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Dynamical evolution of young binaries and multiple systems

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Abstract. Most stars, and perhaps all, are born in small multiple systems whose components interact, leading to chaotic dynamic behavior. Some components are ejected, either into distant orbits or into outright escapes, while the remaining components form temporary and eventually permanent binary systems. More than half of all such breakups of multiple systems occur during the protostellar phase, leading to the occasional ejection of protostars outside their nascent cloud cores. Such orphaned protostars are observed as wide companions to embedded protostars, and thus allow the direct study of protostellar objects. Dynamic interactions during early stellar evolution explain the shape and enormous width of the separation distribution function of binaries, from close spectroscopic binaries to the widest binaries.

Key words. Stars: pre-main sequence – Stars: protostars – Binaries: close

1. Introduction

With the sensitivity and resolution of modern observing techniques that can probe the interior of star forming clouds, it has become increasingly clear that formation of binaries and multiple stars is the norm, and that the formation of single stars is the exception. It has even been suggested that *all* stars form in multiple systems, and that subsequent dynamical evolution creates the mixture of single, double, triple, etc., systems that we observe in the field (Larson 1972). The number of multiple systems is indeed observed to decrease from Class 0 to Class I to Class II and to field stars (e.g., Connelley et al. 2008, Chen et al. 2013, Duchêne & Kraus 2013, Reipurth et al. 2014).

The separation distribution function of binaries has a peak around 30 AU (Duquennoy & Mayor 1991), and at large separations a it approximately follows $f(a) \propto 1/a$ as originally proposed by Öpik (1924). Binaries are found with a very large range of separations, from very short-period spectroscopic binaries with separations of a few stellar radii to ultrawide common proper motion pairs with separations of more than a parsec. This represents a factor of more than a million in separation, which is a major challenge for any theory of star formation. The key to understanding such a huge spread in semimajor axes can be found in the dynamics of higher-order multiple systems.

2. Dynamics of triple systems

Triple systems are the most common multiple systems and are consequently the best studied. Almost all observed triple systems are *hierarchical*, that is, the ratio of separation of the outer and inner pairs is large, typically larger than 10, which allows orbital motion

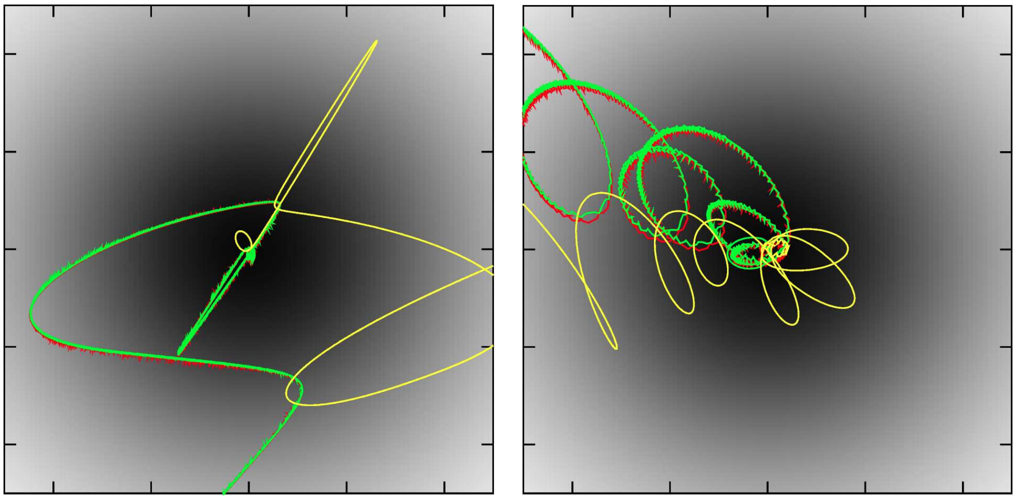

Fig. 1. Examples from numerical simulations of the dynamical evolution of triple systems moving in and accreting from a dense cloud core modelled as a Plummer core. In both cases two of the stars rapidly form a close binary which dynamically interacts with the third body. In the left panel the triple system eventually breaks up into a binary and an unbound single star, while in the right panel a bound triple system drifts out of the core. The width of each panel is 10,000 AU. From Reipurth & Mikkola (2015).

that does not destabilize the system. Triple systems, however, are generally believed to form in *non-hierarchical* configurations, which lead to highly unstable behaviors. Chaotic motion of the three bodies occasionally leads to close triple encounters, during which the three bodies occupy a small volume of space at the same time, which allows a transfer of energy and momentum. Close triple encounters lead to the ejection of a member of the system, often the least massive, either into a distant bound orbit or into an escape. At the moment of breakup, the two remaining bodies are bound into a binary system (e.g., van Albada 1968, Anosova 1986). The components are usually modelled as point sources, but for young stars embedded in a cloud core from which the stars can accrete, additional phenomena take place. Figure 1 shows two examples of the dynamical evolution of triple systems born in a cloud core, from which the three bodies can accrete. Figure 2 shows schematically the possible outcomes of three identical stellar seeds formed in and accreting from a cloud core: either one body falls to the dense center of the cloud core where it rapidly grows while banishing the two other bodies to the tenuous outskirts of the core, or two bodies form a rapidly growing binary in the center leaving the third body to grow much slower. The exact distribution of final masses depends on the specific dynamical evolution of each body, and to analyze the outcome of hundreds of thousands of numerical simulations it is useful to employ the *triple diagnostic diagram*, seen in Figure 3, in which two dimensionless parameters are plotted against each other: the mass ratio of the binary vs the mass of the third body relative to the total system mass. Broadly speaking, the diagram is divided into systems where the binary is dominant (left side), or the single is dominant (right side) or the two are approximately equal (center), with binaries with a high mass ratio near the top and with a low mass ratio at the bottom of the diagram. All observed triple systems will fall within these categories and the relative numbers of different types gives a diagnosis of the dynamical evolution that the three bodies have undergone (Reipurth & Mikkola 2015).

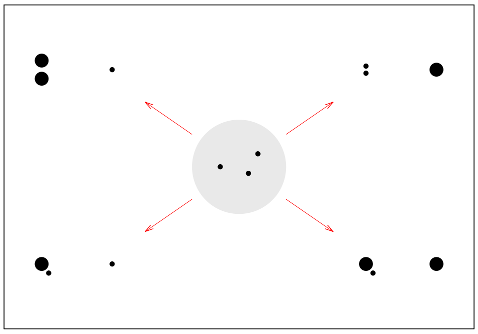

Fig. 2. A schematic presentation of possible outcomes of an initially non-hierarchical triple system accreting within a cloud core. From Reipurth & Mikkola (2015).

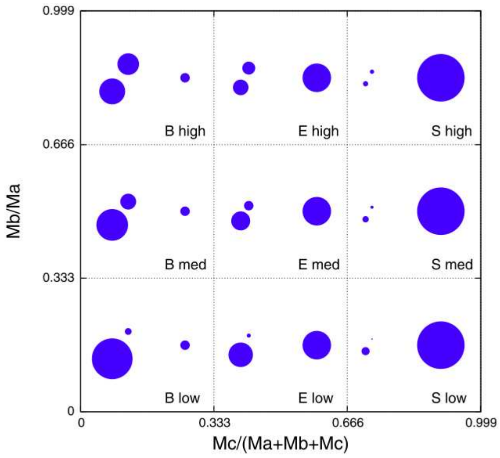

Fig. 3. The triple diagnostic diagram plots two dimensionless parameters of hierarchical triple systems against each other: the mass ratio of the binary along the Y-axis and the mass of the single body relative to the total system mass on the X-axis. All triple systems find a place in this diagram, with triple systems dominated by a more massive binary to the left and systems dominated by a massive single to the right. From Reipurth & Mikkola (2015).

3. Orphaned protostars

In a major study of the binarity of isolated IRAS sources representing embedded Class I objects, Connelley et al. (2008a,b) found a surprising excess of wide companions with separations from about 1000 AU to 4500 AU. Even more surprising, when the fraction of these wide binary companions were plotted as a function of spectral index for the IRAS sources, a steep decline was seen (Figure 4). Since spectral index is a measure of circumstellar material, and this is likely to decline with time, the spectral index can be used as a proxy for age. In other words, as the objects age, the wide companions disappear. In order to understand the cause of this, Reipurth et al. (2010) carried out numerical N-body experiments of triple system behavior each spanning 10 Myr. It was found that more than half of the triple systems break up already while the systems are embedded within their nascent cloud cores and are in their protostellar phases. Objects ejected to the outskirts of the core or beyond must climb out of the potential well of the core before they can escape. Many end up falling back into the core for further dynamical interactions, thus leading to a sequence of ejection events in a yo-yo like motion (Figure 5). Eventually, either a particularly strong ejection allows an escape or an ejected body must await that the core has lost most of its mass. Reipurth et al. (2010) coined the term *orphan* to describe a protostellar object which has been dynamically ejected from a newborn multiple system, either into a tenuously bound wide orbit or into an escape. The wide companions discovered by Connelley et al. (2008a,b) that gradually disappear with time are the orphans found in the simulations. As a consequence of such dynamical interactions some protostellar objects are observable outside their cores as near-infrared or even as optical objects. Those objects that are ejected into escapes so early that they have not yet accumulated 0.08 $M_\odot$ of mass will remain forever as brown dwarfs (Reipurth & Clarke 2001).

4. Formation of close binaries

Binaries cannot form with such close separations as observed for spectroscopic binaries, and hence they must have spiraled in from initially wider separations. For this to happen the binaries must be embedded in a medium, and hence spectroscopic binaries must form during the protostellar phase. Stahler (2010) showed that a binary embedded in very dense

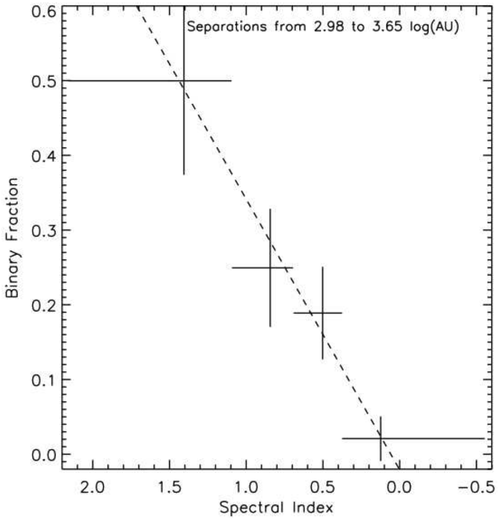

Fig. 4. The fraction of wide companions to embedded Class I protostars is found to decline steeply as a function of the spectral index of the protostars, an indicator of circumstellar material, and thus a proxy for age. These tenuously bound companions are orphaned protostars that eventually become unbound and drift away. From Connelley et al. (2008b).

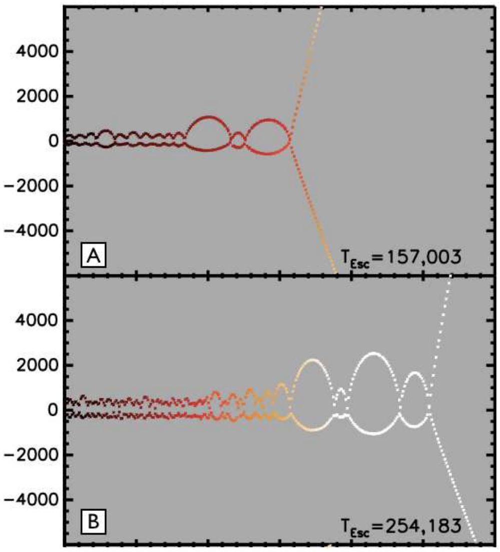

Fig. 5. Two examples of the dynamical behavior of single and binary components of unstable triple systems. The single is towards the top of each plot and the binary beneath it. The X-axis is 300,000 years and the Y-axis is 10,000 AU. From Reipurth et al. (2010).

gas can spiral in due to dynamical friction. A way to start this process is when a triple system breaks up, forming a tight highly eccentric binary with a distant or escaping third body. As already mentioned above, more than half of all triple systems break up during the embedded phase, some very early, others later when the gas reservoir is more depleted (Reipurth et al. 2010). Depending on how much gas the binary is surrounded by at the time of its formation, it may shrink to become a spectroscopic binary. Statistics of Population II field stars indicate that 18 ± 4% are spectroscopic binaries (Carney et al. 2003). If everything else is equal, we would thus expect that very short period spectroscopic binaries are those binaries that became bound very early, during the Class 0 phase. It is conceivable that some in-spiraling binaries may even merge, which may account for at least some of the FU Orionis type eruptions observed in star forming regions. A possible observational signature of the in-spiraling phase would be that circumstellar disks around the individual components perturb each other during periastron passages of the highly eccentric binary, thus causing massive accretion and outflow. As the binary shrinks, such increasingly frequent outflow events would appear as giant, bright Herbig-Haro jets, as opposed to the common faint microjets expected from single stars (Reipurth 2000).

5. Formation of wide binaries

The definition of a wide binary varies from study to study, but generally describes binaries with separations larger than 500 - 1000 AU. A number of models have been proposed for the formation of wide binaries. Kouwenhoven et al. (2010) and Moeckel & Clarke (2011) considered the possibility that when a young star cluster expands and dissolves following gas dispersal, two stars may drift away in the same direction, forming a wide binary. Alternatively, Sadavoy & Stahler (2017) envisaged collapse within a single cloud core leading to a wide binary, while Tokovinin (2017) suggested that two adjacent cloud cores that move slowly rel-

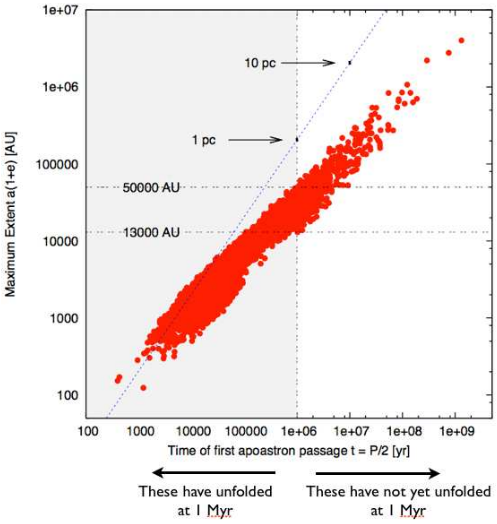

Fig. 6. A system with outer period P of 2 Myr will for the first time reach apastron after 1 Myr. All systems in the grey-shaded area have reached apastron at least once within 1 Myr. During that time, no system has reached a separation of more than 50,000 AU. The dotted line shows how far the centre of mass of a triple system has moved in a given amount of time assuming a velocity of 1 km s^{-1}. Values are shown for 1 Myr and 10 Myr. The widest systems, which take tens or hundreds of millions of years to unfold, will have moved away from the denser and more perilous environment in which they were born before being fully unfolded. From Reipurth & Mikkola (2012).

ative to each other can form a bound wide binary system. In the context of multiple systems discussed here, Reipurth & Mikkola (2012) showed that when a triple system breaks up, the third component can be ejected into a very distant bound orbit with a semimajor axis of thousands of AU, even in rare cases reaching separations of a parsec or more. Systems born with such wide separations would be unlikely to survive in a complex star forming region with numerous stars and clouds. But the key is that a triple system is born compact and only after breakup does it begin to unfold. For very wide systems it can take several million years to reach apastron for the first time, and during that period of unfolding the system will have drifted away from its site of formation (Figure 6). In this scenario, a very wide binary is protected against external disruption by being much more compact during the critical journey out of its birth site. Many wide binaries would thus turn out to be triple systems upon close examination, although of course wide binaries formed by some of the other mechanisms mentioned above could produce wide binaries with only two bodies. The wide binaries observed in the field may thus have several different formation histories.

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