grazing encounter between two 3-M$_\odot$ pre-main-sequence stars that results in the formation of a binary ($r_{\rm min}$ = 25.8 solar radii). Bottom: A detached encounter between a 3-M$_\odot$ pre-main-sequence star and a 10-M$_\odot$ zero-age main-sequence star with the same minimum periastron distance as the top encounter. The stars have radii of 12.9 and 3.92 solar radii respectively. The greater density of the 10-M$_\odot$ star results in tidal disruption of the low-density 3-M$_\odot$ star to form a disc around the massive star. The encounters have zero relative velocity at infinity (i.e. parabolic encounters).