High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
Proceedings IAU Symposium No. 346, 2019
L. M. Oskinova, E. Bozzo, T. Bulik & D. Gies, eds.

doi:10.1017/S1743921318008074

The formation of massive binaries as a result of the dynamical decay of trapezium systems

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Abstract. We propose that a significant fraction of the wide massive binaries in the field are formed as a result of the disintegration of multiple systems of trapezium type. As examples we discuss here the binaries formed from the evolution of the mini-cluster associated with the B component of the Orion Trapezium, from that of the Orion Trapezium itself, and from 10 additional massive trapezia for which we found reliable data in the literature.

Keywords. binaries: general — stars: early-type — stars: kinematics and dynamics — stars: formation

1. Introduction

The formation of massive wide binaries, which are quite abundant among early-type field stars, is still an open problem. One plausible mechanism is the dynamical disintegration of small star clusters (Reipurth 2000; Kouwenhoven *et al.* 2010, Reipurth & Mikkola *et al.* 2012, Reipurth *et al.* 2014). Indeed, as a by-product of our studies of the dynamical evolution of massive trapezium-type multiple systems we have found that at least one binary remains at the end of the evolution (Allen *et al.* 2015, 2017, 2018). These binaries will end up as field binaries, and it is interesting to compare their properties with the observational data.

We follow the definition of Ambartsumian (1954) for a trapezium. Let a multiple star system (of 3 or more stars) have components a, b, c,... If three or more distances among the components are of the same order of magnitude, then the system is a trapezium; otherwise, the system is of ordinary (or hierarchical) type. Two distances are of the same order of magnitude in this context if their ratio is greater than 1/3 but less than 3. Since only the angular separations are available, the sample of observed trapezia will contain also optical trapezia and pseudotrapezia. An optical trapezium is an apparent multiple system whose components are not physically connected. A pseudo-trapezium is a hierarchical system that appears as a trapezium due to projection. Ambartsumian and later Abt & Corbally (2000) showed that the number of pseudotrapezia is small only among multiple systems of spectral types B3 and earlier.

To model the dynamical evolution of trapezia we performed Monte Carlo N-body simulations for each system. As initial conditions we used the planar positions, transverse velocities, distances and masses from the best observations found in the literature. Radial velocities (when unavailable) and z-positions were modeled by Monte Carlo simulations. In the following sections we discuss the results we obtained for the mini-cluster associated with the B component of the Orion Trapezium, for the Orion Trapezium itself, and for 10 additional massive trapezia with data from the literature, with particular emphasis on the properties of the binaries formed.

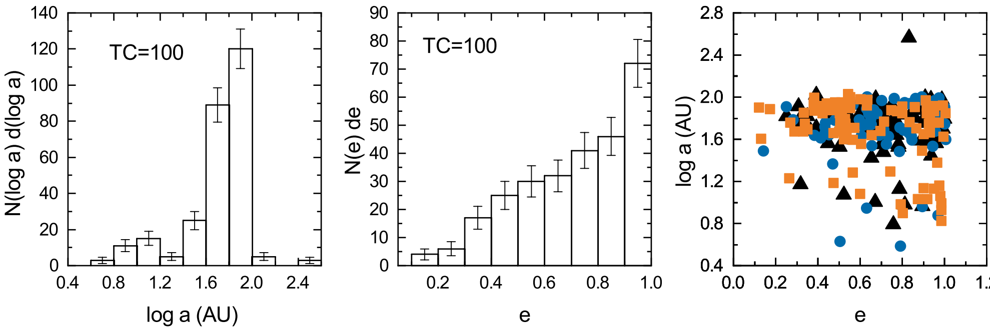

Figure 1. Properties of the binaries formed during the dynamical evolution of θ^1 Ori B at TC=100 (100 crossing times or about 30,000 years). Left panel: Frequency distribution of the major semi-axes. Middle panel: Frequency distribution of eccentricities. Right panel: Semi-axes as a function of eccentricities. Triangles, dots, and squares correspond to simulations with slightly different initial conditions.

2. N-body simulations of the mini-cluster θ^1 Ori B

This mini-cluster was studied in detail by Close *et al.* (2013), providing us with a suitable set of initial conditions to simulate its dynamical evolution (Allen *et al.* 2015). We obtained 300 Monte Carlo realizations for this mini-trapezium, by randomly perturbing each quantity according to its associated observational uncertainty. The N-body integrations showed that the systems evolved and disintegrated rapidly, with lifetimes of about 30 thousand years. Interestingly, the most massive stars, designated as (B1+B5) and B2 by Close *et al.* (2013) formed a close stable binary in 60 % of the cases. Binaries with major semi-axes as small as 6 AU were formed. Most of the escaping single stars were of low mass, but in 4 % of the cases the most massive binary (B1+B5) escaped. Most of the escapers were ejected with low velocities, but in 7 % of the cases runaway stars (stars with velocities larger than 3 times the escape velocity) were ejected. The statistical properties of the resulting binaries are shown in Figure 1. These properties are similar to those of field binaries (Duquennoy & Mayor 1991; Raghavan *et al.* 2010; Sana *et al.* 2012, 2014; Duchêne & Kraus 2013; Moe & Di Stefano 2017).

3. N-body simulations of the Orion Trapezium

The initial conditions for this system (distance, planar positions, radial velocities and masses) were taken from the literature (Allen *et al.* 2017). The separation velocities were computed from a combination of historical and modern measures of the separations among the components as a function of time. This provided us with a time span of over 180 years. For the other quantities, we tried to select the most reliable observational values. Since the z-positions are not available, they were randomly assigned, with a dispersion equal to the radius of the system. Random perturbations to each quantity were applied to obtain 100 realizations of the Orion Trapezium. We found that the systems disintegrated in less than 10 thousand years when we adopted the recently determined value for the mass of component C, $M_C = 45\ M_\odot$. We obtained more plausible lifetimes adopting $M_C = 65\ M_\odot$. With this value,the systems survived for about 30 to 40 thousand years, a lifetime compatible with that we found for θ^1 Ori B. The result of the integrations was usually a wide massive binary, always with star C as the primary. In 66% of the cases Star C was accompanied by the second most massive star. Hence, the dynamical decay of such systems is able to populate the field with wide massive binaries. The properties of the resulting binaries are shown in Figure 2. As mentioned before, these properties are similar to those observed for field binaries.

https://doi.org/10.1017/S1743921318008074 Published online by Cambridge University Press

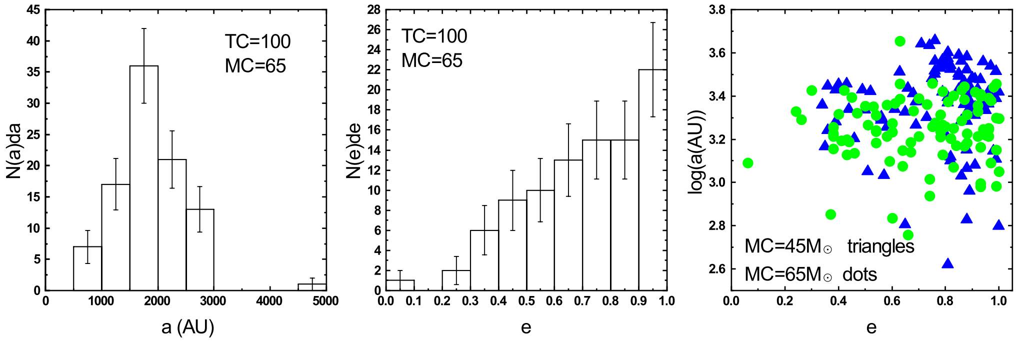

Figure 2. Properties of the binaries formed during the dynamical evolution of the Orion Trapezium at TC=100 (100 crossing times or about one million years). Left panel: Frequency distribution of the major semi-axes. Middle panel: Frequency distribution of the eccentricities. Right panel: Semi-axes as a function of eccentricities.

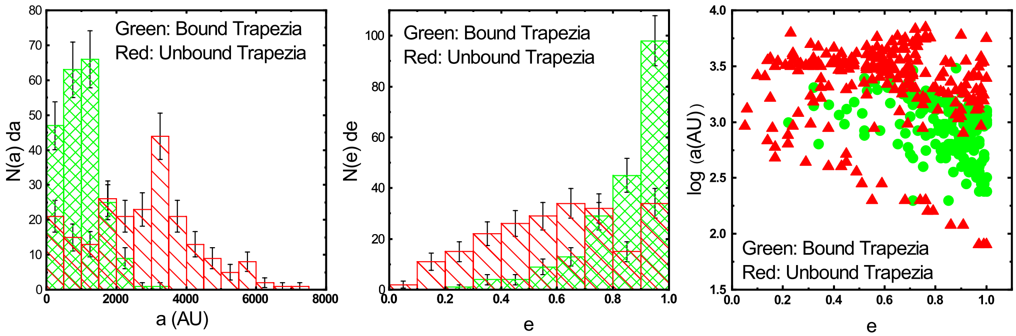

Figure 3. Properties of the binaries formed during the dynamical evolution of 10 massive trapezia. Binaries from bound systems are depicted as green-cross hatched bins, those from unbound systems as red-single hatched bins. Left panel: Frequency distribution of the major semi-axes. Middle panel: Frequency distribution of the eccentricities. Right panel: Semi-axes as a function of the eccentricities. Triangles and dots correspond to unbound and bound systems respectively.

4. N-body simulations of ten massive trapezia

To complete our study of the dynamical evolution of trapezia we conducted an extensive search of the literature. This search produced only 10 early-type systems likely to be true trapezia and with sufficient data to compute separation velocities among their components.

Here again, we obtained some initial conditions (planar positions, distances and masses) from the literature. Separation velocities among the components were calculated combining historical and modern measures of the separations among the components, as they change over time. Since neither z-positions nor radial velocities are available, they were randomly assigned, with dispersions compatible with the positions and transverse velocities of each trapezium. Random perturbations representing the observational uncertainties were applied to the observed data. In this way we obtained 100 Monte Carlo realizations for each of the 10 trapezia studied.

The numerical integrations showed that most systems resulted unbound; they remained unbound even doubling the values of the component masses to account for probable undiscovered binaries in them. The unbound systems rapidly dispersed, but in most of them energy redistribution among the components took place, and binaries were formed.

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The bound systems evolved dynamically and disintegrated in about 10 thousand years. The result was usually a binary, sometimes a triple system of either hierarchical or non-hierarchical type. Hierarchical triples remained stable over the whole integration time of 1 million years. Non-hierarchical triples could survive for up to 300 thousand years.

Among the realizations for the bound trapezium ADS 719 we found that in all but 2 cases the most massive star formed a binary, and in 63 % of the cases it was accompanied by the second most massive star.

The properties of the resulting binaries are shown in the three panels of Figure 3. The binaries formed in bound systems have properties similar to those of field binaries, those stemming from unbound systems do not accord well with observations.

5. Conclusions

Our results show that the dynamical lifetimes of trapezium-type systems are extremely short, much shorter than the evolutionary lifetimes of their massive components. Only assuming much larger masses for the components could the lifetimes become longer. The end result of the simulations is usually a massive binary, sometimes a triple system. The dynamical disintegration of trapezium systems thus produces wide binaries that end up as field massive binaries.

Most semiaxes are of a few thousands AU, but binaries as close as a few AU are formed in some trapezia. Finally, the distributions of major semi-axes and eccentricities of binaries formed during the integrations are similar to those observed for wide massive field binaries.

Acknowledgments

A. R.-M and L. J. S. thank DGAPA-UNAM for financial support under PAPIIT projects IN102617 and IN102517.

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