Multiplicity in Early Stellar Evolution

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Observations from optical to centimeter wavelengths have demonstrated that multiple systems of two or more bodies is the norm at all stellar evolutionary stages. Multiple systems are widely agreed to result from the collapse and fragmentation of cloud cores, despite the inhibiting influence of magnetic fields. Surveys of Class 0 protostars with mm interferometers have revealed a very high multiplicity frequency of about 2/3, even though there are observational difficulties in resolving close protobinaries, thus supporting the possibility that all stars could be born in multiple systems. Near-infrared adaptive optics observations of Class I protostars show a lower binary frequency relative to the Class 0 phase, a declining trend that continues through the Class II/III stages to the field population. This loss of companions is a natural consequence of dynamical interplay in small multiple systems, leading to ejection of members. We discuss observational consequences of this dynamical evolution, and its influence on circumstellar disks, and we review the evolution of circumbinary disks and their role in defining binary mass ratios. Special attention is paid to eclipsing PMS binaries, which allow for observational tests of evolutionary models of early stellar evolution. Many stars are born in clusters and small groups, and we discuss how interactions in dense stellar environments can significantly alter the distribution of binary separations through dissolution of wider binaries. The binaries and multiples we find in the field are the survivors of these internal and external destructive processes, and we provide a detailed overview of the multiplicity statistics of the field, which form a boundary condition for all models of binary evolution. Finally we discuss various formation mechanisms for massive binaries, and the properties of massive trapezia.

1. INTRODUCTION

Many reviews have been written on pre-main sequence binaries over the past 25 years, e.g., *Reipurth* (1988), *Zinnecker* (1989), *Mathieu* (1994), *Goodwin* (2010), and particular mention should be made of IAU Symposium No. 200 (*Zinnecker and Mathieu,* 2001), which is still today a useful reference. Most recently, *Duchêne and Kraus* (2013) review the binarity for stars of all masses and ages.

Stimulated by the growing discoveries of multiple systems among young stars, there is increasing interest in the idea, first formulated by *Larson* (1972), that all stars may be born in small multiple systems, and that the mixture of single, binary, and higher-order multiples we observe at different ages and in different environments, may result from the dynamical evolution, driven either internally or externally, of a primordial population of multiple systems. While more work needs to be done to determine the multiplicity of newborn protostars, at least – as has been widely accepted for some time – binarity and multiplicity is clearly established as the principal channel of star formation. The inevitable implication is that dynamical evolution is an essential part of early stellar evolution. In the following we explore the processes and phenomena associated with the early evolution of multiple systems, with a particular emphasis on triple systems.

2. PHYSICS OF MULTIPLE STAR FORMATION

The collapse and fragmentation of molecular cloud cores (*Boss and Bodenheimer*, 1979) is generally agreed to be the mechanism most likely to account for the formation of the majority of binary and multiple star systems. Major advances in our physical understanding of the fragmentation process have occurred in the last decade as a result of the availability of adaptive mesh refinement (AMR) hydrodynamics (HD) codes, which allow the computational effort to be concentrated where it is needed, in regions with large gradients in the physical variables. Many of these AMR codes, as well as smoothed particle hydrodynamics (SPH) codes with variable smoothing lengths, have been extended to include such effects as radiative transfer (RHD) and magnetic fields (MHD), allowing increasingly realistic three dimensional (3D) numerical models to be developed. We concentrate here on the theoretical progress made on 3D models of the fragmentation process since *Protostars and Planets V* appeared in 2007.

In *Protostars and Planets V*, the focus was on purely hydrodynamical models of the collapse of turbulent clouds initially containing many Jeans masses, leading to abundant fragmentation and the formation of multiple protostar systems and protostellar clusters (*Bonnell et al.*, 2007; *Goodwin et al.*, 2007; *Whitworth et al.*, 2007). 3D HD modeling work has continued on initially turbulent, massive clouds, with an eye toward determining cluster properties such as the initial mass function (e.g., *Clark et al.*, 2008; *Offner et al.*, 2009) and the number of brown dwarfs formed (e.g., *Bonnell et al.*, 2008; *Bate*, 2009a,b; *Attwood et al.*, 2009). 3D HD SPH calculations by *Bate* (2009a) made predictions of the frequency of single, binary, triple and quadruple star systems formed during the collapse of a highly unstable cloud with an initial mass of 500 $M_\odot$, a Jeans mass of 1 $M_\odot$, and a turbulent, high Mach number (13.7) velocity field. This simulation involved a sufficiently large population of stars and brown dwarfs (1250) so as to provide an excellent basis for comparison with observed multiple systems. It is remarkable that this simulation – which clearly omits important physical ingredients such as magnetic fields and radiative feedback – nevertheless results in a reasonable match to a wide range of observed binary parameters. In parallel with this study of binarity within the context of cluster formation, other groups have instead pursued high resolution core scale simulations of HD collapse of much lower mass, initially Bonnor-Ebert-like clouds, delineating how factors such as the initial rotation rate, metallicity, turbulence, and density determine whether the cloud forms a single or multiple protostar system (see *Arreaga-García et al.*, 2010 and *Walch et al.*, 2010 for SPH and *Machida*, 2008 for AMR calculations of this type).

Despite this striking agreement between the outcomes of the simplest barotropic models and observations, it is nevertheless essential to conduct simulations that incorporate a more realistic set of physical processes. *Offner et al.* (2009) found that radiative feedback in 3D RHD AMR calculations could indeed have an important effect on stellar multiplicity, primarily by reducing the number of stars formed. They also emphasized (*Offner et al.*, 2010) that the inclusion of radiative feedback changes the dominant mode of fragmentation: with a barotropic equation of state, fragmentation normally occurs at the point when the flow is centrifugally supported – i.e., when it collapses into a disk at radii < 100 AU. This mode is relatively suppressed when radiative feedback is included and the fragments mainly form from turbulent fluctuations within the natal core, at separations ~ 1000 AU. Such initially wide pairs, however, spiral in to smaller separations, an effect also found in the simulations of *Bate* (2012) which are the radiative counterparts of the previous (*Bate*, 2009a) calculations (see also *Bate*, 2009b). The resulting binary statistics are scarcely distinguishable from those in the earlier barotropic calculations and again in good agreement with observations (see Figure 1).

Observations of molecular clouds have shown that magnetic fields are generally more dynamically important than turbulence, but are only one source of cloud support against gravitational collapse for cloud densities in the range of 10^3 to 10^4 cm^{-3} (*Crutcher*, 2012). While it has long been believed that magnetic field support is lost through ambipolar diffusion, leading to gravitational collapse, current observations do not support this picture (*Crutcher*, 2012), but rather one where magnetic reconnection eliminates the magnetic flux that would otherwise hinder star formation (*Lazarian et al.*, 2012). 3D MHD calculations of collapse and fragmentation have become increasingly commonplace, though usually assuming ideal magnetohydrodynamics (i.e., frozen-in fields) rather than processes such as ambipolar diffusion or magnetic reconnection.

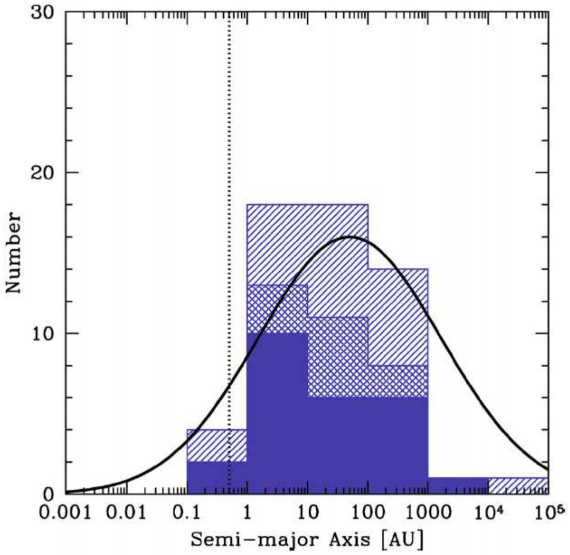

Fig. 1.— Distributions of semi-major axes for primaries with masses greater than 0.1 $M_\odot$ (histogram) from *Bate* (2012), compared to observations (solid line, *Raghavan et al.*, 2010). Solid, double-hatched, and single-hatched histograms are for binaries, triples and quadruples, respectively. The vertical line is the resolution limit of the SPH calculation.

Machida et al. (2008) found that fragmentation into a wide binary could occur provided that the initial magnetic cloud core rotated fast enough, while close binaries resulted when the initial magnetic energy was larger than the rotational energy. *Hennebelle and Fromang* (2008) and *Hennebelle and Teyssier* (2008) found that initially uniform density and rotation magnetic clouds could fragment if a density perturbation was large enough (50% amplitude), as in the standard isothermal test case of *Boss and Bodenheimer* (1979). *Price and Bate* (2007), *Bürzle et al.* (2011), and *Boss and Keiser* (2013) all studied the collapse of initially spherical, 1 $M_\odot$ magnetic cloud cores, with uniform density, rotation, and magnetic fields, the MHD version of *Boss and Bodenheimer* (1979). They found that clouds could collapse to form single, binary, or multiple protostar systems, depending on such factors as the initial magnetic field strength and its orientation with respect to the rotation axis. When fragmentation did occur, binary star systems were the typical outcome, along with a few higher order systems. *Joos et al.* (2012) found that the initial direction of the magnetic field with respect to the rotation axis had an important effect on whether the collapse produced a protostellar disk that might later fragment into a multiple system.

Radiative transfer effects were included in the models of

Commercon et al. (2010), who studied the collapse of 1 $M_\odot$ clouds with an AMR RMHD code, finding that frozen-in fields always inhibited cloud fragmentation. *Boss* (2009) used a 3D pseudo-MHD code with radiative transfer in the Eddington approximation to study the collapse and fragmentation of prolate and oblate magnetic clouds, including the effects of ambipolar diffusion, finding that the oblate clouds collapsed to form rings, susceptible to subsequent fragmentation, while prolate clouds collapsed to form either single, binary, or quadruple protostar systems. *Kudoh and Basu* (2008, 2011) also included ambipolar diffusion in their true MHD models, finding that collapse could be accelerated by supersonic turbulence.

There has also been progress in adding magnetic fields and feedback from radiation and outflows into simulations of more massive clouds, although many such simulations do not resolve fragmentation on scales less than ~ 100 AU (e.g., *Krumholz et al.*, 2012; *Hansen et al.*, 2012) and are thus not the simulations of choice for following binary formation. *Hennebelle et al.* (2011) followed the collapse of a 100 $M_\odot$ cloud with their AMR MHD code, and found that the magnetic field could reduce the degree of fragmentation, compared to a nonmagnetic cloud collapse, by as much as a factor of two. *Commercon et al.* (2011) extended their previous work on 1 $M_\odot$ clouds to include 100 $M_\odot$ clouds, but again found that magnetic fields and radiative transfer combined to inhibit fragmentation. *Seifried et al.* (2012) found that their 100 $M_\odot$ turbulent, magnetic clouds collapsed to form just a relatively small number of protostars. Likewise the high resolution simulations of *Myers et al.* (2013) (which combine the inclusion of radiative transfer and magnetic fields with a resolution of 10 AU within a 1000 $M_\odot$ cloud) find that these effects in combination strongly suppress binary formation within the cloud.

While powerful theoretical tools now exist, along with widespread access to large computational clusters, the huge volume of parameter space that needs to be explored has to date prevented a comprehensive theoretical picture from emerging. Nevertheless, it is clear that in spite of the various magnetic field effects, MHD collapse and fragmentation remains as a possibility in at least some portions of the parameter space of initial conditions. When fragmentation does occur in the collapse of massive, magnetic clouds, relatively small numbers of fragments are produced, compared to the results of 3D models of non-magnetic, often turbulent collapse, where much larger numbers of fragments tend to form (e.g., *Bonnell et al.*, 2007; *Whitworth et al.*, 2007). While such massive clouds might form small clusters of stars, low-mass magnetized clouds are more likely to form single or binary star systems.

In summary, then, it is premature to draw definitive conclusions about the conditions required to produce a realistic population of binary systems. Those simulations that can offer a statistical ensemble of binary star systems for comparison with observations are able to match the data very well, regardless of whether thermal feedback is employed (*Bate*, 2009a, 2012). The thermal feedback in these latter simulations is, however, under-estimated somewhat (*Offner et al.*, 2010) and so represents an interim case between the full feedback and no feedback case. It remains to be seen whether simulations with magnetic fields and full feedback do an equally good job at matching the binary statistics, despite the indications from the studies listed above that these effects tend to suppress binary fragmentation.

3. DEFINITION OF MULTIPLICITY

In order to discuss observational results and compare the multiplicity for different evolutionary stages and/or in different regions, we need simple and precise terminology. Following *Batten* (1973), the fractions of systems containing exactly n stars are denoted as f_n. The *multiplicity frequency* or *multiplicity fraction* $MF = 1 - f_1 = f_2 + f_3 + f_4 + \ldots$ gives the fraction of non-single systems in a given sample. This is more commonly written

$$MF = \frac{B+T+Q}{S+B+T+Q}$$

where S, B, T, Q are the number of single, binary, triple, and quadruple, etc systems (*Reipurth and Zinnecker*, 1993).

Another common characteristic of multiplicity, the *companion star fraction* $CSF = f_2 + 2f_3 + 3f_4 + \ldots$ quantifies the average number of stellar companions per system; it is commonly written

$$CSF = \frac{B+2T+3Q}{S+B+T+Q}$$

which is the average number of companions in a population, and in principle can be larger than 1 (e.g., *Ghez et al.* 1997). Measurements of MF are less sensitive to the discovery of all sub-systems than CSF, explaining why MF is used more frequently in comparing theory with observations. The fraction of higher-order multiples is simply $HF = 1 - f_1 - f_2 = f_3 + f_4 + \ldots$.

The vast majority of observed multiple systems are *hierarchical*: the ratio of separations between their inner and outer pairs is large, ensuring long-term dynamical stability. Stellar motions in stable hierarchical systems are represented approximately by Keplerian orbits. Hierarchies can be described by binary graphs or trees (Figure 2). The position of each sub-system in this graph can be coded by its *level*. The outermost (widest) pair is at the root of the tree (level *1*). Inner pairs associated with primary and secondary components of the outer pair are called levels *11* and *12*, respectively, and this notation continues to deeper levels. Triple systems can have inner pairs at level *11* or *12*. When both sub-systems are present, we get the so-called *2+2 quadruple*. Alternatively, a *planetary* quadruple system consists of levels *1*, *11*, and *111*; it has two companions associated with the same primary star.

In principle, the most precise description of multiplicity statistics would be the joint distribution of the main orbital parameters (period or semi-major axis, mass ratio, and eccentricity) at all hierarchical levels. But even for

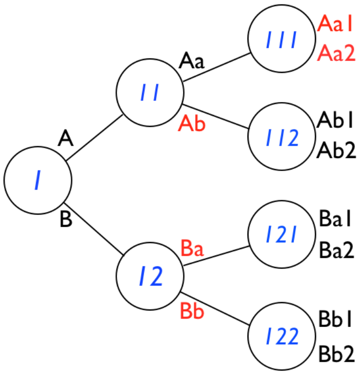

Fig. 2.— The structure of hierarchical multiple systems can be represented by a binary graph, the figure describes all possible multiples up to an octuple system. The position of each subsystem is coded by *levels* shown in blue in the circles. An example of a pentuple system is marked with red letters, the outer pair A,B is at level *1*, the innermost sub-sub-system Aa1,Aa2 is at level *111*. The nomenclature follows the IAU recommendation.

simple binaries such a 3-dimensional distribution is poorly known, and the number of variables and complexity increases quickly when dealing with triples, quadruples, etc. To first order, the multiplicity is characterized by the fractions f_n or by their combinations such as MF (which equals the fraction of level-*1* systems), CSF, and HF.

4. OBSERVATIONS OF PROTOSTELLAR BINARIES AND MULTIPLES

Studies of binaries and multiples during the protostellar stage are important, since they offer the best chance of seeing the results of fragmentation of molecular clouds, as discussed in Section 2. However, most protostars are still deeply embedded, so such observations are hampered by extinctions that can exceed $A_V \sim$ 100 mag. Hence, infrared, submillimeter, or radio continuum observations are required.

4.1. Infrared Observations

Class I protostars are often detectable at near-infrared wavelengths, although for disk orientations near edge-on one sees them only in scattered light. In contrast, the massive circumstellar environment of Class 0 sources make them detectable only at longer wavelengths. *Haisch et al.* (2004) performed a near-infrared imaging survey of 76 Class I sources and found a companion star fraction of 18%±4% in the separation range $\sim$300-2000 AU. In a similar study, *Duchêne et al.* (2004) obtained a companion star fraction of 27%±6% in the range 110-1400 AU. To detect closer companions, *Duchêne et al.* (2007) used adaptive optics to survey 45 protostars, and found a companion star fraction of 47%±8% in the range 14-1400 AU; comparison of the two numbers indicate the prevalence of close protostellar companions. In a major survey of 189 Class I sources, *Connelley et al.* (2008a,b) detected 89 companions, and the separation distribution function is shown in Figure 3a. For the closer separations, it is seen to be very similar to that of T Tauri binaries. But for larger separations, a clear excess of wide companions (with separations up to 4500 AU) becomes evident, which is not seen for the more evolved T Tauri stars. When plotting the binary fraction as a function of spectral index, which measures the amount of circumstellar material and is used as a proxy for stellar age, they find a dramatic decline in these wide companions (Figure 3b), from $\sim$50% to $<$5%. In other words, powerful dynamical processes must occur during the Class I phase, leading to the dispersal of a significant population of wide companions. These observations can be understood in the context of the dynamical evolution of newborn multiple systems, which in most cases break up, leading to the ejection of one of the components (see Section 5). Such ejected components should be observable for a while, and *Connelley et al.* (2009) found that of 47 protostars observed with adaptive optics, every target with a close companion has another young star within a projected separation of 25,000 AU.

The study of even closer companions to protostars is still in its infancy. In a pilot program, *Viana Almeida et al.* (2012) found large radial velocity variations in three out of seven embedded sources in Ophiuchus, and speculated that they could be evidence for spectroscopic protobinaries. *Muzerolle et al.* (2013) used the Spitzer Space Telescope to monitor IC 348 and found a protostar showing major luminosity changes on a period of 25.34 days; the most likely explanation is that a companion in an eccentric orbit drives pulsed accretion around periastron.

4.2. Submillimeter Observations

The study of binarity of the youngest protostars, the Class 0 sources, requires longer wavelength observations, and mm interferometry has become a powerful tool to study binarity of protostars. Pioneering work was done by *Looney et al.* (2000), who observed 7 Class 0 and I sources; further small samples of embedded sources were observed by, e.g., *Chen et al.* (2008, 2009), *Maury et al.* (2010), *Enoch et al.* (2011), and *Tobin et al.* (2013). All of these studies suffer from very small samples, and hence yield uncertain statistics. This problem has been alleviated by *Chen et al.* (2013), who presented high angular resolution 1.3 mm and 850 μm dust continuum data from the Submillimeter Array for 33 Class 0 sources. No less than twenty-one of the sources show evidence for companions in the projected separation range from 50 to 5000 AU. This leads to a multiplicity frequency MF = 0.64±0.08 and a companion star fraction CSF = 0.91±0.05 for Class 0 protostars. As noted by *Chen et al.* (2013), their survey is complete for systems larger than $\sim$1800 AU, and hence these values must be regarded as lower limits. Given that numerous Class 0 binaries may have much closer companions, these results are consistent with the possibility that virtually all stars are born as binaries or multiples, an idea that dates back to *Larson* (1972). Figure 4 shows in graphical form the observed decrease in binarity as a function of evolutionary stage, a

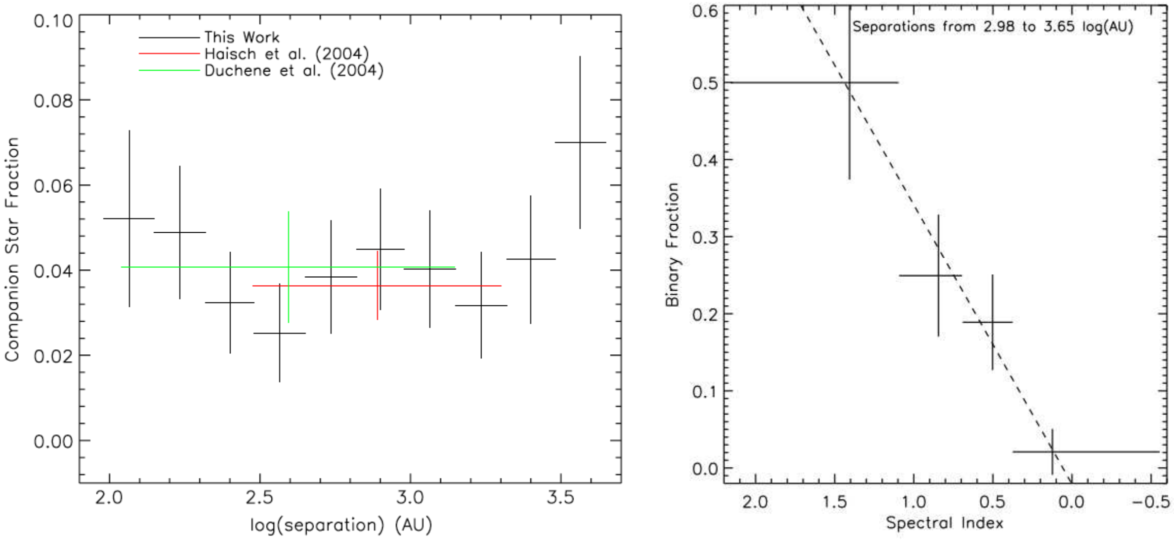

Fig. 3.— (a): The separation distribution function of embedded protostellar binaries. There is a strong excess of widely separated companions with separations larger than 1000 AU. (b): The population of wide companions is found to disappear with decreasing spectral index, which is a proxy for age. From *Connelley et al.* (2008a,b).

result that strongly supports a view of early stellar evolution in which small multiple systems evolve dynamically, break up, and the decay products eventually evolve into the distribution of singles, binaries, and higher-order multiples we observe in the field.

4.3. Radio Continuum Observations

As is clear from the discussion above, it is critically important to study protostars with much higher resolution in order to determine the multiplicity at small separations. Radio observations are the only technique available at present that allows the study with high angular resolution of the earliest stages of star formation. These studies can be performed with an angular resolution of order 0.1 arcsec with radio interferometers such as the Jansky Very Large Array (VLA) and the expanded Multi-Element Radio-Linked Interferometer Network (eMERLIN). What is detected here is the free-free emission from the base of the ionized outflows that are frequently present at early evolutionary stages. These structures trace the star with high precision, and favors the detection of very young Class 0, I, and II objects.

A series of VLA studies (e.g., *Rodríguez et al.*, 2003, 2010; *Reipurth et al.*, 2002, 2004) show binary and multiple sources clustered on scales of a few hundred AU. A binary frequency of order ∼33% is found in these studies. Since not all sources show free-free emission, and those which do are often found to be variable, such statistics provide only lower limits.

If the star has strong magnetospheric activity, the resulting gyrosynchrotron emission is compact and intense enough to be observed with the technique of Very Long Baseline Interferometry (VLBI) that can reach angular resolutions of order 1 milliarcsecond and better, and that allows the study of stellar motions with great detail. This technique favors the detection of the more evolved class III stars. It should be noted, however, that at least one class I protostar, IRS 5b in Corona Australis, has been detected with VLBI techniques (*Deller et al.*, 2013). In a series of studies to determine the parallax of young stars in Gould's Belt (*Loinard*, 2013), it has been found that several are binary and it has been possible to follow their orbital motions (e.g., *Torres et al.*, 2012) and to study the radio emission as a function of separation, finding evidence of interaction between the individual magnetospheres. Radio emission of non-thermal origin has been detected all the way down to the ultracool dwarfs (late M, L, and T types), in some sources in the form of periodic bursts of extremely bright, 100% circularly polarized, coherent radio emission (e.g., *Hallinan et al.*, 2007).

With the new generation of centimeter and millimeter interferometers, especially ALMA, the field of radio emission from binary and multiple young stellar systems faces a new era of opportunity that should result in much better statistics, especially in the protostellar stage.

5. DYNAMICS OF MULTIPLE STARS

If three bodies are randomly placed within a volume, then more than 98% of the systems will be in a non-hierarchical configuration, that is, the third body is closer than ∼10 times the separation of the other two bodies. It is well known that such configurations are inherently unstable, and will on a timescale of around 100 crossing times decay into a hierarchical configuration, in a process where the third body is ejected, either into a distant orbit or into an escape, see Figure 5, (e.g., *Anosova*, 1986; *Sterzik and Durisen*, 1998; *Umbreit et al.*, 2005). The energy to do this comes from the binding energy of the remaining binary, which as a result shrinks and at the same time fre-

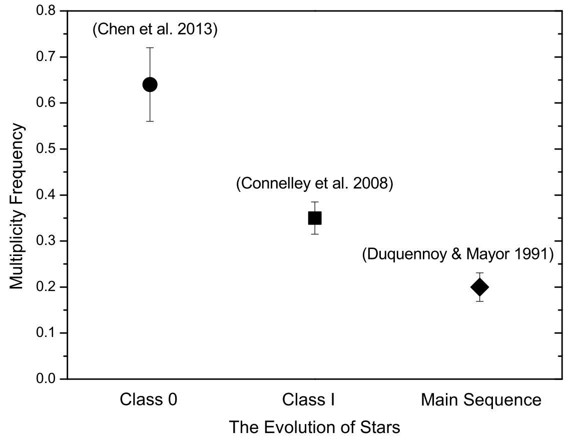

Fig. 4.— The multiplicity frequency declines through the protostellar phase because of the breakup of small multiple systems. From *Chen et al.* (2013).

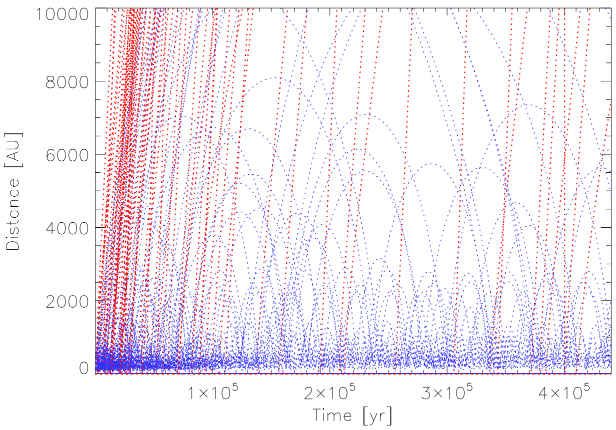

Fig. 5.— 100 simulations showing the dynamical evolution of a triple system of three 0.5 $M_\odot$ stars with initial mean separations of 100 AU embedded in a 3 $M_\odot$ cloud core. Many of the initial ejections are escapes, but the majority fall back, to be ejected sometimes again and again. From *Reipurth et al.* (2010).

quently gets a highly eccentric orbit. For such an ejection to take place, the three bodies must first meet in a close triple approach, during which energy and momentum can be exchanged. A detailed analysis of the dynamics of triple systems can be found in *Valtonen and Karttunen* (2006).

N-body simulations that include the potential of a cloud core reveal that many systems break up shortly after formation, sending the third body into an escape, but the majority goes through several or many ejections that are too weak to escape the potential well, and the third body thus falls back (*Reipurth et al.*, 2010). As the cloud core gradually shrinks through accretion, outflows, and irradiation, the third body eventually manages to escape. In some cases the triple remains bound until after the core has disappeared (see Figure 6), but only about ∼10% of triples are stable enough to survive on long timescales. The body that is ejected is most often the lowest-mass member, but complex dynamics can lead to many other configurations and outcomes. Stochastic events play an essential but unpredictable role in the early stages of triple systems, and so their evolution can only be understood statistically.

A stability analysis of hierarchical bound triple systems formed in N-body simulations shows that they divide into stable and unstable systems. Any time that a distant third component passes through a periastron passage and comes close to the inner binary, there is the possibility of an instability of the system, depending on the configuration of the inner binary. Stable triples remain bound for hundreds of millions or billions of years, but unstable systems can break apart at any time. Figure 7 shows the fraction of triples that after 100 Myr are stable, unstable, or already disrupted, as function of their projected separation, from a major N-body simulation. For separations less than 10,000 AU (vertical line) the majority is stable, but for wider separations unstable systems dominate. For young systems in star-forming regions, however, unstable systems significantly dominate at all separations. These unstable systems will soon break apart. For young ages, one therefore observes many more triple systems than at older ages (*Reipurth and Mikkola*, 2012).

Triple systems can be classified in the *triple diagnostic diagram* (Figure 8a), where the mass ratio of the binary is plotted as a function of the mass of the third body relative to the total system mass (*Reipurth and Mikkola*, 2014). In the right hand of the diagram reside the systems that are dominated by a massive single star (*S-type*), to the left are those where a massive binary dominates (*B-type*) and in the middle are the systems where the mass is about equally distributed in the binary and the single (*E-type*). Sub-divisions can additionally be made depending on the mass ratio of the binary (high, medium, low). Note that since the axes represent ratios, i.e., dimensionless numbers, then the absolute mass of the system is not involved. This simple classification system encompasses all categories of triple systems. As the name indicates, the distribution of systems in the diagram harbors important diagnostics for understanding the early evolution of triple systems. Figure 8b shows the result of N-body calculations that include accretion as the three bodies move around each other inside the cloud core. All systems in the diagram are long-term stable. To better isolate the interplay between dynamics and accretion, all three components started out with equal masses, i.e. they were initially placed at (0.333, 1.000). As is evident, the interplay between dynamics and accretion can lead to very different outcomes, with some areas of the diagram populated much more densely than others. Comparison with complete, unbiased samples of triples will provide much insight into the formation processes of triple systems.

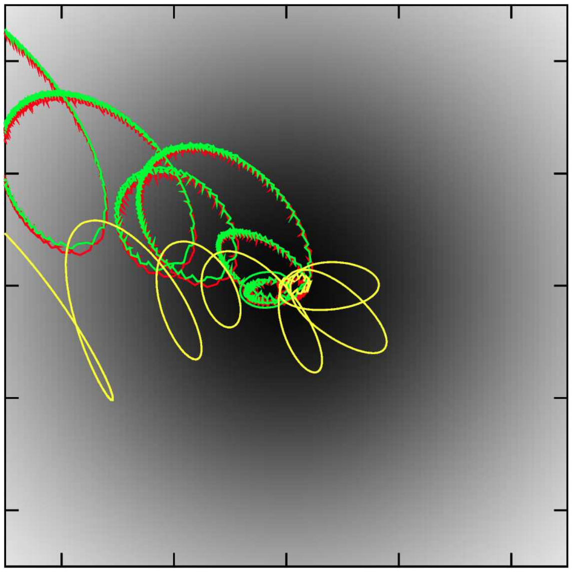

Fig. 6.— An example of the chaotic orbits of three bodies born in and accreting from a cloud core. The triple system in this simulation remains bound as it drifts away from the core, but is unstable and will eventually break apart. The figure is 10,000 AU across. From *Reipurth and Mikkola* (2014).

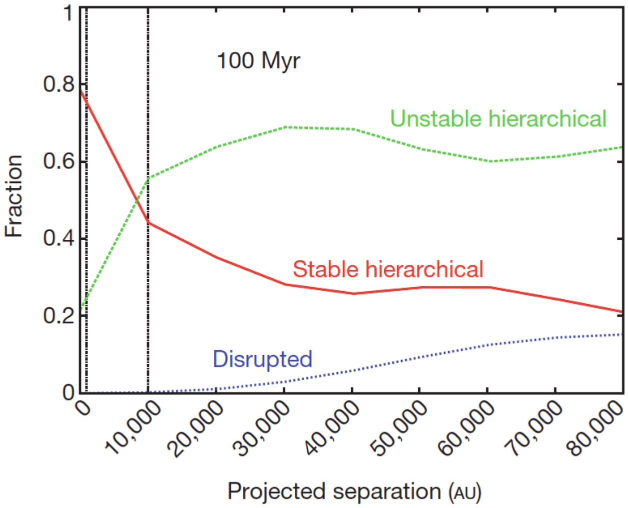

Fig. 7.— The relative numbers of bound stable, bound unstable, and unbound triple systems as function of the projected separation of the outer pairs, from a major N-body simulation after 100 Myr. The majority of very wide binaries is unstable at this age. At much younger ages, say 1 Myr, unstable systems dominate at all separations. (From *Reipurth and Mikkola*, 2012).

5.1. Origin of Brown Dwarf/VLM Binaries

The formation of very low mass ($M \lesssim 0.1\ M_\odot$) objects has been debated for a long time, and three basic ideas have emerged: a very low mass (VLM) object can form if the nascent core has too little mass (*Padoan and Nordlund*, 2004), or it can form if the stellar seed is removed from the infall zone through dynamical ejection (*Reipurth and Clarke*, 2001; *Stamatellos et al.*, 2007; *Basu and Vorobyov*, 2012), or the cloud core can photoevaporate if a nearby OB star is formed (*Whitworth and Zinnecker*, 2004). The emerging consensus is that all three mechanisms are likely to operate under different circumstances, and that the relevant question is not which mechanism is correct, but how big their relative contributions are to the production of VLM objects (*Whitworth et al.*, 2007). Similarly, BD/VLM binaries are likely to have several formation mechanisms.

Extensive numerical studies combining N-body simulations with accretion have shown that the large majority of brown dwarf ejections are not violent events, but rather the result of unstable triple systems that eventually drift apart at very small velocities, typically within the first 100 Myr (*Reipurth and Mikkola*, 2014). When brown dwarfs are released from triple systems, by far the majority of the remaining binaries are VLM objects. These binaries gently recoil and become isolated VLM binaries. These VLM binaries have a semimajor axis distribution that peaks at around 10-15 AU, but with a tail stretching out to ∼250 AU. At shorter separations, the simulations show a steep decline in number of systems, although the simulations underestimate the number of close binaries because they do not take viscous orbital evolution into account. Brown dwarf and VLM binaries formed through dynamical interactions can in principle have much larger separations, of many hundreds or thousands of AU, but in that case they must be bound triple systems, where one component is a close, often unresolved, binary. More than 90% of bound triple systems at 1 Myr have dispersed by 100 Myr, and *all* VLM triple systems with *outer* semimajor axes less than a few hundred AU have broken up. In this context, it is interesting that *Biller et al.* (2011) found an excess of 10-50 AU young brown dwarf binaries in the 5 Myr old Upper Scorpius association compared to the field.

5.2. Origin of Spectroscopic Binaries

Spectroscopic binaries is a generic term for all binaries that have separations so close that their orbital motion is measurable with radial velocity techniques. In practical terms, the large majority of known spectroscopic binaries has a period less than ∼4,000 days. Surveys of metal-poor field stars (for which statistics is particularly good) find that 18%±4% are spectroscopic binaries (*Carney et al.*, 2003).

Radial velocity studies of young stars are complicated by the sometimes wide and/or complex line profiles, but an increasing number of pre-main sequence spectroscopic binaries are now known (e.g., *Mathieu*, 1994; *Melo et al.*, 2001; *Prato*, 2007; *Joergens*, 2008; *Nguyen et al.*, 2012). In the Orion Nebula Cluster, *Tobin et al.* (2009) has up to now found that 11.5% of the observed members are spectroscopic binaries, but the survey is still ongoing.

Spectroscopic binaries have semi-major axes that are often measured in units of stellar radii, and rarely exceed a few AU. These binaries cannot form with such close separations, and they must therefore result from processes that cause a spiral-in of an initially wider binary system. Given

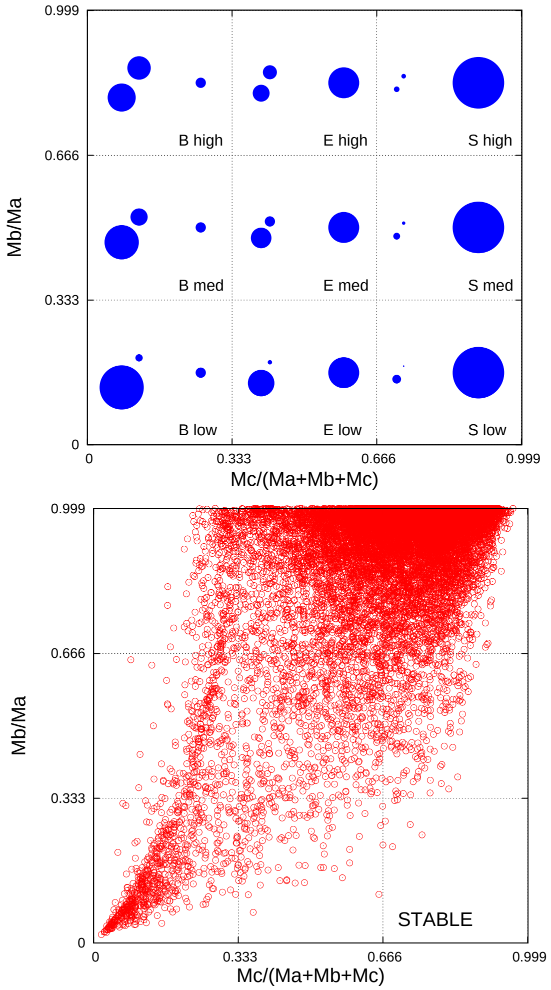

Fig. 8.— *(a)*: Location and definition of nine different types of triple systems in the triple diagnostic diagram. *(b)*: The location of 15,524 stable triple systems in the triple diagnostic diagram at an age of 1 Myr. Since all triple systems in these simulations were started out with three identical bodies, the original systems were all located at the point (0.333,1.000). Their final location is determined by their dynamical evolution and resulting accretion. From *Reipurth and Mikkola* (2014).

that newborn binaries and multiples are surrounded by a viscous medium during the protostellar phase, components can naturally spiral in during the star-forming process because of dynamical friction with the surrounding medium (e.g., *Gorti and Bhatt*, 1996; *Stahler*, 2010; *Korntreff et al.*, 2012), see Section 9.

The evolution of embedded triple systems can enhance or initiate this process. When a newborn triple system is transformed from a non-hierarchical configuration to a hierarchical one, the newly bound binary shrinks in order for the third body to be ejected into a more distant orbit or into an escape. The binary also gets a highly eccentric orbit as a result of this process. Given that the components are surrounded by abundant circumstellar material at early evolutionary stages, the shrinkage and the eccentric orbits force regular dissipative interactions, leading to orbital decay. As discussed by *Stahler* (2010), the ultimate result can be a merger. But if the infall of new material from an envelope ceases before that, then the orbital decay is halted, and the binary ends up with the orbital parameters it happens to have when the viscous interactions cease (except for very close binaries, where orbital circularization will occur – *Zahn and Bouchet*, 1989).

Spectroscopic binaries originating in a triple system therefore have an important stochastic element in their evolution, depending on when the triple system broke up and when circumstellar material became exhausted.

5.3. Origin of Single Stars

The strong increase in number of stars (single and non-single) for decreasing mass combined with the strong decrease in number of binaries also for decreasing mass (see Section 12) led *Lada* (2006) to conclude that the majority of stars in our Galaxy are single. And for solar-type stars in the solar neighborhood, *Raghavan et al.* (2010) found that 56% are single. This high preponderance of single stars is not consistent with the very high multiplicity frequency determined among protostars (see Section 4.2), and leads to interesting questions about the origin of single stars.

When we observe a single star, it may have one of three origins: it can be born in isolation; it may have been born in a multiple system that decayed and ejected one component; or it may even be the product of two stars in a binary that spiraled in and merged during the protostellar phase.

Historically, mergers have been considered almost exclusively in the contexts of late stellar evolutionary stages or massive stars. Intriguingly, new N-body simulations of low-mass small-N multiple systems and studies of orbital decay in a viscous medium indicate that mergers may occur in a non-negligible number of cases during early stellar evolution (*Rawiraswattana et al.*, 2012; *Stahler*, 2010; *Leigh and Geller*, 2012; *Korntreff et al.*, 2012).

Small triple systems, whether formed in isolation or in a cluster, will evolve dynamically, and ∼90% break up, each producing a single star, which drifts away with a velocity around 1 km/sec. This corresponds to ∼100,000 AU in half a million years, so very soon such ejecta will disperse and any trace of their origin will be lost. Because of dynamical processing, it is the lowest mass components that tend to escape. Newborn higher-order multiples such as quadruples, pentuples, sextuples, etc., may produce more than one single star per star forming event.

The formation of a single star from a collapse event is – not surprisingly – the standard view of the origin of single stars. However, the very high multiplicity of protostars (see Section 4.2) has by now made it clear that single-star collapse is not the principal channel of star formation. And it should by no means be automatically assumed that young single stars found in a low-mass star-forming region represent cases of single, isolated star formation.

6. OBSERVATIONAL CONSEQUENCES

The dynamical evolution discussed above has observational consequences:

FUor Eruptions. The close triple encounters in triple systems, that are prerequisites for the ejection of one of the components, are statistically most likely to occur during the protostellar stage (*Reipurth*, 2000). At this stage the three bodies are surrounded by significant amounts of circumstellar material, which will interact and cause a major brightening, from accretion and shock-heating. These events we here call *Encounters of Type 1*. After the hierarchical configuration has been achieved, the shrinking of the binary orbit and its high eccentricity will lead to a series of disk-disk interactions at each periastron passage (Figure 9). The disks will be seriously disturbed, causing eruptions, but much of the mass will fall back and reassemble in the disk again (*Clarke and Pringle*, 1993; *Hall et al.*, 1996; *Umbreit et al.*, 2011; see Section 9.6). As a result of this viscous evolution, the binary shrinks until the point when the stars are so close that the circumstellar material shifts from being in two circum*stellar* disks to instead assemble in one circum*binary* disk (*Reipurth and Aspin*, 2004). This sequence of eruptions is called *Encounters of Type 2*. Finally, if the triple evolution occurs so early that abundant gas is present, then the inspiral phase of the binary can result in the coalescence of the two stars (e.g., *Stahler*, 2010; *Rawiraswattana et al.*, 2012; *Leigh and Geller*, 2012); such events are called *Encounters of Type 3*. Observations have revealed various types of outbursts among young stars, the main one being the FUor eruptions (*Herbig*, 1977), see the *Audard et al.* chapter. Once enough detailed observations have become available, it may be possible to identify those that result from triple evolution, since each of the above types of encounters are likely to have characteristic energy releases and timescales, which may make them identifiable. It will be challenging to disentangle the various types of eruptions observed, since disks obviously can be disturbed also internally through instabilities, and disks have limited ways to react to perturbations, whether internal or external.

Herbig-Haro Flows. Accretion and outflow is generally coupled, and so the abovementioned encounters will give rise to different outflow characteristics, at young ages manifested as Herbig-Haro flows (*Reipurth and Bally*, 2001). Encounters of Type 1 from close triple approaches will result in one or a few giant bow shocks, while a sequence of Type 2 encounters will produce closely spaced knots, driven by cyclic accretion modulated on an orbital timescale, as seen in the finely collimated Herbig-Haro jets. Once the binary components have spiraled in so close that disk truncation rips up the magnetic field anchoring that supports the jet launch platform, then the collimated outflow phase is terminated, and subsequent mass loss will appear as massive but uncollimated winds, like those seen in the spectra of FUor eruptions. Seen in this perspective, giant HH flows represent a fossil record of the accretion history primarily dictated by the orbital evolution of their driving sources, which are expected to be multiple, as frequently observed (*Reipurth*, 2000). Other disk instabilities can also form Herbig-Haro flows, but on a smaller scale.

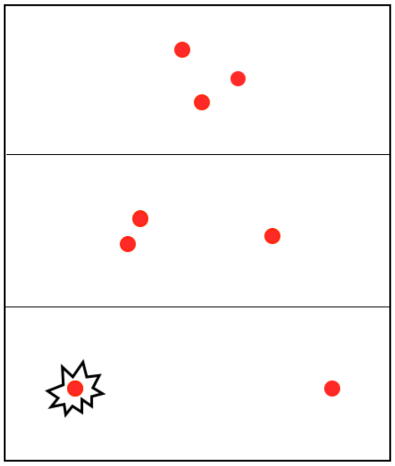

Fig. 9.— A schematic plot of the evolution of a triple system, from non-hierarchical to hierarchical (top two panels) followed by the binary viscous in-spiral phase leading to disk-disk interactions and in some cases stellar mergers.

Orphaned Protostars. The many dynamical ejections in which the third body fails to escape the potential well of the core plus remaining binary instead lead to large excursions, where the third body for long periods is tenuously bound in the outskirts or outside the cloud core. If such ejections occur during the protostellar stage, as many do, then these *orphaned protostars* open the possibility to study naked protostars still high up on their Hayashi tracks at near-infrared and even at optical wavelengths (*Reipurth et al.*, 2010). The triple system T Tauri may be a case.

Formation of Wide Binaries. Binaries with semimajor axes as large as 10,000 AU are now frequently found thanks to increasing astrometric precision. They challenge our understanding of star formation because their separations exceed the typical size of a collapsing cloud core. The dynamical evolution of multiple systems offers a simple way to form such wide binaries: although born compact, a triple system can dynamically scatter a component to very large distances, thus unfolding the triple system into an extreme hierarchical architecture. Many very wide binaries are therefore likely to be triples or higher-order multiples, although true binaries can also form when a merger has taken place in an encounter of Type 3 (*Reipurth and Mikkola*, 2012). Another independent mechanism that forms wide binaries in clusters is discussed in Section 10.2.

7. PRE-MAIN SEQUENCE BINARIES/MULTIPLES

It has been known since the early studies of T Tauri stars that some are binaries (*Joy and van Biesbroeck*, 1944; *Herbig*, 1962). Further interest was spurred by the discovery of an infrared companion to T Tauri by *Dyck et al.* (1982). In 1993, three major surveys appeared which established that

T Tauri stars have about twice the binary frequency compared to field stars, at least for the wider pairs (*Reipurth and Zinnecker*, 1993; *Leinert et al.*, 1993; *Ghez et al.*, 1993). In the following, we examine the status 20 years later.

7.1. Statistics and Environment

When comparing the multiplicity of young stars to the field, the key reference for solar-type field stars has been *Duquennoy and Mayor* (1991). Since that study, observational techniques have improved, and *Raghavan et al.* (2010) have studied 454 F6-K3 dwarf and subdwarf stars within 25 pc using many different techniques. Their observed fractions of single, binary, triple and quadruple stars are 56±2%:33±2%:8±2%:3±1%, yielding a completion-corrected multiplicity frequency of 46%, and implying that among *solar type* stars, the majority are single. They also found that 25% of non-single stars are higher-order multiples, and that the percentage of triple and quadruple systems is roughly twice that estimated by *Duquennoy and Mayor* (1991). Systems with larger cross sections, i.e., those with more than two components or with long orbital periods, tend to be younger, indicating the loss of components with time.

De Rosa et al. (2014) have studied 435 A-type stars and, within the errors, they find the precise same fractions of singles, binaries, etc., as *Raghavan et al.* (2010) did for later-type stars.

Among more massive stars, the radial velocity study of *Chini et al.* (2012) examined 250 O-stars and 540 B-stars and found that more than 82% of stars with masses above 16 $M_\odot$ form *close* binaries, but that this high frequency drops monotonically to less than 20% for stars of 3 $M_\odot$ (see Section 11). For late type stars, *Fischer and Marcy* (1992) found a binary frequency of 42±9% among nearby M dwarfs, while *Bergfors et al.* (2010) for M0-M6 dwarfs measured 32±6% in the range 3-180 AU. For very late-type stars (M6 and later) *Allen* (2007) determined a binary frequency of 20-22%, consistent with the ∼24% binary frequency found for L dwarfs by *Reid et al.* (2006). And *Kraus and Hillenbrand* (2012) found a smooth decline in binary frequency from 0.5 $M_\odot$ to 0.02 $M_\odot$. Altogether, these results confirm the trends seen in various other investigations (e.g., *Raghavan et al.*, 2010), namely that *binarity is a strongly decreasing function with decreasing stellar mass*.

For young stars, getting good statistics is obviously more difficult. The more massive young stars, the Herbig Ae/Be stars, have long been known to have a high binarity. *Leinert et al.* (1997) used speckle interferometry to find a binary frequency of 31% to 42%, while *Baines et al.* (2006) used spectro-astrometry to determine a binary frequency of 68±11%, with a hint that the binarity of Herbig Be stars is higher than for the Herbig Ae stars. To this should be added the spectroscopic binaries, which *Corporon and Lagrange* (1999) found to be around 10%. *Kouwenhoven et al.* (2007) analyzed several data sets on the Upper Sco association, and found that intermediate mass stars have a binary frequency >70% at a 3σ confidence level.

The most thoroughly examined low-mass star-forming region is Taurus-Auriga, and in a detailed study *Kraus et al.* (2011) found an observed multiplicity frequency of ∼60% for separations in the range 3–5000 AU. When corrections are done to account for missing very close and very wide companions, the multiplicity frequency rises to ∼67–75%.

Taurus-Auriga, however, appears to be different from other low mass star-forming regions (e.g., *Correia et al.*, 2006), see Section 10.3. Chamaeleon I was studied by *Lafrenière et al.* (2008), who found a multiplicity frequency of 30±6% over the interval ∼16-1000 AU. In Ophiuchus, *Ratzka et al.* (2005) determined a multiplicity frequency of 29±4% in the range 18–900 AU, while in the Upper Scorpius region of the Scorpius-Centaurus OB association *Kraus et al.* (2008) found a binary frequency of 35±5% in the 6-435 AU range. When properly scaled and compared, these values are consistent within their errors, suggesting that Taurus is atypical.

Other observations indicate that multiplicity differs among some regions. For example, *Reipurth and Zinnecker* (1993) found that young stars in clouds with ten or fewer stars were twice as likely to have a visual companion as clouds with more stars. *Brandeker et al.* (2006) found a deficit of wide binaries in the η Chamaeleontis cluster. *Kraus and Hillenbrand* (2007) noted that the wide binary frequencies in four star-forming regions are dependent on both the mass of the primary star and the environment, but did not find a relation with stellar density. *Connelley et al.* (2008b) found that the binary separation distribution of Class I sources in a distributed population in Orion (not near the Orion Nebula Cluster) is significantly different from other nearby, low-mass star-forming regions.

Naturally, these results raise the question whether the environment plays a role for the population of binaries and multiples. It is conceivable that different physical conditions can affect the frequency and properties of newborn binaries (*Durisen and Sterzik*, 1994; *Sterzik et al.*, 2003). And longer-term dynamical interactions between binaries and single stars will depend on the stellar density in the birth environment (e.g., *Kroupa*, 1998; *Kroupa and Bouvier*, 2003; *Kroupa and Petr-Gotzens*, 2011). Assuming all stars are formed as binaries in groups and clusters of different densities, *Marks and Kroupa* (2012) show that – using an inverse dynamical population synthesis – the abovementioned binary properties in different star-forming regions can be reproduced. This is further discussed in Section 10.

7.2. The Separation Distribution Function

Binaries have separations spanning an enormous range, from contact binaries to tenuously bound ultrawide binaries and proper motion pairs with separations up to a parsec (and possibly even more). The way binaries are distributed along this vast range in separations carries information on both the mechanisms of formation and subsequent dynamical (and sometimes viscous) evolution. We note that almost all authors for practical reasons use projected separations. Because most binaries are eccentric and therefore spend more time near apastron than at periastron, one can show that – for reasonable assumptions about eccentricity – the mean instantaneous projected separations and mean semi-major axes differ by only $\sim$5% (e.g., *van Albada*, 1968).

Öpik (1924) suggested that the distribution of separations for field binaries follows a log-flat distribution *f(a)* $\propto$ *1/a*, whereas *Kuiper* (1942) found a log-normal distribution; the latter has been supported by both *Duquennoy and Mayor* (1991) and *Raghavan et al.* (2010), who found the peak of the distribution of solar-type binaries to be at $\sim$30 AU and $\sim$50 AU, respectively, and Öpik's Law is no longer considered for closer binaries. But the distribution of the widest binaries can be fitted with a power law, although with an exponent between -1.5 and -1.6, decreasing somewhat faster than Öpik's Law (*Lépine and Bongiorno*, 2007; *Tokovinin and Lépine*, 2012).

For young low-mass stars the separation distribution function is less well known. For clusters, the absence of wide binaries has been noted in the Orion Nebula Cluster (*Scally et al.*, 1999; *Reipurth et al.*, 2007), see Section 10.3. Among less densely populated low-mass star-forming regions, the most detailed study is of Taurus by *Kraus et al.* (2011). They find that the separation distribution function for stars in the mass range from 0.7 to 2.5 $M_\odot$ is nearly log-flat over the wide separation range 3–5000 AU, that is, there are relatively more wide binaries among young stars than in the field.

For very low mass (VLM) objects, it has been known for some time that the mean separation and separation range of binaries, both young and old, shrink with decreasing mass (see *Burgasser et al.*, 2007 and references therein). Where *Fischer and Marcy* (1992) found that M-star binary separations peak around 4-30 AU, *Burgasser et al.* (2007) estimated that VLM objects peak around $\sim$3-10 AU. *Kraus and Hillenbrand* (2012) studied low-mass (0.02–0.5 $M_\odot$) young stars and brown dwarfs in nearby associations and found that the mean separation and separation range of binaries decline smoothly with mass; a degeneracy between total binary frequency and mean binary separation, however, precludes a more precise description of this decline.

7.3. Mass Ratios

The mass ratios ($q = M_2/M_1$) we observe for young stars are dominated by processes during the protobinary accretion phase, and subsequent circumbinary disk accretion will have only limited effect on the mass ratios (see Section 9.2). Spectroscopic determinations of YSO binary component masses are still rare (e.g., *Daemgen et al.*, 2012, 2013; *Correia et al.*, 2013), and estimates of mass ratios for young stars are mostly based on component photometry, with the significant caveats that come from accretion luminosity, differences in extinction of the components, and biases towards detecting brighter companions. For young intermediate mass stars in the Sco OB2 association, *Kouwenhoven et al.* (2005) could fit the mass ratio distribution with a declining function for rising mass ratios ($f(q) \sim q^{-0.33}$), revealing a clear preference for low-q systems. In contrast, low mass YSOs have a gently rising distribution for rising mass ratios, which becomes increasingly steep for VLM objects, showing a clear preference for $q{\sim}1$ binaries (*Kraus et al.* 2011; *Kraus and Hillenbrand*, 2012), as do VLM binaries in the field (e.g., *Burgasser et al.*, 2007). It is noteworthy that this naturally results from dynamical interactions in VLM triple systems (*Reipurth and Mikkola*, 2014).

7.4. Eccentricities

The eccentricity of binaries in the solar neighborhood has been studied by *Raghavan et al.* (2010), who finds an essentially flat distribution from circular out to $e{\sim}0.6$ for binaries with periods longer than $\sim$12 days (to avoid the effects of circularization). Higher eccentricities are less common, but this may be due to observational bias. For VLM binaries, *Dupuy and Liu* (2011) found eccentricities with a distribution very similar to the solar neighborhood.

Little is known about eccentricities of young binaries, except for the $\sim$50 mostly short-period spectroscopic PMS binaries that have been analyzed to date; *Melo et al.* (2001) found that binaries with periods less than 7.5 days have already circularized during pre-main sequence evolution, in agreement with theory (*Zahn and Bouchet*, 1989).

8. PRE-MAIN SEQUENCE ECLIPSING BINARIES

Accurate measurements of the basic physical properties – masses, radii, temperatures, metallicities – of PMS stars and brown dwarfs are essential to our understanding of the physics of star formation. Dynamical masses and radii from eclipsing binaries (EBs) remain the gold standard, and represent the fundamental testbed with which to assess the performance of theoretical PMS evolution models. In turn these models are the basis for determining the basic properties of all other young stars generally – individual stellar masses and ages, mass accretion rates – and thus help to constrain key aspects of star-forming regions, such as cluster star-formation histories and initial mass functions.

8.1. Performance of PMS Evolutionary Models

The *PPV* volume included a summary of the properties of the 10 PMS stars that are components of EBs known at that time (*Mathieu et al.*, 2007), and summarized the performance of four different sets of PMS evolutionary tracks (*D'Antona and Mazzitelli*, 1997; *Baraffe et al.*, 1998; *Palla and Stahler*, 1999; *Siess et al.*, 2000) in predicting the dynamically measured masses of these stars from their H-R Diagram positions. To summarize briefly the current status: *(1)* All of the above models correctly predict the measured masses to $\sim$10% above 1 $M_\odot$; *(2)* the models overall perform poorly below 1 $M_\odot$, generally predicting masses larger than the observed masses by up to 100%, and *(3)* the models of *Palla and Stahler* (1999) and *Siess et al.* (2000)

are performing the best, predicting the observed masses to 5% on average although with a large scatter of 25%.

There are now as of this writing 23 PMS stars that are components of 13 EBs, including two brown dwarfs in one EB (*Stassun et al.*, 2006, 2007). An important development is the emergence of new models – the first in more than a decade – with physics attuned to PMS stars, namely the Pisa models (*Tognelli et al.*, 2011) and the Dartmouth models (e.g., *Dotter et al.*, 2008; *Feiden and Chaboyer*, 2012). A full assessment of the latter models against the sample of PMS EBs is underway (*Stassun et al.*, in prep.), but preliminary results are promising. For example, the dynamically measured masses are correctly predicted by the Dartmouth models to ∼15% over the range of masses 0.2–1.8 $M_\odot$.

The major review by *Torres et al.* (2010), while focused on main-sequence EBs, highlights the importance of reliable metallicities, temperatures, and (when possible) apsidal motions. Among PMS EBs, metallicity determinations are not commonly reported, but should in principle be determinable from the spectra used for the radial-velocity measurements. Temperatures remain vexing because of uncertainties over the spectral-type to temperature scale for PMS stars, especially at very low masses. Only recently was the first apsidal motion for a very young EB reported (V578 Mon; *Garcia et al.*, 2011, 2013a). As demonstrated by *Feiden and Dotter* (2013), such apsidal motion measurements can provide particularly stringent constraints on the models, specifically on the interior structure evolution with age, a critically important physical ingredient.

Importantly, *Torres et al.* (2013) have used the quadruple PMS system LkCa3 to perform a stringent test of various PMS evolutionary models. They find clearly that the Dartmouth models perform best, and moreover find that these models can fit another benchmark quadruple system, GG Tau, whereas previous generation models cannot (Fig. 10).

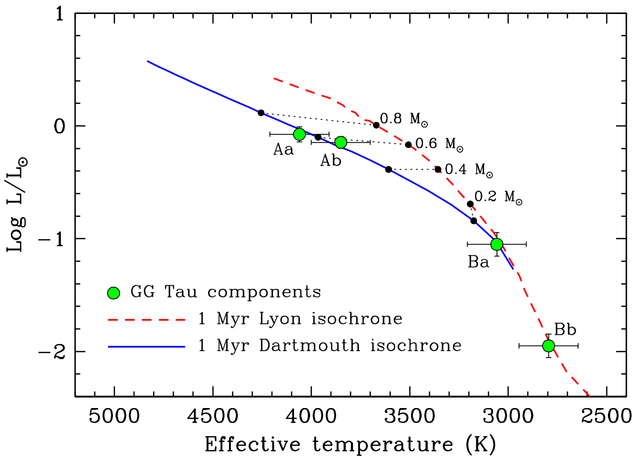

Fig. 10.— Application of Dartmouth models to the quadruple PMS system GG Tau (*Torres et al.* 2013). Previous generation models (here compared to the Lyon models), which have been used to calibrate the PMS temperature scale, do not perform as well.

8.2. Impact of Activity on Temperatures, Radii, and Estimated Masses of Young Stars

Stars in short-period binaries are often chromospherically active, and thus may suffer from activity-reduced temperatures and/or -inflated radii, causing them to appear discrepant relative to standard model isochrones (e.g., *Torres*, 2013). In particular, such activity-reduced temperatures can cause the derived stellar masses to be underestimated by up to a factor of ∼2.

A particularly important case in point is 2M0535–05, the only known EB comprising two brown dwarfs (*Stassun et al.*, 2006, 2007), which proved enigmatic from the start. The system is a member of the very young Orion Nebula Cluster, and thus the expectation is that both components of the EB should have an age of ∼1 Myr. However, a very peculiar feature of the system is a reversal of temperatures with mass – the higher mass brown dwarf is cooler than its lower-mass brown dwarf companion – making the higher mass brown dwarf appear younger than the lower-mass companion and a factor of 2 lower in mass than its true mass. *Reiners et al.* (2007) showed that the higher mass brown dwarf is highly chromospherically active as measured by the luminosity of its Hα emission, whereas the lower mass brown dwarf is a factor of 10 less active and appears "normal" relative to the evolutionary tracks.

Motivated by this peculiar but important system, *Stassun et al.* (2012) have used a sample of low-mass EBs to determine empirical corrections to stellar temperatures and radii as a function of chromospheric Hα activity (*Morales et al.*, 2010). Notably, these corrections indicate that the nature of the temperature reduction and radius inflation is such that the bolometric luminosity is roughly conserved. The *Stassun et al.* (2012) relations are able to fully explain the anomalous temperature reversal found in the 2M0535–05 brown-dwarf EB.

However, there is not as yet consensus on the underlying physical cause of this effect. *Chabrier et al.* (2007) suggest that surface spots and convection inhibited at the surface are the driver, whereas *MacDonald and Mullan* (2009) suggest a global inhibition of convection through strong fields threading the interiors of the stars. *Mohanty and Stassun* (2012) performed detailed spectrocopic analysis of the eclipsing brown-dwarf EB 2M0535–05, the results of which appear to disfavor the *Chabrier et al.* (2007) hypothesis. However, questions remain as to the physical plausibility of the magnitude of interior fields required in the *MacDonald and Mullan* (2009) hypothesis.

At the same time, the Dartmouth models also now incorporate the effects of internal magnetic fields, which successfully accounts for the effects of temperature reduction and radius inflation in a physically self-consistent fashion (*Feiden and Chaboyer*, 2012).

8.3. Impact of Triplicity on Properties of PMS Stars

There is increasing evidence that the presence of third bodies in young binaries can significantly alter the properties of the component stars, either directly through tidal heating effects and/or indirectly by impacting the accretion history of the system. As an exemplar case, *Stassun et al.* (2008) identified Par 1802 to be an unusual PMS EB whose component stars have identical masses ($q = 0.99$) yet radii that differ by 7%, temperatures that differ by 9%, and luminosities that differ by 60%. Thus the pair cannot be fit by any standard PMS stellar evolution models under the usual assumption of coevality for the component stars because the stars' highly unequal luminosities cause them to appear highly non-coeval. *Gomez Maqueo Chew et al.* (2012) used 15 yr of eclipse timing measurements to reveal the presence of a wide tertiary component in the system. Modeling the tidal heating on the EB pair arising from the previous orbital evolution can explain the over-luminosity of the primary eclipsing component, and moreover suggests a close three-body (perhaps exchange) interaction in the past.

Relatedly, recent theoretical work has suggested that accretion history (e.g., FU Ori outbursts, differential accretion in proto-binaries) can alter the PMS mass-radius relationship (e.g., *Simon and Obbie*, 2009; *Baraffe and Chabrier*, 2010). Consequently, new generation PMS evolution models are seeking to simulate these effects. For example, the new Pisa models are being further developed to include thin-disk accretion episodes during the early PMS phase.

As suggested by the example of Par 1802 above, PMS EBs provide a unique opportunity to assess the frequency of higher-order multiples among close binaries, because of the high quality and multi-faceted ways in which these benchmark systems are studied. Among the sample of 11 PMS EB systems that have detailed EB solutions published as of this writing (i.e., excluding PMS EBs with preliminary reports such as the 6 systems announced in *Morales-Calderon et al.*, 2012) and that have stellar mass components (i.e., excluding the double brown-dwarf EB 2M0535–05), 6 are now known to include a third body. This preliminary census implies a very high ratio of triples to binaries, consistent with the view that tertiaries may be critical to the formation of tight pairs.

9. GAS IN BINARIES AND MULTIPLE SYSTEMS

9.1. Observations of Circumbinary Structures

Circumbinary disks play an important role in shaping binary orbital properties: mass flow from the disk affects the ultimate binary mass ratio while the flow of angular momentum from binary to disk drives changes in the binary period and eccentricity. The observational study of circumbinary accretion flows is, however, challenging: massive circumbinary disks are rare amongst binaries with separations in the range of a few to 100 AU (*Jensen et al.*, 1996; *Harris et al.*, 2012), which constitute the bulk of the pre-main sequence binary population. To date, only a handful of circumbinary disks have been imaged directly (see *Hioki et al.*, 2009) and here the limitations of coronagraphic imaging do not allow the study of the structures – critical to the binary's evolution – that link the disk to the binary. Circumbinary disks are considerably more abundant around the closest binaries (a few AU or less); on the main sequence such binaries are – unlike wider pairs – preferentially associated with circumbinary *debris* disks (*Trilling et al.*, 2007) and are in the regime where *Kepler* has recently revealed a number of circumbinary planets (e.g., *Doyle et al.*, 2011; *Welsh et al.*, 2012). The reason for the higher incidence of massive circumbinary disks in close pairs is unclear – i.e., whether it reflects the initial configuration at formation or whether such disks drive binaries to small orbital separations. Alternatively, this association may be a matter of disk survival: *Alexander* (2012) has argued that disks around close binaries should be long lived, since viscous draining is impeded by the binary's tidal barrier while the gas is too tightly bound to be readily photo-evaporated.

Interferometric studies are just beginning to probe the dust morphology in these systems (*Boden et al.*, 2009; *Garcia et al.*, 2013b) and so the bulk of our knowledge derives from time domain studies. For example, in eccentric binaries, periodic optical and X-ray variations have been attributed to a dynamically modulated accretion flow (e.g., *Mathieu et al.*, 1997 in DQ Tau; *Gomez da Castro et al.*, 2013 in AK Sco), although optical variability also accompanies synchotron flares at mm wavelengths, which can be understood as reconnection events when the two stellar magnetospheres interact at periastron (e.g., *Salter et al.*, 2010). *Muzerolle et al.* (2013) have recently interpreted large scale periodic variations in a *protostellar* source as deriving from a binary-modulated pulsed accretion flow. Variations in the observer's viewing angle also modulate line emission in low eccentricity binaries: for example in V4046 Sgr, hydrodynamical modeling (*de Val-Borro et al.*, 2011) reproduces the periodic changes in the wings of the Balmer lines observed by *Stempels and Gahm* (2004). In CS Cha, the binary's variable illumination of dusty accretion streams has been invoked to explain its periodic infrared variability (*Nagel et al.*, 2012); it is, however, notable that the spectral energy distribution of CS Cha implies that the inner edge of the optically thick circumbinary disk is at about 10× the binary orbital separation (*Espaillat et al.*, 2011), which is several times larger than what is expected from dynamical truncation by the binary. This finding exemplifies the difficulty of connecting models and observations, since the dust emission is apparently not merely being shaped by the response of the gas to the binary potential.

9.2. Simulations of Circumbinary Disks

While observed circumbinary disks are generally low in mass during the Classical T Tauri phase, this was almost certainly not the case at earlier evolutionary phases. In hydrodynamic collapse simulations, proto-binaries are surrounded by circumbinary disks formed from higher angular momentum material in the natal core, and the interaction between the disk and the binary is key to shaping the system's ultimate orbital elements (*a, e, q*). A complete theory of binary formation should require not only the creation of the protobinary fragments but should contain a clear prescription for the evolution of these quantities as a function of the properties of the circumbinary disk.

Unfortunately this goal remains elusive, despite comprehensive (SPH) studies devoted to this problem (e.g., *Bate and Bonnell*, 1997; *Bate*, 2000). Qualitative features of these studies (especially the preferential accretion of gas onto the secondary and hence the increase of the binary mass ratio) were challenged by *Ochi et al.* (2005) and *Hanawa et al.* (2010) whose AMR simulations were morphologically distinct and involved a preferential accretion of gas onto the primary (thus driving $q = M_2/M_1$ downwards). It now seems likely that these differences arose from the different parameters of the latter studies (i.e., warm, two dimensional flows) rather than from a code difference: nevertheless there are no fully converged simulations of circumbinary accretion that have been run to a steady state and this probably explains the variety of results reported in the literature with regard to the sign and magnitude of effects associated with circumbinary accretion (see also *Fateeva et al.*, 2011; *de Val Borro et al.*, 2011). This raises a cautionary note with regard to the fidelity of cluster scale simulations in modeling this process, since disks in such simulations are always relatively poorly resolved.

If there is still no clear consensus in the purely hydrodynamical case, the situation becomes still more complicated when magnetic fields are involved. This is illustrated by two recent studies. *Zhao and Li* (2013) modeled accretion onto a 'seed binary' placed within a moderately magnetised core and found that severe magnetic braking of the accreting gas has two notable effects: the binary shrinks to small separations, while the low angular momentum of the braked gas ensures that the flow is predominantly to the primary, thus lowering the binary mass ratio. In another study, *Shi et al.* (2012) conducted the first simulation of binary/circumbinary disk interaction which – rather than adopting a parameterized 'α-type' viscosity in the disk (*Shakura and Sunyaev*, 1973) as in most previous works (e.g., *Artymowicz and Lubow*, 1994; *MacFadyen and Milosavljevic*, 2008; *Cuadra et al.* 2009; *Hanawa et al.*, 2010) – instead simulated the self-consistent angular momentum transfer associated with the development of magneto-hydrodynamic turbulence in the disk. The simulation considered the limit of ideal MHD and is therefore not applicable to 'dead zones' of low ionization (*Bai*, 2011; *Mohanty et al.*, 2013): in practice this limits it to radii within ~ 0.5 AU or beyond ~ 10 AU.

It is found that the effective efficiency of angular momentum transport (e.g., as parameterized by the *Shakura and Sunyaev* α parameter) is about an order of magnitude higher in the accretion streams that link the binary to the disk than in the body of the disk, and this results in a much more vigorous flow through the accretion streams than in previous simulations that do not treat the development of magneto-turbulent stresses self-consistently (see *MacFadyen and Milosavljevic*, 2008). Indeed in the *Shi et al.* (2012) simulations the flow through the accretion streams is $\sim 30\%$ of the flow through the outer disk. In such a situation the net evolution of the binary is governed by two nearly cancelling terms (the spin-up effect of accretion and the spin-down torque associated with the non-axisymmetric disk/accretion streams) and is thus very sensitive to numerical inaccuracies/uncertainties in the disk thermodynamics. So although this simulation is undoubtedly more realistic than previous calculations, it raises awkward issues: apparently the derivation of a simple relationship between circumbinary disk properties and associated orbital evolution may be more elusive than ever.

9.3. Disk Lifetimes in Binaries

Since the review of this subject by *Monin et al.* (2007) in PPV, a number of studies have charted the relative lifetimes of disks in binaries compared with single stars, and studied the relative lifetimes of the primaries' and secondaries' disks. Early studies in this area (e.g., *Prato and Simon*, 1997) had argued that circumstellar disks must be replenished from a circumbinary reservoir during the Classical T Tauri phase, a requirement that was puzzling given the observed lack of circumbinary material in all but the closest binaries. This conclusion was based on *a)* the fact that disks in binaries were not apparently shorter lived than disks in single stars and *b)* the scarcity of 'mixed pairs' (i.e., those with only one disk). Re-supply of circumstellar disks would extend their lifetimes and coordinate the disappearance of the disks, since otherwise – in isolation – the secondary's disk would drain first on account of its smaller tidal truncation radius and shorter viscous timescale (*Armitage et al.*, 1999).

However, recent studies have undermined the observational basis for these arguments. *Cieza et al.* (2009) and *Kraus and Hillenbrand* (2009) demonstrated that the lifetime of disks in close binaries is indeed reduced compared with single stars or wide pairs, concluding that incompleteness of the census of close binaries, the use of unresolved disk indicators and projection effects had all previously masked this correlation in smaller samples (see also *Kraus et al.*, 2012; *Daemgen et al.*, 2013). Moreover, the census of binaries for which spectral diagnostics have been measured for each component has been augmented by *Daemgen et al.* (2012, 2013) in the ONC and Chamaeleon I. These new results have reinforced the suggestion of *Monin et al.* (2007), that the early conclusions about the absence of mixed pairs was skewed by results from Taurus which are not borne out in other regions. *Kneller and Clarke* (2014) argue that the observed incidence of disks in binaries as a function of q and separation is compatible with clearing by combined viscous draining and X-ray photo-evaporation. Such models predict a strong tendency for the secondary's disk to disappear before the primary's for binaries closer than 100 AU while predicting that in wider mixed pairs, disks are equally likely to exist around the secondary and primary components: this latter prediction needs to be tested observationally in larger samples.

9.4. Eclipses by Disks

Disks may cause eclipses of their central stars, and these events present rare but valuable opportunities to study the detailed structure of disks during the planet forming era. The best studied example is KH15D (e.g., *Herbst et al.*, 2010). KH15D is a binary that is occulted by a circumbinary screen of material that moves slowly across the binary components, occulting them in turn. Modeling of the screen suggests its origin to be a precessing, warped circumbinary ring of material several AU from the tight binary. The obscuring ring has very sharp edges – it is well modeled as a knife edge – indicating a high degree of coherence to the material despite the dynamics of the system.

RW Aur is a newly discovered exemplar of this class (*Rodriguez et al.*, 2013). In this case, light curve observations by the KELT exoplanet transit survey (*Pepper et al.*, 2007) witnessed a sudden dramatic eclipse of the star with a depth of $\sim$2 mag and lasting approximately 180 days. Archival photometric observations can rule out a similarly long and deep eclipse over the past 100 years. This singular event is interpreted and modeled as an occultation of the primary star (RW Aur A) by the long tidal arm observed by *Cabrit et al.* (2006) resulting from tidal disruption of its circumstellar disk by the recent fly-by of RW Aur B (see Figure 11). RW Aur B may itself be a tight binary, making the RW Aur system a triple (*Ghez et al.*, 1993). The eclipse observations indicate a knife-edge structure to the occulting feature, consistent with the dynamical simulations of *Clarke and Pringle* (1993), which demonstrate a high degree of coherence in the tidal arm persisting long after the fly-by (see Section 9.6).

9.5. Alignment of Orbital Planes in Young Binaries

A number of systems show evidence that they have undergone dynamical events that have perturbed the orientation of the binary and/or its circumstellar disks. For example, *Bisikalo et al.* (2012) presents evidence that the disk around RW Aur A (discussed above) is *counter-rotating* with respect to the binary orbital motion. Similarly, *Albrecht et al.* (2009) used Rossiter-McLaughlin measurements during the eclipse of the massive binary DI Her to show that the projected spin of one of its B-type components was highly misaligned (72°) with respect to the binary orbital plane. There is no unique explanation for such systems. One idea is that, whereas the spin of the stars reflects that of the local gas reservoir (material that collapsed first), the spin direction of circumbinary structures (or the orbital plane of binary systems) may inherit a different direction from a larger region within the turbulent medium, because of chaotic changes in the mean angular momentum vector of accreting material (this effect is significant in the whole cluster simulations of *Bate* 2009a, where misaligned systems are common). Alternatively, dynamical interactions (for example an exchange interaction within a non-hierarchical system) can play a similar role, although this again requires that the natal gas contains a range of spin directions. On the other hand, the Kozai-Lidov (*Kozai*, 1962; *Lidov*, 1962) mechanism within triple systems can induce spin-orbit misalignment even in the absence of exchange interactions: *Fabrycky and Tremaine* (2007) suggested that while Kozai-Lidov induced oscillations in eccentricity and inclination can deliver companions to small peri-center distances, tidal dissipation could allow such systems to free themselves from the Kozai-Lidov regime, trapping them in a state where their spins are decoupled from their orbital inclination. Triple companions, however, have not been detected to date in either of these systems. Other recent measurements of misalignment of orbital planes within pre-main sequence binaries include KH15D (*Capelo et al.*, 2012) and FS Tau (*Hioki et al.*, 2011), while circumbinary *debris* disks present a mixed picture with respect to the alignment of orbital and circumbinary disk planes (*Kennedy et al.*, 2012a,b).

Facchini and Lodato (2013) and *Foucart and Lai* (2013) have recently presented analytic and numerical calculations of the evolution of the warp and twist of a disk that is initially misaligned with the binary orbit. *Foucart and Lai* showed that the back-reaction on the binary orbit re-aligns the system on a timescale that is short compared with that required for the binary to accrete significant mass from the circumbinary disk. They therefore argued that close binaries (which gain significant mass from the circumbinary disk) should become aligned with their disks during the pre-main sequence period, thus explaining the surprising abundance of (necessarily aligned) planets in circumbinary orbit in the Kepler sample (e.g., *Doyle et al.*, 2011; *Welsh et al.*, 2012).

9.6. Retention of Disks in Dynamical Encounters

Dynamical interactions within multiple systems result in the pruning of circumstellar disks, leading *Reipurth and Clarke* (2001) to argue that disk *size* may provide a diagnostic of an object's previous history of close encounters in a few-body system. The influence of stellar fly-by's on disk structure was first examined by *Clarke and Pringle* (1993), while *Hall* (1997) reconstructed disk surface profiles post-encounter from ballistic calculations through the assumption that bound particles should re-circularize while retaining their individual angular momenta. The SPH calculations of *Pfalzner et al.* (2005) (see Figure 11) showed that this is a reasonable approximation, and more recently *Umbreit et al.* (2011) have applied the same procedure to stars undergoing close encounters within triple systems. This study (which started from non-hierarchical co-planar triples with co-planar disks) showed that the reconstructed density profiles show a boosted power law profile in the inner disk and an exponential cut-off at a radius of a few tenths of the minimum encounter distance. It is found that disk stripping during triple decays is qualitatively very similar and only slightly stronger than that occurring during two-body fly-by's.

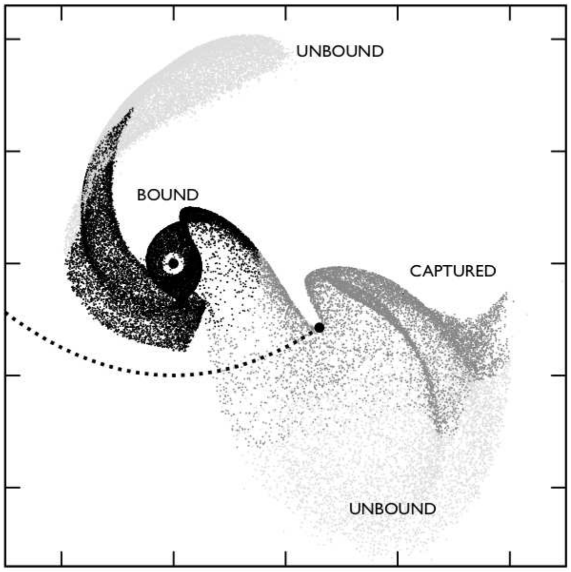

Fig. 11.— Severe disk disturbances occur during close periastron passages. This simulation shows an encounter between two solar-type stars, one with and one without a disk; black dots show material that remains bound, grey dots show material captured by the intruder, and light grey dots show unbound material. The box is 500 × 500 AU. Courtesy S. Pfalzner and M. Steinhausen.

9.7. Planetary Systems in Multiple Stellar Systems

Around 7% of currently detected planets are in binary systems, most of which are located in circum*stellar* orbits in wide systems. Two categories of system have attracted considerable recent interest, i.e., the circumbinary (P-type) planets around close (sub-AU) separation binaries discovered by Kepler (*Doyle et al.*, 2011; *Welsh et al.*, 2012) and the circumstellar (S-type) planets discovered in relatively close ($a < 20$ AU) pairs (*Chauvin et al.*, 2011; *Dumusque et al.*, 2012). Planetesimal accumulation in binary environments faces a well known problem (*Thebault et al.*, 2008) on account of the pumping of the planetesimal velocity dispersion by gravitational perturbations from the binary; a high velocity dispersion implies destructive collisions (*Leinhardt and Stewart*, 2012) and thus limits the possibilities for planetesimal growth. Some suggested solutions to this problem fall into the category of simply forming planets in a more benign dynamical regime (i.e., further from the perturber) and then invoking migration – of either the planet or the binary companion – to achieve the observed planet/binary architecture: see *Payne et al.* (2009), *Thebault et al.* (2009). Alternatively, *Xie et al.* (2010) have explored the effect of a modest inclination between the binary and disk plane. In terms of *in situ* formation models, gas drag has been invoked as a mechanism for enforcing apsidal alignment of perturbed planetesimal orbits: this produces local velocity coherence in objects of a given size. However, since gas drag is a size-dependent phenomenon, this does not prevent destructive collisions in a planetesimal population with a realistic size distribution and is thus unlikely to solve the problem (*Thebault et al.*, 2006, 2008).

Recent works on this topic concentrate on the effect of the disk's gravitational field upon the growth of planetesimal velocity dispersion. *Rafikov* (2013) argued that *if* the disk is approximately axisymmetric, then its gravitional influence induces *size independent* apsidal precession, which acts to reduce the eccentricity excitation by the companion. However, the simulations of *Marzari et al.* (2013) show that the planet induces a strong eccentricity in the disk, and that gravitational coupling with the eccentric disk actually amplifies the stirring of the planetesimal population. In effect, therefore, these studies come to qualitatively opposite conclusions as to whether binarity is a major obstacle to planet formation. These divergent conclusions essentially hinge on the axisymmetry of the gas disk in the region of interest; further hybrid hydrodynamical/N-body modeling is required in order to delineate the areas of parameter space in which planetesimal growth is possible.

Finally, although planets are known in stellar triple systems (e.g., *Bechter et al.*, 2013), the issue of planet formation in higher order multiples is unexplored (although several works have examined the stability boundaries of particle disks within triple systems, e.g., *Verrier and Evans*, 2007; *Domingos et al.*, 2012). While the presence of three bodies in general restricts the stability regions available, there are certain configurations where a third body can stabilize particle orbits. In particular, whereas particles in a circumstellar disk with an inclined companion can be subject to Kozai-Lidov instability, this can be suppressed if the central object within the disk is itself a binary, since in this case the binary induces nodal libration which stabilizes the particles (*Verrier and Evans* 2009). Such studies will be important in interpreting the statistics of debris disks within multiple star systems.

10. BINARIES IN CLUSTERS

We have seen (see Section 5) that multiple systems can change due to internal (secular) interactions. But dynamical interactions with other systems can play an extremely important role in altering multiple systems (changing their orbital parameters, or even destroying them). In the relatively dense environments of star forming regions or star clusters the initial multiple population can be very significantly altered. This means that any multiple population we observe is almost certainly not what formed, and different populations can evolve in (very) different ways depending on the environment. Therefore, to extrapolate back to formation from any observations, we must fold-in the (possibly very complex) dynamical evolution (called 'inverse population synthesis' by *Kroupa*, 1995).

10.1. External dynamical interactions

The dynamical destruction of binaries was first studied in detail by *Heggie* (1975) and *Hills* (1975; see also *Hills*, 1990). They placed binaries into two broad categories: 'hard' and 'soft'. Hard binaries are those which are so tightly bound that encounters are extremely unlikely to alter their properties (to destroy them, or even to change their orbital parameters much). Soft binaries are those that are so weakly bound, that they are almost certain to be destroyed by any encounter. Generally, if the kinetic energy of a perturber is greater than the binding energy of the binary, then the binary is destroyed. An alternative way of looking at this is that a binary is hard if its orbital speed is greater than the speed of an encounter (*Hills*, 1990). Investigation of the dynamics of encounters leads to the Heggie-Hills law, that states that hard binaries get harder (encounters typically take energy from the binary), and soft binaries get softer (encounters typically give energy to the binary).

The hard-soft boundary is basically set by the velocity dispersion of the perturbing stars, and the mass of the binary. The faster that perturbers are moving, the closer the hard-soft boundary, and the more massive the binary is, the more difficult it is to destroy. It might be expected that binary destruction will depend on the mass ratio, however simulations show that destructive encounter energies are almost always significantly greater than the binding energy, and so destruction does not depend on the mass ratio (*Parker and Reggiani*, 2013).

However, the ‘hardness’ of a binary is not the only thing that decides if a binary will survive. To destroy even a soft binary an encounter is required, therefore the encounter rate is crucial. In the field, many formally soft binaries survive for significant amounts of time, because the encounter rate is very low.

Therefore, the survival of a binary depends on *(a)* the energy of the binary, *(b)* the energy of encounters, and *(c)* the frequency of encounters. The more massive and dense a star-forming region or star cluster is, the more frequent and energetic encounters will be, and so binary destruction/alteration should be more efficient.

In any given environment, hard binaries should survive, and soft binaries will almost certainly be destroyed. The most interesting binaries, however, are often ‘intermediates’ between hard and soft, which may or may not survive depending on the exact details of their dynamical histories (e.g., *Parker and Goodwin*, 2012).

Let us take an ‘average’ binary system of component masses m, where $m \sim 0.4\,\mathrm{M}_\odot$ is the average mass of a star. Let us put this binary in a virialized cluster of N stars of total mass $M = Nm$, and radius R. The hard-soft boundary, $a_{\rm hs}$ will be at approximately

$$a_{\rm hs} \sim 10^5 \left(\frac{R}{\rm pc}\right)\left(\frac{1}{N}\right) \quad \mathrm{AU} \qquad (1)$$

(see *Parker and Goodwin*, 2012). Numerical experiments show that a safe value for a hard binary that will almost certainly survive is about $a_{\rm hs}/4$. For clusters like the Orion Nebula Cluster (ONC; $N \sim 10^3$, $R \sim 1$ pc) $a_{\rm hs} \sim 100$ AU. For relatively nearby regions, the ONC is very massive and dense, and so in local regions we tend not to expect processing of binaries with $a < 100$ AU. This means that the $a < 100$ AU population of binaries is ‘pristine’ (i.e., unprocessed), whilst $a > 100$ AU binaries may (or may not) have been processed (*Goodwin*, 2010; *King et al.*, 2012b).

It is important to remember, however, that it is not necessarily the *current* density of a region that is important in assessing the possible impact of binary processing. Rather, it is the (usually unknown) density history of the region.

The values of $N \sim 10^3$ and $R \sim 1$ pc used above for the ONC are the present-day values, and the calculated hard-soft boundary of $a \sim 100$ AU is the current safe hard-soft boundary. If the ONC was much denser in the past (as has been argued, see *Scally et al.*, 2005; *Parker et al.*, 2009), then the hard-soft boundary in the past could have been much smaller. If a region spends at least a crossing time in a dense state, then it is that dense state that imposes itself in binary destruction (*Parker et al.*, 2009). This could be very important if regions undergo expansion due to gas expulsion (e.g., *Marks and Kroupa*, 2011, 2012), or process binaries in short-lived substructures (*Kroupa et al.*, 2003; *Parker et al.*, 2011).

10.2. Binary Formation through Encounters

Dynamics are usually associated with binary destruction rather than formation. But hard binaries can be formed by three-body encounters (with the third body carrying away energy). The rate of binary creation per unit volume, $\dot{N}_{\rm b}$, depends on the stellar masses (m), velocity dispersion (σ), and number density of stars (n)

$$\dot{N}_{\rm b} = 0.75 \frac{G^5 m^5 n^3}{\sigma^9} \qquad (2)$$

(*Goodman and Hut*, 1993). In the Galactic field this number is essentially zero ($\sim 10^{-21}$ pc^{-3} Gyr^{-1}). However, in dense star-forming regions and clusters the rate may be significant, especially for higher-mass stars. Simulations show that initially single massive stars can pair-up in hard binaries, and can form complex higher-order systems similar to the Trapezium (*Allison and Goodwin*, 2011). This is due to the very strong dependency of $\dot{N}_{\rm b}$ on the higher m and n, and the lower σ in clusters (which can make 30 orders of magnitude difference).

Kouwenhoven et al. (2010) and *Moeckel and Bate* (2010) independently found that dissolving dense regions can also form very wide binaries by ‘chance’, when two stars leaving the region find themselves bound once outside of the region. Similarly, *Moeckel and Clarke* (2011) find that dense regions constantly form soft binaries. While the region remains dense, these binaries are destroyed as fast as they are made. However, when the region dissolves into the field they can be ‘frozen in’ at lower densities and survive. On average, one region produces one wide binary with a median separation of about 10^4 AU, almost independently of the number of stars in that region (*Kouwenhoven et al.*, 2010). Since the stars are paired randomly, it is quite possible for the wide binaries to be made of one or two hard binaries (making triple or quadruple systems). The mass ratio distribution of wide binaries would be expected to be randomly paired from the IMF. This process acts independently of the wide binaries that form through the unfolding of triple systems, as discussed in Section 5.

10.3. Observations of Young Multiples in Clusters

It is only in nearby star-forming regions that we can examine in any detail the (especially low-mass) binary properties. Locally, young star-forming regions cover a wide range of densities from a few stars pc^{-3} (e.g., Taurus) to a few thousand stars pc^{-3} (e.g., the ONC; see *King et al.*, 2012a,b). These are often – rather arbitrarily – divided by density into low-density 'associations', and high-density 'clusters'. More formally, 'clusters' are often thought of as bound objects, or objects at least a few crossing times old (e.g., *Gieles and Portegies Zwart*, 2011). We will take the *Gieles and Portegies Zwart* (2011) definition of a cluster as dynamically old systems, since these are systems which we might expect to have significantly processed their multiple populations. Locally, this probably safely includes the ONC and IC 348 as 'clusters' for which we have some detailed information on the stellar multiplicity.

It is worth noting that the level of processing of binaries will not simply depend on mass, but rather on the dynamical age of a system. For example, *Becker et al.* (2013) suggest that the binary properties (and unusual IMF) of the low-mass 'cluster' η Cha could be explained by an initially very high density and rapid dynamical evolution.

Observations of the ONC and IC 348 show a lower binary frequency than associations (e.g., *Köhler et al.*, 2006; *Reipurth et al.*, 2007 for the ONC; *Duchêne et al.*, 1999 for IC 348). The ONC is also found to have an almost complete lack of wide (> 1000 AU) systems (*Scally et al.*, 1999).

King et al. (2012a,b) collated binary statistics for 7 young regions and attempted to correct for the different selection effects and produce directly comparable samples. Only in the range 62–620 AU is it possible to compare regions as diverse as Taurus (with an average density of < 10 stars pc^{-3}) to the ONC (around 5000 stars pc^{-3}). In this separation range, the binary fraction of Taurus is around $21 \pm 5\%$, compared to around 10% in regions with densities greater than a few 100 stars pc^{-3} (Cha I, Ophiuchus, IC 348, and the ONC). The Solar field values in the same range are roughly 10%.

Given the densities of the ONC, it is almost impossible to imagine a scenario in which we are observing the birth population. The binaries we observe have separations of 62–620 AU, almost all above the hard-soft boundary in the ONC. Taking a size for the ONC of 1 pc, a density of 5000 stars pc^{-3}, and a velocity dispersion of 2 km s^{-1}, the typical encounter timescale at 1000 AU is about a Myr – roughly the age of the ONC.

It is often stated that clusters have a field-like binary distribution, however this is somewhat misleading. Binary studies of the ONC and IC348, the only dense clusters analyzed so far, are of a limited range of around 50–700 AU and in this range they have a similar binary fraction to the field. However, we have no information on smaller separations, and they are certainly not field-like at large separations, where there is an almost complete lack of systems.

Reipurth et al. (2007) find a significant (factor of 2–3) difference between the ratio of wide (200–620 AU) to close (62–200 AU) binaries between the inner pc of the ONC and outside of this. This could suggest a difference in dynamical age, and hence the degree of processing, between the inner and outer regions of the ONC (*Parker et al.*, 2009).

Interestingly, *King et al.* (2012b) find that whilst the binary frequency in the ONC is significantly lower than in associations, the binary separation distribution looks remarkably similar. Such distributions in the 62–620 AU range are always approximately log-flat in all regions and show no statistically significant differences. Taurus has twice as many binaries as the ONC in the same separation range, but the distribution of binary separations is the same.

This is worth remarking on, because it is very unexpected. A reasonable assumption would be that associations and clusters form the same primordial population, but that clusters are much more efficient at processing that population. The field is then the sum of relatively unprocessed binaries from associations, and relatively highly processed binaries from clusters (e.g., *Kroupa*, 1995; *Marks and Kroupa*, 2011, 2012). But processing is separation-dependent, and wider binaries should be processed more efficiently than closer binaries. Therefore, if we take initially the same binary frequency and separation distribution in the 62–620 AU range in both associations and clusters, we would expect *(a)* a lower final binary frequency in clusters (which we see), and *(b)* fewer wider binaries in clusters than associations (which we do not see). Note that by wide, we do not mean > 1000 AU, which are missing in the ONC (*Scally et al.*, 1999), but rather fewer, say, 200-620 AU binaries than 62–200 AU binaries.

That the separation distributions in low-density and high-density environments is the same could suggest that high-density regions somehow over-produce slightly wider systems, which are then preferentially destroyed to fortuitously produce the same final separation distribution. This would seem rather odd (*King et al.*, 2012b).

The 62–620 AU range of binaries for which we have observations in the ONC are mostly (rather frustratingly) intermediate binaries whose processing depends on the details of their dynamical histories. *Parker and Goodwin* (2012) show that in ONC-like systems the tendency is to preferentially destroy wider systems, but small-N statistics means that some clusters can produce separation distributions in the observed range that sometimes retain the initial shape. So maybe the separation distribution in the ONC is statistically slightly unusual? However, the difference between the inner and outer ratio of wide (200–620 AU) to close (62–200 AU) binaries observed by *Reipurth et al.* (2007) suggests that the inner regions of the ONC have been efficient at processing the wider binaries.

In summary, in clusters we expect significant binary destruction. However, interpreting observations of binaries in clusters is difficult. This is due to the lack of nearby clusters, and the limited range of binary separations that are observable. But in the binary populations of clusters should be clues to the formation and assembly of clusters, and differences between star formation in different environments.

11. THE MULTIPLICITY OF MASSIVE STARS

We here define massive stars to be OB stars on the main sequence, above ~ 10 $M_\odot$ (about B2V) capable of ionizing atomic hydrogen, with the dividing line between O and B stars around 16 $M_\odot$ (about B0V, *Martins et al.*, 2005). Massive stars occur mostly in young clusters and associations, but to a small degree also in the field and as runaway stars. There are some 370 O-stars known in the Galactic O Star Catalog (*Maiz-Apellaniz et al.*, 2004; *Sota et al.*, 2008), with 272 located in young clusters and associations, 56 in the field, and 42 classified as runaway stars.

11.1. Recent Observational Progress

A comprehensive review of the multiplicity of massive stars was given by *Zinnecker and Yorke* (2007), emphasizing the difference in multiplicity between high- and low-mass stars and its implication for their different origins. In the meantime, *Mason et al.* (2009) in a statistical analysis summarized the multiplicity of massive stars based on the Galactic O-star catalog (see above), both for visual and for spectroscopic multiple systems. *Chini et al.* (2012), in a vast spectroscopic study, presented evidence for a nearly 100% binary frequency among the most massive stars, dropping substantially for later-type B-stars, thus confirming the mass dependence of the multiplicity. At the same time, *Sana et al.* (2012) for the first time derived the distributions of orbital periods and mass ratios for an unbiased sample of some 70 O-stars based on a multi-epoch, spectroscopic monitoring effort. Three important results emerged: *(i)* the mass-ratio distribution is nearly flat with no statistically significant peak at q=1 (identical twins); *(ii)* the distribution of orbital periods peaks at very short periods (3-5 days) and declines towards longer periods; and *(iii)* a large fraction (>70%) of massive binaries are so close that the components will be interacting in the course of their lifetime, thus affecting the statistics of WR-stars, X-ray binaries, and supernovae, and of these one third will actually merge (*Sana et al.*, 2012).

In yet another recent study, based on the VLT-FLAMES Tarantula Survey, *Sana et al.* (2013) probed the spectroscopic binary fraction of 360 massive stars in the 30 Doradus starburst region in the Large Magellanic Cloud. They discovered that at least 40% of the massive stars in the region are spectroscopic binaries (both single and double lined). The unmistakable conclusion of all these studies is that the processes that form massive stars strongly favor the production of (mostly tight) binary and multiple systems.

Detailed studies of the multiplicity and orbital parameters of massive stars in young clusters (NGC 6231, NGC 6611; *Sana et al.*, 2008, 2009) and OB associations (Cyg OB2, *Kiminki and Kobulnicky*, 2012) have also been published, in an effort to find correlations with cluster properties and statistical differences between cluster and "field" stars. None were found (see the review by *Sana and Evans*, 2011). A contentious issue is the multiplicity among *bona fide* runaway O-stars, which was believed to be low (*Gies and Bolton*, 1986; *Mason et al.*, 2009), but following the new results of *Chini et al.* (2012), it seems to be very high (75%). In the case of runaway O-stars, it may eventually be useful to discriminate between high-velocity runaway stars (>40 km/s), presumably originating from supernovae explosions in binary systems (*Blaauw*, 1961), and slow runaways ("walk-aways", <10 km/s, which are harder to identify) whose origin is likely due to dynamical ejection from dense young clusters (*Poveda et al.*, 1967; *Clarke and Pringle*, 1992; *Kroupa*, 2000). The multiplicity of truly isolated field O-stars (if they do exist, cf. *de Wit et al.*, 2005; *Bressert et al.*, 2012; *Oey et al.*, 2013) still needs to be investigated.

11.2. Origin of Short-Period Massive Binary Systems

In recent years it has become evident that at least 44% of all O stars are close spectroscopic binaries (see the review by *Sana and Evans*, 2011). There are several – at least five – ideas to explain the origin of such close massive spectroscopic binaries; these are briefly discussed below. In addition, we need to explain the origin of hierarchical triple systems among massive stars; such systems could either result from inner and outer disk fragmentation or from a more chaotic dynamical N-body interaction.

Massive tight binaries cannot originate from the simple gravitational fragmentation of massive cloud cores and filaments into two Jeans-masses. The Jeans-radius (10,000 AU) is far too large compared with the separations of the two binary components (1-10 AU). More sophisticated physical processes must be at play, such as:

(1) Inner disk fragmentation (*Kratter and Matzner*, 2006) followed by circumbinary accretion, to make the components grow in mass (*Artymowicz and Lubow*, 1996).

(2) Roche lobe overflow of a close rapidly accreting bloated proto-binary (*Krumholz and Thompson*, 2007).

In both cases, the authors argue that the accretion flow would drive the component masses to near equality (massive twins). These theories, however, do not explain how to get the initially lower-mass close binaries in the first place.

(3) Accretion onto a low-mass initially wide binary system (*Bonnell and Bate*, 2005). While growing in mass by accretion, the orbital separation of the binary system keeps shrinking. In this case, one can show analytically that – depending on the angular momentum of the accreting gas – the wide binary, while growing in mass, will shrink its orbital separation substantially (for example: two 1 solar mass protostars at 30 AU separation can easily end up as two 30 solar mass components at about 1 AU separation if the specific angular momentum of the accreted gas is constant; that is, if accreting gas angular momentum scales lin-

early with the accreted gas mass).

(4) Magnetic effects on fragmentation. As noted in Section 2, 3D MHD calculations are just now becoming commonplace, and effects such as magnetic torques on rotating clouds might well lead to the formation of closer binary star systems than those found to date by 3D HD and RHD models of the fragmentation process (*Price and Bate*, 2007).

(5) Viscous evolution and orbital decay. When a triple system breaks up and ejects a component, the orbit of the remaining binary tightens and becomes highly eccentric (see Section 5). When this occurs at early evolutionary stages while the binary components are still surrounded by dense circumstellar material, the components interact viscously during periastron passages and their orbits decay (e.g., *Stahler*, 2010; *Korntreff et al.*, 2012). At the same time, the UV radiation field photoevaporates the circumstellar material, leaving many binaries stranded in close orbits.

11.3. Trapezia

The famous Orion Trapezium (e.g., *Herbig and Terndrup*, 1986; *Close et al.*, 2012) is the prototype of non-hierarchical compact groups of OB stars. The concept was first introduced by *Ambartsumian* (1954), who recognized that such systems are inherently unstable. Kinematic studies of trapezia show the internal motions expected for bound, virialized small clusters, but occasionally having components with velocities exceeding the escape speed (*Allen et al.*, 2004).

High precision astrometry from radio interferometry has demonstrated that three of the sources in the Becklin-Neugebauer/Kleinman-Low (BN/KL) region in Orion have large motions and are receding from a point in between them, suggesting that they were all part of a small stellar group, which disintegrated ∼500 yr ago (*Rodríguez et al.*, 2005; *Gómez et al.*, 2006, but see *Tan*, 2004). Just like the disintegration of small low-mass, very young stellar systems can lead to giant Herbig-Haro bow shocks (*Reipurth*, 2000), so will the break-up of a trapezium of massive protostars with abundant gas lead to an energetic, explosive event, as observed around the BN/KL region (*Bally and Zinnecker*, 2005; *Zapata et al.*, 2009; *Bally et al.*, 2011).

Trapezia are common in regions of massive star formation (e.g., *Salukvadze and Javakhishvili*, 1999; *Abt and Corbally*, 2000). Of particular interest are studies of the earliest stages of formation of a trapezium at centimeter and millimeter wavelengths (e.g., *Rodón et al.*, 2008). N-body simulations of massive trapezia in clusters demonstrate that these systems are highly dynamical entities, interacting and exchanging members with the surrounding cluster before eventually breaking apart (*Allison and Goodwin*, 2011).

12. STATISTICAL PROPERTIES OF MULTIPLE STARS

Multiple systems with three or more components (hereafter *multiples*) are a natural and rather frequent outcome of star formation. Compared to binaries, they have more parameters (periods, mass ratios, etc.), so their statistics bring additional insights on the formation mechanisms.

We focus here on stars with primary components of about one solar mass, as their multiplicity statistics are known best. *Raghavan et al.* (2010) estimated a multiplicity fraction $MF = 0.46$ and a higher-order fraction (triples and up) $HF \approx 0.12$ in a sample of 454 solar-mass dwarfs within 25 pc of the Sun. A much larger sample is needed, however, for a meaningful statistical study of hierarchical systems. Here we present preliminary results on F- and G-dwarfs within 67 pc selected from Hipparcos, the *FG-67pc* sample (*Tokovinin*, 2014). It contains a few hundred hierarchical systems among ∼5000 stars.

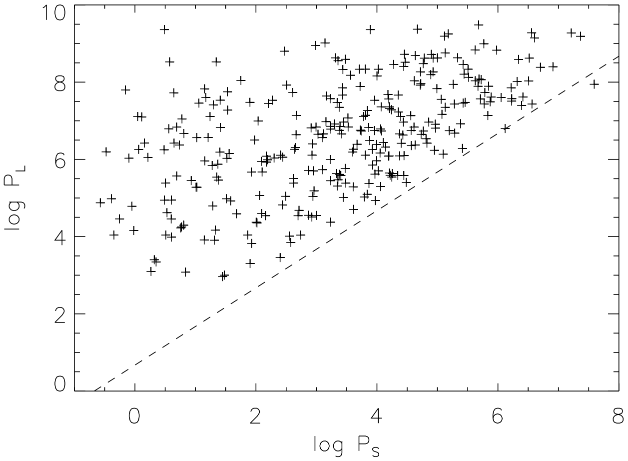

Fig. 12.— Orbital periods P_S at inner hierarchical levels *11* and *12* are compared to the periods of outer systems P_L from the FG-67pc sample. The periods are expressed in days and plotted on the logarithmic scale. The dashed line marks the dynamical stability limit $P_L/P_S = 4.7$.

Period ratio and dynamical stability. Figure 12 compares the inner, *short* periods P_S at levels *11* and *12* to the outer, *long* periods P_L at level *1* for the FG-67pc sample (for a definition of levels, see Section 3). Note that orbital periods of wide pairs are estimated statistically by assuming that projected separation equals orbital semi-major axis. Such estimates P^* are unbiased and differ from the true periods P by less than 3 times, in most cases.

The points in Fig. 12 fill the space above the dashed line, reflecting the fact that all combinations of inner and outer periods allowed dynamically are actually possible. The minimum period (or separation) ratio allowed by dynamical stability has been studied by several authors. The stability criterion of Mardling & Aarseth (2001), for example, can be written as

$$P_L/P_S > 4.7(1-e_L)^{-1.8}(1+e_L)^{0.6}(1+q_{\rm out})^{0.1}, \quad (3)$$

where e_L is the eccentricity of the outer orbit, while the ratio of the distant-companion mass to the combined mass of the inner binary $q_{\rm out}$ plays only a minor role. The dashed line in Fig. 12 corresponds to $P_L/P_S = 4.7$; all points are above it (with one exception caused by the uncertainty of

P^*). Although orbits of outer systems tend to have moderate e_L (*Shatsky*, 2001), its variation spreads the value of the P_L/P_S threshold over at least one order of magnitude.

Outer systems with $P < 10^3$ d do not exist or are rare (see the empty lower-left corner in Fig. 12). Such triples can be readily discovered by radial-velocity variations superposed on the short (inner) orbit, so their absence is not an observational bias. However, tight triples are found among massive stars.

Distribution of periods and mass ratios, fraction of hierarchies. Accounting for the observational selection is critical. In the FG-67pc sample, the probability of detecting a companion to the main target over the full range of periods and mass ratios has been determined to be about 78%. This means that only $0.78^2 \approx 0.61$ fraction of level-*11* triples is actually discovered (assuming that detections of inner and outer companions are uncorrelated). The observed fractions of S:B:T:Q systems are 64:29:6:1 percent. The selection-corrected fractions are 54:31:6:7. The difference between observed (raw) and corrected fractions increases with increasing multiplicity. Some systems known presently as binaries are in fact triples, some triples are quadruples, etc.

The joint distribution of period P and mass ratios $q = M_2/M_1$ is frequently approximated by the Gaussian distribution of $x = \log_{10}(P/1d)$ and by the power-law distribution of q (see e.g., *Duchêne & Kraus*, 2013):

$$f(x,q) = C\,\epsilon\,q^\beta \exp[-(x-x_0)^2/(2\sigma^2)], \qquad (4)$$

where ϵ is the fraction of systems and C is the normalization constant. It is likely that the mass-ratio distribution depends on period, but this is still being debated.

The parameters of equation (4) for the FG-67pc sample are found by maximum likelihood, accounting for the incomplete detections and missing data. When all stellar pairs are considered regardless of their hierarchical levels, the result is $\epsilon = CSF = 0.57 \pm 0.02$, while the median period is $x_0 = 4.53 \pm 0.09$. If, on the other hand, we count only the outer level-*1* systems, the result is different: $\epsilon = MF = 0.47 \pm 0.01$ and $x_0 = 4.97 \pm 0.06$. Binary periods at the outer hierarchical level are thus almost 3 times longer than the periods of *all* binaries. Similarly, for the *inner* pairs at levels *11* and *12* we derive much shorter median periods $x_0 = 3.12$ and $x_0 = 2.45$, respectively. Note that the formal errors quoted above are only lower statistical limits; the results are influenced by several assumptions and approximations made in the analysis, making the real uncertainty larger. The exponent of the mass-ratio distribution turns out to be small, $\beta \approx 0.2$, meaning that the distribution of q is almost uniform.

We derive the selection-corrected fractions of sub-systems of level *11* and level *12* as 10% and 8%, respectively. Discovery of sub-systems in the *secondary* companions (level *12*) is more problematic than at level *11*. Usually researchers concentrate on discovering companions to their primary targets and forget that some of those companions may, in turn, be close pairs. The estimated detection rate of level-*12* sub-systems in the FG-67pc sample is only ~ 0.2, so their true frequency depends on the large, hence uncertain, correction. However, there is a strong evidence that the occurrence of sub-systems in the secondary components is nearly as frequent as in the main (primary) targets.

Among the 88 sub-systems of level *12*, about a half also have sub-systems of level *11*. There is hence a correlation between those levels: the frequency of 2+2 quadruples is larger than could be inferred from the frequency of levels *11* and *12* if they were independent (uncorrelated). Among the 8% of systems containing secondary pairs of level *12*, half also contain level-*11* pairs, they are 2+2 quadruples. Considering this, the fraction of systems with at least 3 companions is $HF \approx 0.10 + 0.04 = 0.14$, not $0.10 + 0.08 = 0.18$ as one might naively assume by summing up the frequencies of levels *11* and em 12.

Statistical model of hierarchical multiplicity. It is remarkable that inner pairs in hierarchical multiples are statistically similar to simple binaries. The mass ratios in spectroscopic binaries with and without distant tertiary companions are distributed in the same way (*Tokovinin et al.*, 2006). The frequency of spectroscopic sub-systems in visual binaries is similar to the frequency of spectroscopic binaries in the open-cluster and field populations (*Tokovinin & Smekhov,* 2002). The frequency of resolved sub-systems in wide binaries is again comparable to binaries in the field (*Tokovinin et al.,* 2010). To first order, we can construct a hierarchical triple by selecting two binaries randomly from the same *generating distribution* of periods and keeping only stable (hierarchical) combinations. This recipe is applied recursively to simulate higher-order multiples.

To test this idea, *Tokovinin* (2014) simulated multiples, filtered them by the average detection probability, and compared to the real sample, following the strategy of *Eggleton* (2009). The parameters of the generating distribution (equation 4) were taken from the maximum-likelihood analysis and could be further adjusted to improve the agreement between the simulated and real samples. If the multiplicity fraction ϵ is kept constant, the HF in the simulated sample is too low. So, to reach an agreement between simulations and reality, we had to increase ϵ at inner hierarchical levels and to introduce a correlation between levels *11* and *12*. Alternatively, the agreement can be obtained by assuming a variable (stochastic) binary frequency ϵ. Cases with a high ϵ produce many hierarchies, while the cases of small ϵ generate mostly single and binary stars. This finding suggests that the field population is a mixture coming from binary-rich and binary-poor environments. Differences of the multiplicity fraction among star-forming regions are well documented (see Section 10.3).

Interestingly, the simulated quadruples outnumber triples, resembling in this respect the hydrodynamical simulations of *Bate* (2012). The 2+2 quadruples are much more frequent (∼4-5% of all stars) than the 3+1 quadruples. The large number of 2+2 quadruples in the FG-67pc sample predicted by this model can be verified observationally.

A loose correlation between orientations of the angular momentum vectors in the inner and outer subsystems of triples was found in early works and confirmed by *Tokovinin & Sterzik* (2002). This correlation becomes stronger at moderate P_L/P_S ratios, i.e., in triples with weak hierarchy. These authors tried to match the observational result with simulations of dynamically decaying N-body systems. Agreement could be achieved for certain initial conditions (rotating and/or flattened clusters). However, multiple systems produced by the pure N-body decay without gas drag and accretion are statistically very different from the real multiples in their eccentricities and period ratios (*Tokovinin,* 2008), pointing to the importance of viscous interactions and accretion during the earliest phases of multiple evolution.

13. CONCLUDING REMARKS

In summary, it appears that the large majority – and potentially all – of stars are born in small multiple systems. A picture is emerging where the field population of single, binary, and multiple stars derives from a birth population that has been transformed by both internal and external dynamical processes. These processes sculpt the (still unknown) separation distribution function at birth into the log-normal distribution (with a power-law tail for the wider binaries) observed in the evolved field population.

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REFERENCES

Abt, H. A. & Corbally, C. J. (2000) *Astrophys. J., 541*, 841.
Albrecht, S. et al. (2009) *Nature 461*,373.
Albrecht, S. et al. (2011) *Astrophys. J. 726*,68.
Alexander, R. (2012) *Astrophys. J. Lett. 757*, L29.
Allen, P. R. (2007) *Astrophys. J., 668*, 492.
Allen, C. et al. (2004) IAU Coll. No.191, eds. C. Allen & C. Scarfe, *Rev. Mex. Astron. Astrofis. SC, 21*, 195.
Allison, R. J. & Goodwin, S. P. (2011) *MNRAS, 415*, 1967.
Ambartsumian, V. A. (1954) *Contrib. Byurakan Obs., 15*, 3.
Anosova, J. P. (1986) *Astrophys. Spa. Sci., 124*, 217.
Armitage, P. J. et al. (1999) *MNRAS, 304*, 425.
Arreaga-García, G. et al. (2010) *Astron. Astrophys., 509*:A96.
Artymowicz, P. (1983) *Acta. Astron., 33*, 223.
Artymowicz, P. & Lubow, S. H. (1994) *Astrophys. J., 421*, 651.
Artymowicz, P. & Lubow, S. H. (1996) *Astrophys. J., 467*, L77.
Attwood, R. E. et al. (2009) *Astron. Astrophys., 495*, 201.
Bai, X.-N. (2011) *Astrophys. J., 739*, 50.
Baines, D. et al. (2006) *MNRAS, 367*, 737.
Bally, J. & Zinnecker, H. (2005) *Astron. J., 129*, 2281.
Bally, J. et al. (2011) *Astrophys. J., 727*:A113.
Baraffe I., & Chabrier G. (2010) *Astron. Astrophys., 521*:A44.
Baraffe I. et al. (1998) *Astron. Astrophys., 337*, 403.
Basu, S. & Vorobyov, E.I. (2012) *Astrophys. J., 750*:A30.
Bate, M. R. (2000) *MNRAS, 314*, 33.
Bate, M. R. (2009a) *MNRAS, 392*, 590.
Bate, M. R. (2009b) *MNRAS, 397*, 232.
Bate, M. R. (2012) *MNRAS, 419*, 3115.
Bate, M. R. & Bonnell, I. A. (1997) *MNRAS, 285*, 33.
Bate, M. R. et al. (2002) *MNRAS, 336*, 705.
Batten, A. H. (1973) Binary and Multiple Star Systems, *Pergamon Press, Oxford*
Bechter, E. B., Creep, J. R., Ngo, H. et al. (2013) arXiv:1307.6857
Becker, C. et al. (2013) *Astron. Astrophys., 552*:A46.
Bergfors, C. et al. (2010) *Astron. Astrophys., 520*:A54.
Biller, B. et al. (2011) *Astrophys. J., 730*:A39.
Bisikalo, D. V. et al. (2012) *Astronomy Reports, 56*, 686.
Blaauw, A. (1961) *Bull. Astr. Inst. Netherlands, 15*, 265.
Boden, A. F. et al. (2009) *Astrophys. J 696*, L111.
Bonnell, I. A. & Bastien, P. (1992) *Astrophys. J., 401*, L31.
Bonnell, I. A. & Bate, M. R. (2005) *MNRAS, 362*, 915.
Bonnell, I. A. et al. (2007) in *Protostars and Planets V*, eds. B. Reipurth, D. Jewitt, K. Keil, Univ. of Arizona Press, p. 149.
Bonnell, I. A. et al. (2008) *MNRAS, 389*, 1556.
Boss, A. P. (2009) *Astrophys. J., 697*, 1940.
Boss, A. P. & Bodenheimer (1979) *Astrophys. J., 234*, 289.
Boss, A. P. & Keiser, S. A. (2013) *Astrophys. J., 763*:A1.
Bürzle, F. et al. (2011) *MNRAS, 412*, 171.
Brandeker, A. et al. (2006) *Astrophys. J., 652*, 1572.
Bressert, E. et al. (2012) *Astron. Astrophys., 542*, 49.
Burgasser, A. J. et al. (2007) in *Protostars and Planets V*, eds. B. Reipurth, D. Jewitt, K. Keil, Univ. of Arizona Press, 427.
Cabrit S. et al. (2006) *Astron. Astrophys., 452*, 897.
Capelo, H. et al. (2012) *Astrophys. J., 757*:L18
Carney, B. W. et al. (2003) *Astron. J., 125*, 293.
Chabrier G. et al. (2007) *Astron. Astrophys., 472*, L17.
Chauvin, G. et al. (2011) *Astron. & Astrophys. 528*:A8.
Chen, X. et al. (2008) *Astrophys. J., 683*, 862.
Chen, X. et al. (2009) *Astrophys. J., 691*, 1729.
Chen, X. et al. (2013) *Astrophys.J., 768*:A110.
Chini, R. et al. (2012) *MNRAS, 424*, 1925.
Cieza, L. et al. (2009) *Astrophys. J., 696*, L84.
Clarke, C. J. & Pringle, J. E. (1992) *MNRAS, 255*, 423.
Clarke, C. J. & Pringle, J. E. (1993) *MNRAS, 261*, 190.
Clark, P. C. et al. (2008) *MNRAS, 386*, 3.
Close, L. M. et al. (2012) *Astrophys. J., 749*:A180.
Commercon, B. et al. (2010) *Astron. Astrophys., 510*:L3.
Commercon, B. et al. (2011) *Astrophys. J., 742*:L9.
Connelley, M. S. et al. (2008a) *Astron. J, 135*, 2496.
Connelley, M. S. et al. (2008b) *Astron. J, 135*, 2526.
Connelley, M. S. et al. (2009) *Astron. J, 138*, 1193.
Corporon, P. & Lagrange, A.-M. (1999) *Astron. Astrophys. Suppl., 136*, 429.
Correia, S. et al. (2006) *Astron. Astrophys., 459*, 909.
Correia, S. et al. (2013) *Astron. Astrophys., 557*:A63.
Crutcher, R. M. (2012) *Ann. Rev. Astron. Astrophys., 50*, 29.
Cuadra, J. et al. (2009) *MNRAS, 393*, 1423.
Daemgen, S. et al. (2012) *Astron. Astrophys., 540*:A46.
Daemgen, S. et al. (2013) *Astron. Astrophys., 554*:A43.
D'Antona F. & Mazzitelli I. (1997) *Mem. Soc. Astr. Ital., 68*, 807.
Deller, A. T. et al. (2013) *Astron. Astrophys., 552*:A51.
De Rosa, R.J. et al. (2014) *MNRAS, 437*, 1216.
de Val-Borro, M. et al. (2011) *MNRAS, 413*, 2679.
de Wit, W. J. et al. (2005) *Astron. Astrophys., 437*, 247.
Domingos, R. et al. (2012) *Astron. Astrophys., 544*:A63.
Dotter A. et al. (2008) *Astrophys. J. Supp., 178*, 89.
Doyle, L. R. et al. (2011) *Science, 333*, 1602.
Duchêne, G. & Kraus, A. (2013) *Ann. Rev. Astron. Astrophys., 51*, 269

Duchêne, G. et al. (1999) *Astron. Astrophys., 343*, 831.
Duchêne, G. et al. (2004) *Astron. Astrophys., 427*, 651.
Duchêne, G. et al. (2007) *Astron. Astrophys., 476*, 229.
Dumusque, X. et al (2012) *Nature, 491*, 207.
Dupuy, T. J. & Liu, M. C. (2011) *Astrophys. J., 733*:A122.
Duquennoy, A. & Mayor, M. (1991) *Astron. Astrophys., 248*, 485.
Durisen, R. H. & Sterzik, M.F. (1994) *Astron. Astrophys., 286*, 84.
Dyck, H. M. et al. (1982) *Astrophys. J., 255*, L103.
Eggleton, P. (2009) *MNRAS, 399*, 1471.
Enoch, M. L. et al. (2011) *Astrophys. J. Suppl. Ser., 195*:A21.
Espaillat, C. et al. (2011) *Astrophys. J. 728*, 49.
Fabrycky, D. & Tremaine, S., (2007) *Astrophys. J., 669*, 1298.
Facchini, S. & Lodato, G., (2013) *MNRAS, 433*, 2142
Fateeva, A. M. et al. (2011) *Astrophy. Space Sci., 335*, 125.
Feiden, G. & Chaboyer, B. (2012) *Astrophys. J., 761*, 30.
Feiden, G. A. & Dotter, A. (2013) *Astrophys. J., 765*:A86.
Fischer, D. A. & Marcy, G. W. (1992) *Astrophys. J., 396*, 178.
Foucart, F. & Lai, D., (2013) *Astrophys. J., 764*:A106.
Garcia, V. et al. (2011) *Astron. J., 142*, 27.
Garcia, V. et al. (2013a) *Astrophys. J., 769*, 114.
Garcia, P. J. V. et al. (2013b) *MNRAS, 430*, 1839.
Ghez, A. M. et al. (1993) *Astron. J., 106*, 2005.
Ghez, A. M. et al. (1997) *Astrophys. J., 481*, 378.
Gieles, M. & Portegies Zwart, S. F. (2011) *MNRAS, 410*, L6.
Gies, D.R. & Bolton, C.T. (1986) *Astrophys. J. Suppl., 61*, 419.
Gomez da Castro et al. (2013) *Astrophys. J., 766*, 62.
Gómez, L. et al. (2006) *Astrophys. J., 635*, 1166.
Gómez Maqueo Chew, Y. et al. (2012) *Astrophys. J., 745*, 58.
Goodman, J. & Hut, P. (1993) *Astrophys. J.*, *403*, 271.
Goodwin, S. P. (2010) *Phil.Trans.Roy.Soc.A*, *368*, 851.
Goodwin, S. P. et al. (2007) in *Protostars and Planets V* eds. B. Reipurth, D. Jewitt, K. Keil, Univ. of Arizona Press, p. 133.
Gorti, U. & Bhatt, H. C. (1996) *MNRAS, 283*, 566.
Haisch, K. E. et al. (2004) *Astron. J., 127*, 1747.
Hall, S. (1997) *MNRAS, 287*, 148.
Hall, S. et al. (1996) *MNRAS, 278*, 303.
Hallinan, G. et al. (2007) *Astrophys. J., 663*, L25.
Hanawa, T. et al. (2010) *Astrophys. J., 708*, 485.
Hansen, C. et al. (2012) *Astrophys. J., 747*:A22.
Harris, R. J. et al. (2012) *Astrophys. J., 751*:A115.
Heggie, D. C. (1975) *MNRAS, 173*, 729.
Hennebelle, P. & Fromang, S. (2008) *Astron. Astrophys., 477*, 9.
Hennebelle, P. & Teyssier, R. (2008) *Astron. Astrophys., 477*, 25.
Hennebelle, P. et al. (2011) *Astron. Astrophys., 528*:A72.
Herbig, G. H. (1962) *Advances Astron. Astrophys., 1*, 47.
Herbig, G. H. (1977) *Astrophys. J., 217*, 693.
Herbig, G. H. & Terndrup, D. M. (1986) *Astrophys. J., 307*, 609.
Herbst, W. et al. (2010) *Astron. J., 140*, 2025.
Hills, J. G. (1975) *Astron. J.*, *80*, 809.
Hills, J. G. (1990) *Astron. J.*, *99*, 979.
Hioki, T. et al. (2009) *Pub. Astr. Soc. Japan, 61*, 1271.
Hioki, T. et al. (2011) *Pub. Astr. Soc. Japan, 63*, 543.
Jensen, E. L. et al. (1996) *Astrophys. J., 458*, 312.
Harris, R. J. at al. (2012) *Astrophys. J., 751*:A115.
Joergens, V. (2008) *Astron. Astrophys., 492*, 545.
Joos, M. et al. (2012) *Astron. Astrophys., 543*:A128.
Joy, A. H. & van Biesbroeck, G. (1944) *PASP, 56*, 123.
Kennedy, G. M. et al. (2012a) *MNRAS, 421*, 2264.
Kennedy, G. M. et al. (2012b) *MNRAS, 426*, 2115.
Kiminki, D.C. & Kobulnicky, H.A. (2012) *Astrophys. J., 751*, 4.
King, R. R. et al. (2012a) *MNRAS, 421*, 2025.
King, R. R. et al. (2012b) *MNRAS, 427*, 2636.
Kneller, S. A. & Clarke, C. J. (2014) in prep.
Köhler, R. et al. (2006) *Astron. Astrophys.*, *458*, 461.
Korntreff, C. et al. (2012) *Astron. Astrophys., 543*:A126.
Kouwenhoven, M. B. N. et al. (2005) *Astron. Astrophys., 430*, 137.
Kouwenhoven, M. B. N. et al. (2007) *Astron. Astrophys., 474*, 77.
Kouwenhoven, M. B. N. et al. (2010) *MNRAS, 404*, 1835.
Kozai, Y. (1962) *Astron. J., 67*, 591.
Kratter, K.M. & Matzner, C. D. (2006) *MNRAS, 373*, 1563.
Kraus, A. L. & Hillenbrand, L. A. (2007) *Astrophys. J., 662*, 413.
Kraus, A. L. & Hillenbrand, L. A. (2009) *Astrophys. J., 784*, 531.
Kraus, A. L. & Hillenbrand, L. A. (2012) *Astrophys. J., 757*:A141.
Kraus, A. L. et al. (2008) *Astrophys. J., 679*, 762.
Kraus, A. L. et al. (2011) *Astrophys. J. 731*:A8.
Kraus, A. L. et al. (2012) *Astrophys. J., 745*:A19.
Kroupa, P. (1995) *MNRAS, 277*, 1491.
Kroupa, P. (1998) *MNRAS, 298*, 231.
Kroupa, P. (2000) in *Massive Stellar Clusters*, (A. Lancon and C. Boily, ed.) *ASP Conference Series, 211*, 233.
Kroupa, P. & Bouvier, J. (2003) *MNRAS, 346*, 343.
Kroupa, P. & Petr-Gotzens, M. G. (2011) *Astron. Astrophys., 529*:A92.
Kroupa, P. et al. (2003) *MNRAS, 346*, 354.
Krumholz, M. R. & Thompson, T. A. (2007) *Astrophys. J., 661*, 1034.
Krumholz, M. et al. (2012) *Astrophys. J., 754*:A71.
Kudoh, T. & Basu, S. (2008) *Astrophys. J., 679*, L97.
Kudoh, T. & Basu, S. (2011) *Astrophys. J., 728*:A123.
Kuiper, G. P. (1942) *Astrophys. J., 95*, 201.
Lada, C. J. (2006) *Astrophys. J., 640*, L63.
Lafrenière, D. et al. (2008) *Astrophys. J., 683*, 844.
Larson, R. B. (1972) *MNRAS, 156*, 437.
Lazarian, A. et al. (2012) *Astrophys. J., 757*:A154.
Leigh, N. & Geller, A. M. (2012) *MNRAS, 425*, 2369.
Leinert, Ch. et al. (1993) *Astron. Astrophys., 278*, 129.
Leinert, Ch. et al. (1997) *Astron. Astrophys., 318*, 472.
Leinhardt, Z. & Stewart, S. (2012) *Astrophys. J., 745*, 79.
Lépine, S. & Bongiorno, B. (2007) *Astron. J., 133*, 889.
Lidov, M., (1962) *Plan. Spa. Sci., 9*, 719.
Loinard, L. (2013) IAU Symposium 289, *Advancing the Physics of Cosmic Distances*, ed. R. de Grijs, 36.
Looney, L. G. et al. (2000) *Astrophys. J., 529*, 477.
MacDonald J. & Mullan D.J. (2009) *Astrophys. J., 700*, 387.
MacFadyen, A. I. & Milosavljevic, M. (2008) *Astrophys. J., 672*, 83.
Machida, M. N. (2008) *Astrophys. J., 682*, L1.
Machida, M. N. et al. (2008) *Astrophys. J., 677*, 327.
Maiz-Appellaniz, J. et al. (2004) *Astrophys. J. Suppl. 151*, 103.
Mardling, R. A. & Aarseth, S. J. (2001) *MNRAS, 321*, 398.
Marks, M. & Kroupa, P. (2011) *MNRAS, 417*, 1702.
Marks, M. & Kroupa, P. (2012) *Astron. Astrophys., 543*:A8.
Martins, F. et al. (2005) *Astron. Astrophys., 436*, 1049.
Marzari, F. et al. (2013) *Astron. Astrophys., 553*:A71.
Mason, B. D. et al. (2009) *Astron. J., 137*, 3358.
Mathieu, R. D. (1994) *Ann. Rev. Astron. Astrophys., 32*, 465.
Mathieu, R. D. et al. (1997) *Astron. J., 113*, 1841.
Mathieu R. D. et al. (2007) in *Protostars & Planets V*, eds. B. Reipurth, D. Jewitt, K. Keil, Univ. of Arizona Press, p. 411.
Maury, A. J. et al. (2010) *Astron. Astrophys., 512*:A40.
Melo, C. H. F. et al. (2001) *Astron. Astrophys., 378*, 898.
Moeckel, N. & Bate, M. R. (2010) *MNRAS, 404*, 721.
Moeckel, N. & Clarke, C. J. (2011) *MNRAS, 415*, 1179.

Mohanty, S. & Stassun, K. G. (2012) *Astrophys. J., 758*, 12.
Mohanty, S. et al. (2010) *Astrophys. J., 722*, 1138.
Mohanty, S. et al. (2013) *Astrophys. J., 764*, 65.
Monin, J.-L. et al (2007) in *Protostars and Planets V*, eds. B. Reipurth, D. Jewitt, K. Keil, Univ. of Arizona Press, p. 395.
Morales, J.C. et al. (2010) *Astrophys. J., 718*, 502.
Morales-Calderon, M. et al. (2012) *Astrophys. J., 753*, 149.
Muzerolle, J. et al. (2013) *Nature, 493*, 378.
Myers, A. et al. (2013) *Astrophys. J., 766*:A97.
Nagel, E. et al. (2011) *Astrophys. J., 747*, 139.
Nguyen, D. C. et al. (2012) *Astrophys. J., 745*:A119.
Ochi, Y. et al. (2005) *Astrophys. J., 623*, 922.
Oey, M.S. et al. (2013) *Astrophys. J., 768*, 66.
Offner, S. S. R. et al. (2009) *Astrophys. J., 703*, 131.
Offner, S. S. R. et al. (2010) *Astrophys. J., 725*, 1485.
Öpik, E. (1924) *Pub. Tartu Obs., 25*, No.6.
Padoan, P. & Nordlund, Å. (2004) *Astrophys. J., 617*, 559.
Palla F. & Stahler S. (1999) *Astrophys. J., 525*, 772.
Parker, R. J. & Goodwin, S. P. (2012) *MNRAS, 424*, 272.
Parker, R. J. & Reggiani, M. M. (2013) *MNRAS, 432*, 2378.
Parker, R. J. et al. (2009) *MNRAS, 397*, 1577.
Parker, R. J. et al. (2011) *MNRAS, 418*, 2565.
Payne, M. et al. (2009) *MNRAS, 336*, 973.
Pepper, J. et al. (2007) *Pub. Astr. Soc. Pacific, 119*, 923.
Pfalzner, S. et al. (2005) *Astrophys. J., 629*, 526.
Poveda, A. et al. (1967) *Bol. Observ. Ton. Tac., 4*, 86.
Prato, L. (2007) *Astrophys. J., 657*, 338.
Prato, L. & Simon, M. (1997) *Astrophys. J., 474*, 455.
Price, D. J. & Bate, M. R. (2007) *MNRAS, 377*, 77.
Rafikov, R. (2013) *Astrophys. J., 765*, L8.
Raghavan, D. et al. (2010) *Astrophys. J. Suppl., 190*, 1.
Ratzka, T. et al. (2005) *Astron. Astrophys., 437*, 611.
Rawiraswattana, K. et al. (2012) *MNRAS, 419*, 2025.
Reid, I. N. et al. (2006) *Astron. J., 132*, 891.
Reiners, A. et al. (2007) *Astrophys. J., 671*, L149.
Reipurth, B. (1988) in *Formation and Evolution of Low-Mass Stars*, eds. A.K. Dupree, M.T.V.T. Lago (Kluwer), p. 305.
Reipurth, B. (2000) *Astron. J., 120*, 3177.
Reipurth, B. & Bally, J. (2001) *Ann. Rev. Astron. Astrophys., 39*, 403.
Reipurth, B. & Clarke, C. (2001) *Astron. J., 122*, 432.
Reipurth, B. & Aspin, C. (2004) *Astrophys. J., 608*, L65.
Reipurth, B. & Mikkola, S. (2012) *Nature, 492*, 221.
Reipurth, B. & Mikkola, S. (2014) in prep.
Reipurth, B. & Zinnecker, H. (1993) *Astron. Astrophys., 278*, 81.
Reipurth, B. et al. (2002) *Astron. J., 124*, 1045.
Reipurth, B. et al. (2004) *Astron. J., 127*, 1736.
Reipurth, B. et al. (2007) *Astron. J., 134*, 2272.
Reipurth, B. et al. (2010) *Astrophys. J., 725*, L56.
Rodón, J. A. et al. (2008) *Astron. Astrophys., 490*, 213.
Rodriguez, J. et al. (2013) *Astron. J., 146*:A112.
Rodríguez, L. F. et al. (2003) *Astrophys. J., 598*, 1100.
Rodríguez, L. F. et al. (2005) *Astrophys. J., 627*, L65.
Rodríguez, L. F. et al. (2010) *Astron. J., 140*, 968.
Salter, D. M. et al. (2010) *Astron. Astrophys., 521*:A32.
Salukvadze, G. N. & Javakhishvili, G. Sh. (1999) *Astrophysics, 42*, 431.
Sana, H. & Evans, C.J. (2011) *IAU Symp., 272*, 474.
Sana, H. et al. (2008) *MNRAS, 386*, 447.
Sana, H. et al. (2009) *MNRAS, 400*, 1479.
Sana, H. et al. (2012) *Science 337*, 444.
Sana, H. et al. (2013) *Astron. Astrophys., 550*, 107.
Scally, A. et al. (1999) *MNRAS, 306*, 253.
Scally, A. et al. (2005) *MNRAS, 358*, 742.
Seifried, D. et al. (2012) *MNRAS, 423*, L40.
Shakura, N. & Sunyaev, R. A. (1973) *Astron. Astrophys., 24*, 337.
Shatsky, N. (2001) *Astron. Astrophys., 380*, 238.
Shi, J.-M. et al. (2012) *Astrophys. J., 747*, 118.
Siess I. et al. (2000) *Astron. Astrophys., 358*, 593.
Simon M. & Obbie R.C. (2009) *Astron. J., 137*, 3442.
Sota, A. et al. (2008) *Rev. Mex. Astron. Astrofis. S.C., 33*, 56.
Stahler, S. W. (2010) *MNRAS, 402*, 1758.
Stamatellos, D. et al. (2007) *MNRAS, 382*, L30.
Stassun, K.G. et al. (2006) *Nature, 440*, 311.
Stassun, K.G. et al. (2007) *Astrophys. J., 664*, 1154.
Stassun, K.G. et al. (2008) *Nature, 453*, 1079.
Stassun, K.G. et al. (2012) *Astrophys. J., 756*, 47.
Stempels, H. & Gahm, G. (2004) *Astron. Astrophys. 421*, 1159.
Sterzik, M. & Durisen, R. (1998) *Astron. Astrophys., 339*, 95.
Sterzik, M. & Tokovinin, A. (2002) *Astron. Astrophys., 384*, 1030.
Sterzik, M. et al. (2003) *Astron. Astrophys., 411*, 91.
Tan, J. (2004) *Astrophys. J., 607*, L47.
Thebault, P. et al. (2006) *Icarus 183*, 193.
Thebault, P. et al. (2008) *MNRAS, 388*, 1528.
Thebault, P. et al. (2009) *MNRAS, 393*, L21.
Tobin, J. J. et al. (2009) *Astrophys. J., 697*, 1103.
Tobin, J. J. et al. (2013) *Astrophys. J., 779*:A93.
Tognelli E. et al. (2011) *Astron. Astrophys., 533*, 109.
Tokovinin, A. & Smekhov, M. (2002) *Astron. Astrophys., 382*, 118.
Tokovinin, A. et al. (2006) *Astron. Astrophys., 450*, 681.
Tokovinin, A. (2008) *MNRAS, 389*, 925.
Tokovinin, A. (2014), in preparation.
Tokovinin, A. & Lépine, S. (2012) *Astron. J., 144*:A102.
Tokovinin, A. et al. (2010) *Astron. J., 140*, 510.
Torres, G. (2013) *Astron. Nach., 334*, 4.
Torres, G. et al. (2010) *Astron. Astrophys. Rev., 18*, 67.
Torres, G. et al. (2013) *Astrophys. J., 773*:A40.
Torres, R. M. et al. (2012) *Astrophys. J., 747*, 18.
Trilling, D. et al. (2007) *Astrophys. J., 658*, 1264.
Umbreit, S. et al. (2005) *Astrophys. J., 623*, 940.
Umbreit, S. et al. (2011) *Astrophys. J., 743*:A106.
Valtonen, M. & Karttunen, H. (2006) *The Three-Body Problem*, Cambridge Univ. Press.
van Albada, T. S. (1968) *Bull. Astron. Inst. Netherlands, 20*, 57.
Verrier, P. & Evans, N. (2007) *MNRAS, 382*, 1432.
Verrier, P. & Evans, N. (2009) *MNRAS, 394*, 1721.
Viana Almeida, P. et al. (2012) *Astron. Astrophys., 539*:A62.
Walch, S. et al. (2010) *MNRAS, 402*, 2253.
Welsh, W. F. et al. (2012) *Nature, 481*, 475.
Whitworth, A. P. & Zinnecker, H. (2004) *Astron. Astrophys., 427*, 299.
Whitworth, A. P. et al. (2007) in *Protostars and Planets V*, eds. B. Reipurth, D. Jewitt, K. Keil, Univ. of Arizona Press, p. 459.
Zhao, B. & Li, Z.-Y. (2013) *Astrophys. J., 763*, 7.
Xie, J.-W. et al. (2010) *Astrophys. J., 708*, 1566.
Zahn, J.-P. & Bouchet, L. (1989) *Astron. Astrophys., 223*, 112.
Zapata, L. A. et al. (2009) *Astrophys. J., 704*, L45.
Zinnecker, H. (1989) in ESO Workshop *Low Mass Star Formation and Pre-Main Sequence Objects*, ed. Bo Reipurth, p. 447.
Zinnecker, H. & Mathieu, R. (2001) *The Formation of Binary Stars*, IAU Symp. No. 200, Astron. Soc. Pacific.
Zinnecker, H. & Yorke, H.W. (2007) *Ann. Rev. Astron. Astrophys., 45*, 481.