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MULTIPLE PROTOSTARS, JETS, AND THE ORIGIN OF BROWN DWARFS[1]

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RESUMEN

El hecho de que las estrellas jóvenes se agrupen en sistemas múltiples de pocos cuerpos y no-jerárquicos tiene profundas consecuencias para la comprensión de la formación de las estrellas, de las binarias y de los planetas que pueden circundarlas. En este trabajo, reseñamos los avances teóricos que en los últimos diez años se han hecho para modelar el rompimiento de estos cúmulos madre, y discutimos una serie de predicciones observacionales que surgen de los modelos, en relación con la cinemática, la estadística de las binarias, y la existencia de discos en estrellas y en enanas marrones. Argumentamos que una de las manifestaciones más espectaculares de las interacciones dinámicas en estrellas múltiples jóvenes debería ser la formación de flujos Herbig-Haro gigantescos, y presentamos evidencia observacional que puede ser interpretada en este sentido.

ABSTRACT

The observation that young stars are clustered in few body non-hierarchical multiple systems at very young ages has profound consequences for our understanding of the formation of stars, binaries and the disks and planets that may surround them. In this chapter we review theoretical progress made over the last decade in modeling the break up of these natal clusters and discuss a range of observational predictions that arise from these models, relating to the kinematics, binary statistics and possession of disks of both stars and brown dwarfs. We also argue that one of the most spectacular manifestations of dynamical interactions in young multiple systems should be the formation of giant Herbig-Haro flows, and present observational evidence that may be interpreted in this light.

Key Words: **BINARIES: CLOSE — ISM: HERBIG-HARO OBJECTS — METHODS: N-BODY SIMULATIONS — STARS: FORMATION — STARS: LOW-MASS, BROWN DWARFS**

1. INTRODUCTION

It is commonly assumed that brown dwarfs are formed the same way as stars, but under conditions that lead to stellar objects with very small masses, i.e. from clouds that are very small, very dense, and very cold. However, with the growing realization that brown dwarfs may be nearly as common as stars, it is becoming disturbing that such special physical conditions are not readily found in the molecular clouds of our Galaxy (although they may exist elsewhere, see Elmegreen 1999).

Alternatively, Lin et al. (1998) suggested that the accidental encounter between two protostars with massive disks could fling out tidal filaments with lengths of about 1000 AU, out of which a brown dwarf might form. However, the fact that brown dwarfs are increasingly discovered also in loose T Tauri associations like Taurus, where such encounters should be extremely rare, suggests that this mechanism is unlikely to be a major source of brown dwarfs.

Taking another approach, it has recently been proposed that brown dwarfs have such extremely low masses because they were ejected from small clusters of nascent stellar embryos (Reipurth & Clarke 2001). This can occur because the timescale for dynamical interactions and ejection is comparable to the timescale for collapse and build-up of a star. The basis for this model is thus closely tied to the evolution of binaries and multiple systems at the very earliest stages of stellar evolution (see, for example, Larson 2002).

Observations over the last decade have established that young T Tauri stars have the same or a slightly higher binary frequency than at the main sequence (e.g. Reipurth & Zinnecker 1993; Ghez, Neugebauer & Matthews 1993; Köhler & Leinert 1998). A small, although not very well determined,

[1]Drs. Reipurth and Clarke each gave an invited talk at the Colloquium. They have, however agreed, with the editors' consent, to publish their contributions in a single paper of somewhat greater length than the others that derive from invited talks.

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fraction of both young and more evolved stars are also triple or higher-order multiple systems. The situation is much less clear among the very youngest, still embedded stars, due to the difficulties of probing into the heavily shrouded environment of such objects. However, new high resolution infrared techniques from the ground and space, as well as centimeter interferometry with e.g. the VLA, are beginning to yield results. In a detailed study of 14 driving sources of giant Herbig-Haro (HH) flows, Reipurth (2000) found that more than 80% are binaries, and of these half are higher order systems. It should be noted that these are the actually observed frequencies, without corrections for the considerable incompleteness of the observations, and so the results are in fact consistent with the possibility that *all* giant HH flow sources may be binary or multiple systems.

Embedded outflow sources are of the order of 10^5 yr old or less, and it follows that some of these systems must decay to reach the lower observed frequencies at later evolutionary stages. It is well established that non-hierarchical triple systems undergo rapid dynamical evolution and evolve into either a binary with a distant companion, i.e. a hierarchical triple system, or into a binary and an unbound, escaping third member.

In the following, we first outline the basic aspects of dynamical interactions in small multiple systems, and then summarize the latest results from N-body calculations based on gas dynamical simulations (Sect. 2). We then compare the theoretical predictions with the currently available observations (Sect. 3). Finally, in Sect. 4 we explore the possibility that the Herbig-Haro jet phenomenon is a manifestation of the dynamical evolution of small clusters of newborn stars.

2. DYNAMICAL INTERACTIONS IN MULTIPLE SYSTEMS

If the dominant mode of star formation involves the splitting of a core into $N > 2$ fragments then important new ingredients enter the dynamics which are not encountered in the cases $N = 1$ or $N = 2$. The reason for this is simply that most $N > 2$ body configurations are dynamically unstable; over several dynamical timescales the components exchange energy through the action of gravitational forces until they attain a stable equilibrium. In practice, this generally means that the mini-cluster disintegrates, the energy for this process being derived from the formation of at least one binary system. After a number of dynamical timescales, therefore, the core no longer consists of a bound stellar system, but of a mixture of binary and single stars that drift apart so as to mingle with the ambient stellar field.

Below we summarize the progress that has been made to date in quantifying such behavior, particularly with regard to the mass spectrum of the stars (and brown dwarfs) produced, their binary statistics and kinematics, and their association with circumstellar material. Although the study of such systems as gas free N-body systems is well developed, it is only recently that it has been possible to address these issues with well resolved hydrodynamical simulations.

2.1. *N-body simulations*

The simplest possibility is if all the gas is instantly accreted on to each protostar so that the ensemble evolves thereafter as a system of point masses. This situation can be modeled as an N-body system and has been analyzed by many authors (e.g. van Albada 1968; Allen & Poveda 1974, Sterzik & Durisen 1998, 2003, Durisen, Sterzik & Pickett 2001). The usual outcome of such simulations is that the two most massive members of the system form a binary, whereas the remainder are ejected as single stars. The ejection velocity of stars is related to their orbital velocity during a close three body encounter and scales as the inverse square root of the encounter distance. For example, in Sterzik and Durisen's simulations, the typical separation between stars is initially around 100 AU, and typical ejection velocities of single stars are 3-4 km s^{-1}. Sterzik and Durisen also quantified the dependence of ejection velocity on stellar mass, and found that for $N > 3$, such a dependence is very weak; however they found a significant difference in the final velocities of single stars and binaries, with the centre of mass velocity of binaries being typically a factor $3 - 6$ less than that of singles.

2.2. *Addition of star-disk interactions in a parameterized form*

The above simulations yield well defined predictions for the fraction of stars of various masses that end up in binaries (McDonald & Clarke 1993), but do not however take account of the fact that the fragments will have their interactions mediated by circumstellar disks. This situation is less straightforward to model numerically, since there are well known numerical difficulties in maintaining disks for many internal orbital timescales against the dispersive action of viscosity. McDonald & Clarke (1995) included the effect of star-disk interactions in a parameterized form (see also Clarke & Pringle 1991) and found that the main role of disks is to harden temporary binaries so as to protect them against disruptive encounters with other cluster members. As a result, more than one binary can be formed in each cluster; although the most massive cluster member was always in a binary, its companion was apparently randomly selected from the cluster members. The net effect of star-disk interaction was thus to boost the numbers of lower mass stars that ended up in binaries (either as primaries or secondaries) relative to the dissipationless (N-body) case.

2.3. *Planting seeds: accreting point masses in a gas-rich environment*

The simulations described above cannot say anything about the stellar initial mass function, since stellar masses are assigned at the outset of the simulation. Such instantaneous mass assignment is of course a very poor approximation to the behavior of real fragmenting cores: the interactions that lead to the formation of binaries and break up of the cluster occur over a few dynamical times, but the infall of mass onto each of the stars happens on a comparable timescale. Thus realistic simulations need to address the whole process as a hydrodynamic one and follow through the evolution of a core that is initially 100% gas.

One approach is to set up cores in which 'seeds' of collapsed gas have been planted (Bonnell et al. 1997; Bonnell et al. 2001). These seeds grow in mass due to gas accretion in an inequitable manner - their orbital histories determine whether they spend much time in the densest central regions of the core and hence how much mass they acquire. Such simulations vividly demonstrate how 'competitive accretion' works: seeds that get an early head start in the race for mass tend to settle into the cluster core and thereby acquire more mass, whereas seeds that do not grow much initially are more likely to be flung out of the core and hence be prevented from further growth. Thus competitive accretion provides a ready mechanism for obtaining a large dynamic range of final stellar masses from arbitrary initial conditions.

Simulations by Delgado-Donate, Clarke & Bate (2003) have quantified the IMF produced by competitive accretion during the break up of small ($N = 5$) clusters (Fig. 1) and find that it is broadly compatible with the observed IMF. (Note that in these simulations no disks are formed around the protostars due to the absence of small scale turbulence in the initial core). This IMF is primarily determined by the mass function of parent cores, being comparable to this core mass function down to stellar masses that

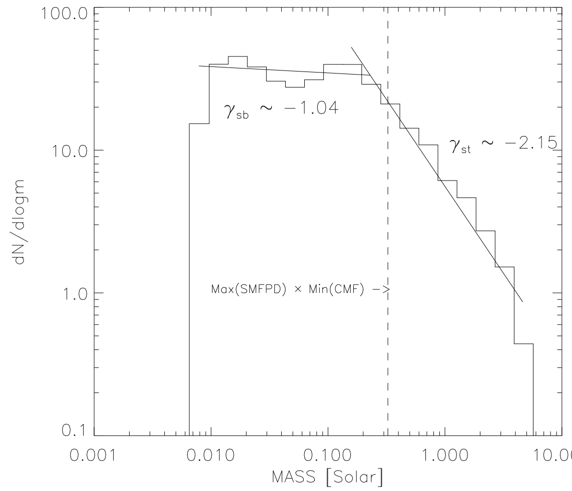

Fig. 1. Initial Mass Function as quantified by Delgado-Donate et al. (2003). The mass function results from the convolution of the core splitting function with a power-law core mass function, in this case extending down to $0.3M_{\odot}$.

are similar to the minimum core mass, and declining at masses below this. The reason for this is that the division of mass *for given core mass* is essentially bimodal - there is a high mass peak corresponding to a binary pair and a lower mass peak corresponding to ejected singles or wide tertiary companions. When this is convolved with a core mass function that declines steeply toward high masses, the majority of stars of given mass belong to the high mass peak of low mass cores rather than the low mass peak of rare, high mass cores. Consequently, the stellar mass function follows the core mass function. Thus the observed similarity between the core mass function and the stellar IMF (Motte, André & Neri 1998) *cannot of itself be used to disprove the hypothesis that most stars arise in small non-hierarchical multiples.*

The outcome of these simulations shares many qualitative similarities with the dissipationless (N-body) results of Sterzik and Durisen. As in their simulations, there is no appreciable dependence of final velocity on resulting stellar mass, but the binaries attain speeds that are a factor ~ 10 less than the typical ejection speeds of the single stars. The reason for this is that these ($N = 5$) simulations produce in general only one binary per core, and this (plus any loosely bound companions) remains close to the core centre of mass, whilst single stars are all ejected from the core.

The central binary typically has a mass ratio in the range $0.5 - 1$: low mass ratio systems are rare, so that the frequency of brown dwarf companions in pure binary systems (or in the central binary of triple systems) is very low. However, low mass stars and brown dwarfs are typically found as the outermost companions in triples and higher-order multiples, since not all ejections yield an unbound escaper.

2.4. *Turbulent initial conditions*

A more realistic approach involves abandoning the artificial distinction between seeds and smoothly distributed background gas in the above simulations. Instead, recent simulations start with gas that is subject to a supersonic turbulent velocity field which rapidly generates a richly non-linear density structure in the gas (Klessen, Heitsch & Mac Low 2000; Klessen 2001). Such simulations follow not only the competitive accretion between contending 'stars' and their dynamical interactions, but also the formation of stars from pockets of Jeans unstable gas. The most ambitious simulation to date is that of Bate and collaborators (Bate, Bonnell & Bromm 2002a,b; 2003) which models a system that will form of the order a hundred stars, whilst resolving structures down to a few Jupiter masses, (see Bate 2004). This simulation readily demonstrates the formation of small-N ensembles in which the sort of behavior described above (binary formation, competitive accretion, ejection of low mass members, star-disk interactions) is observed to occur. Such one-off simulations however make it difficult to extract accurate statistics and probe initial conditions, due to the computational expense involved in modeling a 50 $M_\odot$ cloud.

A complementary strategy has been adopted by Delgado-Donate, Clarke & Bate (2004a) (see also Goodwin, Whitworth & Ward-Thompson 2004), which involves the modeling of individual turbulent cores rather than larger structures containing several cores. In this way, the unpredictable outcome of turbulent fragmentation models can be statistically described using multiple realizations of the same initial conditions, and different initial conditions can be easily explored. Moreover, the system can be followed until any desired fraction of the system mass is incorporated into stars and its further evolution followed by N-body integration.

To date, such explorations of parameter space suggest that the substellar IMF may be quite sensitive to different input assumptions, whereas the IMF in the stellar regime appears rather robust. (We caution here that any inferences about the stellar IMF for masses in excess of $\sim 5 M_\odot$ are not statistically significant). Delgado-Donate et al. (2004a) found that the number of brown dwarfs produced was quite sensitive to the slope of the turbulent power spectrum employed, yielding resulting IMFs in this regime which differed at the $\sim 2\sigma$ level. This result suggests that the final mass of low mass objects (i.e. brown dwarfs) is rather sensitive to the precise timing of ejection events and can therefore respond to small variations in initial conditions that affect the internal dynamics of the resulting small clusters. Current observational data on the IMF in star forming regions suggest that the IMF in the substellar regime may indeed vary much more between different regions than is the case for the IMF in the stellar regime (Briceno et al. 2002, Preibisch, Stanke & Zinnecker 2003, Jameson et al. 2002).

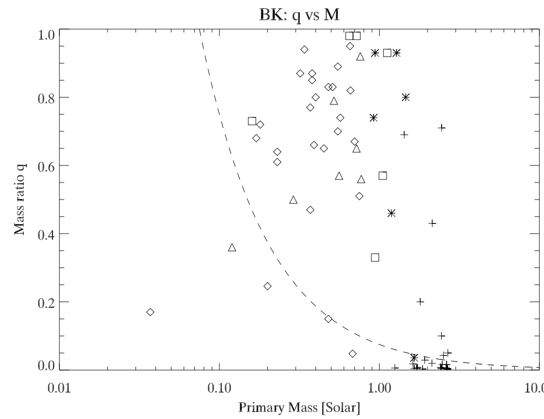

Fig. 2. Mass ratio q versus primary mass for the systems formed in the turbulent models. The symbol code is as follows: binaries=diamonds, triples=triangles, quadruples=squares, asterisks=quintuples, crosses=higher-order multiples. To the left of the dashed line are those systems in which the companion is a substellar object. To the bottom left, the only binary brown dwarf formed in these simulations.

Notwithstanding these differences in the total yield of brown dwarfs as the slope of the turbulent power spectrum is varied, the properties of the resulting multiple systems, both regarding their internal composition and their kinematics, show no dependence on the input turbulent spectrum employed, and henceforth we discuss the results obtained by combining all the turbulent simulations described in Delgado-Donate et al. (2004a). Fig. 2 shows the binary pairing characteristics resulting from these turbulent fragmentation models. As in the *planting seeds* simulations, binary stars tend to have mass ratios close to unity, but the probability of forming low mass ratio systems is higher. Hence, some brown dwarfs are found as companions of low mass stars. Furthermore, the formation of several independent 'units' inside each core enhances the number of bi-

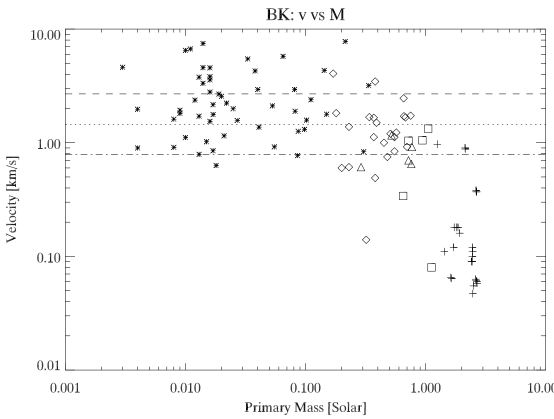

Fig. 3. Velocity with respect to core centre of mass versus primary mass for the systems formed in the turbulent models. The symbols are as in Fig. 2 except that small asterisks now represent singles, and quintuples are included as higher-order multiples (i.e. crosses). The dashed line denotes the mean velocity of singles, the mean velocity of binaries being represented by the dotted line. The dot-dashed line stands for the mean velocity of multiples of an order higher than two. The offset between the velocity dispersion of singles and binaries is very small, in contrast with previous, more simple, simulations.

nary systems formed so that the binary fraction for stars is approximately 0.6, comparable to that found in the field. This multiple binary formation, however, does not lead to the formation of many binary brown dwarfs since, as in the *planting seeds* case, the binary systems are the main focus of accretion and so the stellar boundary is reached in a short timescale, before binary-binary interactions lead to the ejection of one of the systems. Only one out of 27 binaries formed in these models turned out to be a binary brown dwarf, a fraction that is rather lower than current observational estimates.

The kinematics of stars produced in turbulent fragmentation simulations differs from that of previously described models. In the turbulent models, an average of 3 binaries are formed per core, and therefore binary-binary interactions are important. This means that binaries can be ejected as well as singles, and therefore the velocity offset between the two populations is not large. This can be seen in Fig. 3 which shows that although higher-order ($N > 5$) multiples can have a very low velocity dispersion, binaries, triples and quadruples display a distribution of centre of mass velocities that is comparable to that of single stars. This result is similar to that of Bate et al. (2003), and is expected whenever binary-binary interactions are important (i.e.

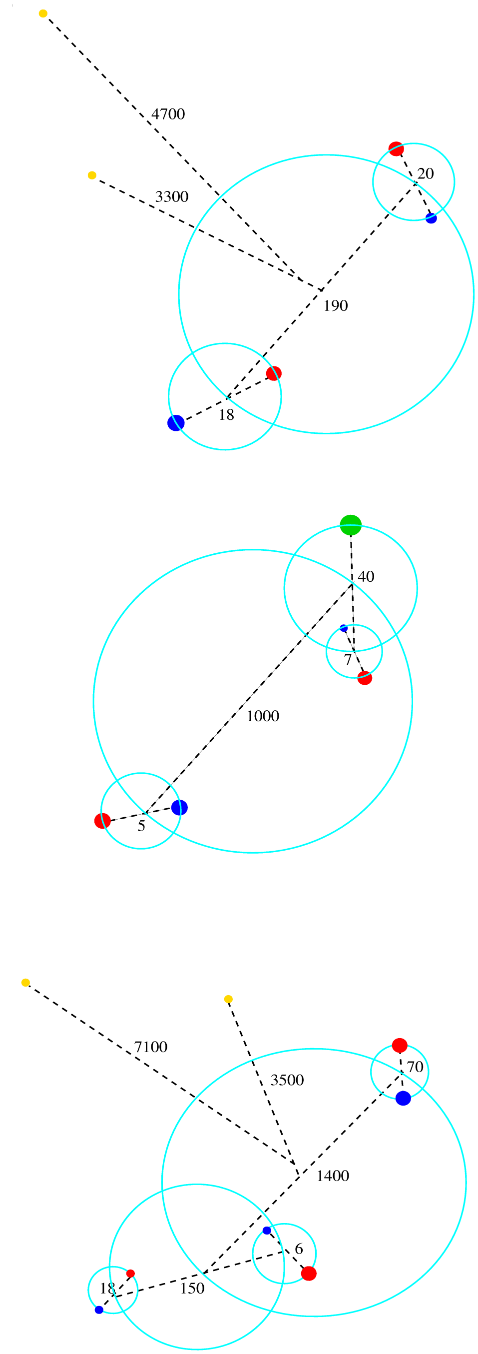

Fig. 4. Pictorial representation of the hierarchical multiple systems commonly produced by turbulent fragmentation calculations. Distances are indicated in AU.

whenever a given core possesses physically separated sites of star formation, so that the formation of one binary does not inhibit the formation of another).

The most robust signature of dynamical simulations, which is shared by the turbulent runs and their simplified predecessors, is the pronounced *mass segregation* within hierarchical multiple systems. The configurations that tend to survive are those in which the most massive objects constitute the central binary and the remaining low mass members (among them many brown dwarfs) are hierarchically distributed at larger distances: Fig. 2 shows the variety of multiple systems that can be formed, whilst Figure 4 is a pictorial representation[5] of the types of hierarchical system that account for $\sim 75\%$ of the multiples produced (see Delgado-Donate et al. 2004b). Therefore, these models predict that a large fraction of observed binaries should turn out, on closer examination, to be triples, either because there is a wide low mass component that might have been missed previously, or because the apparent primary is itself a spectroscopic binary system. It is a crucial test for these models that a substantial number of such systems are investigated.

3. COMPARISON WITH OBSERVATIONS

3.1. *Brown dwarfs in the vicinity of Class 0 objects*

Small N-body systems that are still accumulating mass from an infalling envelope would observationally be seen as a Class 0 or perhaps a Class I source with strong outflow activity. If brown dwarfs are formed by the disintegration of small N-body systems, it follows that the very youngest brown dwarfs should be found in the immediate vicinity of such sources. As a small multiple system breaks up, low mass members are ejected from the nascent envelope, and may on time scales of order 10^3 years emerge from being deeply embedded infrared sources with ample far-infrared and sub-mm emission to being optically visible T Tauri-like stars. In this radically different picture of early stellar evolution, the gradual and smooth transition between Class 0 and Class II sources can be replaced by a rather abrupt transition, and the main accretion phase for the members of a multiple system is terminated not by the infalling envelope running out of gas, or outflow blowing away the last parts of the envelope, but by the newborn members "leaving the nest" (Reipurth 2000).

[5] In this figure the greyscale identifies objects in different mass ranges, light grey for low mass outliers ($M < 0.1 M_\odot$) and dark grey for higher mass inner pairs (with $M > 0.3 M_\odot$)

One observational test of the dynamical formation model of brown dwarfs would be to study carefully the statistics of brown dwarfs in the vicinity of Class 0 sources. For a velocity of 1 km s^{-1}, a brown dwarf moving out of a nearby ($d \sim 130$ pc) cloud at an angle of 60^o to the line-of-sight will already be 5 arcmin away after 2×10^5 yr. (Note that half of all ejected brown dwarfs will move into the cloud from which they formed. Such objects will be detectable only as highly extincted and weak infrared sources).

3.2. *Stars with brown dwarf companions*

It has been known for some time that brown dwarfs are only rarely found as close (less than 3 AU) companions to low mass stars (the "brown dwarf desert"). But recent work by Gizis et al. (2001) has demonstrated that brown dwarfs are commonly companions to normal stars at large separations (greater than 1000 AU). The separation distribution of brown dwarfs in binary systems contains important information about their formation, and establishing its form more precisely will form a crucial test for any theory of brown dwarf formation. The ejection hypothesis readily explains the currently available observations: brown dwarfs should rarely be found as close companions to stars, as they would usually have continued to accrete mass at almost the same rate as their stellar companions, thus pushing through the substellar/stellar boundary at almost the same time. On the other hand, distant brown dwarf companions are readily expected, because not all ejections will lead to unbound systems, though we predict (see Sect. 2) that these wide low mass companions are in fact outliers in triple or higher-order multiple systems.

3.3. *Mass segregation among multiple star systems*

A robust prediction of all simulations to date is that there should be a tendency for mass segregation within multiple star systems, i.e. lower mass objects should more frequently be wide companions whilst higher mass objects should tend to be incorporated in the central binary. Clearly, observations tell us that this is not universally the case (i.e. one can cite examples of triples where the binary is lower mass, or where the least massive member is the binary secondary, rather than the triple companion). Nevertheless, it would be timely to examine this issue in a statistical sense (see Tokovinin 2004). Multiple systems containing brown dwarfs provide a particularly good testbed of these predictions, since they contain a large dynamic range of masses.

3.4. *Binary brown dwarfs*

A number of brown dwarfs have been found to be binaries (e.g. Martín, Brandner, & Basri 1999), but, intriguingly, they appear to be rather close binaries, whereas wide pairs (many hundreds of AU) have so far not been found. In the ejection scenario, a binary with brown dwarf components will remain substellar only if the binary is ejected out of the main accretion region, and thus only tight brown dwarf pairs are expected to survive the ejection event. This expectation (no wide brown dwarf binaries) is confirmed by the numerical simulations, although we note that the number of brown dwarf pairs at any separation is rather low in these simulations.

3.5. *Comparison with cluster color-magnitude diagrams*

Figure 5 compares the color-magnitude diagram for the Praesepe cluster (Hodgkin et al. 1999) with the output of the turbulent simulations detailed in Delgado-Donate et al. (2004b). The filled circles represent the observational data, whilst the open circles and squares are respectively single stars and multiples from the simulations. The spatial resolution of the data implies that binaries tighter than 200 AU are unresolved in this diagram, and the width of the main sequence is an immediate indication that binaries and higher order multiples are abundantly present in this cluster. Indeed the width of the sequence produced by the simulations is very similar to that seen in Praesepe, implying that the observations *require* a star formation model in which high order multiples (i.e. with $N > 2$) are common. Figure 5 also shows up some shortcomings of the models, although these may be an artefact of the fact that the simulations all result from cores with the same total mass ($5M_\odot$). For example, they under-predict the incidence of single stars and/or extreme mass ratio binaries at the higher mass end, since in the simulations binaries are never formed with a mass that is sufficient to eject a solar mass star as a single star. Likewise, the fact that core masses in the simulations do not extend down to low values means that the simulations under-predict the incidence of binaries at low masses. Although the agreement with the data at intermediate masses is encouraging, further comparison must await simulations that include a realistic core mass spectrum.

3.6. *Kinematics of young stars and binaries*

An initial expectation of the outcome of the ejection model (e.g. Reipurth & Clarke 2001) was that young brown dwarfs should have a higher velocity

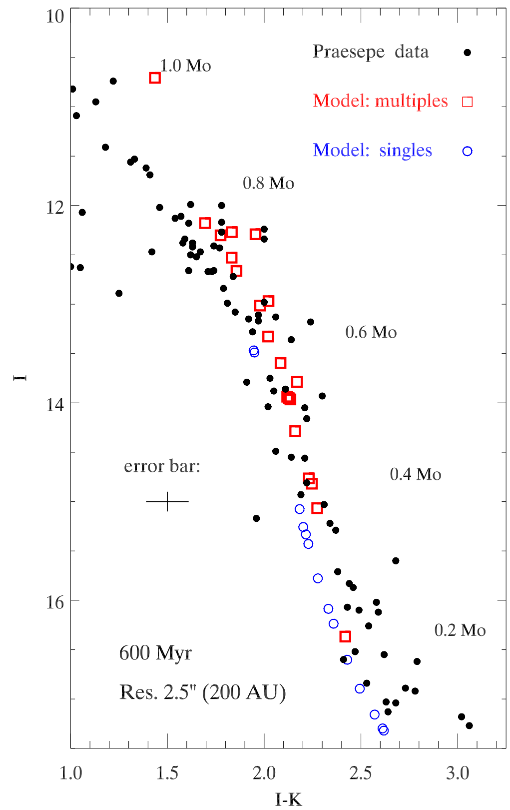

Fig. 5. Observed color-magnitude diagram for Praesepe compared with simulation results

dispersion, with respect to their natal cores, than should young stars (see Joergens & Guenther 2001). This prediction has been successively modified by the results of numerical simulations: in the case that only one binary is formed per star forming core, the main kinematic difference is between single stars and binaries, although, given the lower binary fraction among lower mass stars, this translates into an effective dependence of velocity on mass (i.e. brown dwarfs would have a higher velocity dispersion than stars because the binary fraction is higher among stars: see Delgado et al. 2004a, Kroupa & Bouvier 2003a,b). However, where more than one binary is formed per core, the binaries are themselves ejected from the core and the velocity distribution is neither a strong function of mass or binarity (see Fig. 3). Evidently, measurement of the differential velocity distributions of binaries and single stars in star forming regions will yield important clues to the dynamical environment in which stars are formed. The test is not straightforward, however, since the magnitudes of the velocities predicted (see Fig. 3) are not much larger than the core-core velocity dispersion in star-forming regions.

3.7. *Circumstellar emission in young stars and brown dwarfs*

When objects are ejected from young clusters, any disks they possess will be truncated at a radius that is typically half the distance of closest approach during their closest encounter. In the absence of viscous evolution, therefore, disk radii probe the stellar densities in the natal cluster. As the disk viscously evolves thereafter, its radius following truncation is 'remembered' as setting the timescale for subsequent disk dispersal (Armitage, Clarke & Palla 2003). It is now becoming firmly established that young brown dwarfs commonly possess near-infrared excesses, indicative of optically thick inner disks (e.g. Muench et al. 2001), and that, moreover, the incidence of such disks is similar to that in T Tauri stars (Liu, Najita & Tokunaga 2003). This implies that the lifetimes of disks around brown dwarfs are similar to those around T Tauri stars, which roughly translates into the fact that their disks must be similar in size. Armitage et al. concluded that the lifetimes of disks in T Tauri stars are compatible with mean initial disks sizes of around 10 AU. If one adopts this value, then the disk fractions measured in young brown dwarfs rules out models in which the bulk of objects suffer encounters at radii of a few 10s of AU or less. The detection of millimeter emission around young brown dwarfs would provide better constraints on disk radii and thus further constrain the types of dynamical environments in which they could have been born.

3.8. *Brown dwarfs and extrasolar planets*

Brown dwarfs exceed the mass of planetary mass objects (PMOs) by less than an order of magnitude, but in at least one respect they are very different: radial velocity surveys (e.g. Marcy, Cochran & Mayor 2000) reveal that PMOs are commonly found at close separations around solar type stars, whereas the incidence of brown dwarfs at such radii (< 3 AU) is much lower. Although this result could in principle be explained in terms of enhanced inward orbital migration in the PMOs (due to their lower mass), the lack of a separation-mass correlation among PMOs argues against this hypothesis. Currently there are no observational constraints on the incidence of PMOs at wider orbital separations; observations of star-forming regions suggest the existence of a population of free-floating PMOs (Lucas et al. 2001), although this claim is somewhat dependent on the assumed age of the objects concerned. Thus to date the most robust difference in the distribution of brown dwarfs and PMOs relates to their incidence in tight orbits around solar type stars.

How may one understand these results in the context of the ejection model? The lack of brown dwarfs in close orbits around solar type stars results, in these models, from the fact that even if brown dwarfs are formed in that location, they rapidly accrete mass so as to exceed the hydrogen burning mass limit. Evidently, PMOs at small radii have avoided this fate, and their presence can be understood in the ejection model only if they are formed at a later, less gas-rich, evolutionary phase, probably after the disintegration of the natal cluster. Conventional core accretion models for giant planet formation would certainly satisfy this constraint. Given that we have argued that most brown dwarfs are ejected from small cluster environments, rather than condensing from very low Jeans mass cores in situ, we would likewise not expect free floating PMOs to form in situ and must therefore rely on ejections to produce such a population. It is not clear, however, whether the ejections would result from interactions in the cluster environment (in which case at least some PMOs must form early, as in the models of Boss (2001)) or whether they would instead result from dynamical interactions among multiple planetary systems, as advocated by Papaloizou & Terquem (2001), in which case the timescale for planet formation is not constrained.

4. HERBIG-HARO FLOWS AND THE EVOLUTION OF MULTIPLE SYSTEMS

Outflow activity is associated with all stages of early stellar evolution. Perhaps the most magnificent of the various outflow phenomena are the Herbig-Haro (HH) flows, consisting of luminous shocks on various scales, often along well defined flow axes (for a review see Reipurth & Bally 2001). HH flows can attain dimensions of several parsecs, terminating in giant bow shocks, and with dynamic ages of several times 10^4 yr. When a giant flow has multiple bow shocks, the typical time interval between their ejections is about 2000 yr. More commonly, HH flows have series of knots closer to their driving sources and with characteristic timescales of many hundred years. Finally, some HH flows display finely collimated jets, where the ejection timescale of the jet knots is typically 20-30 yr. Clues to an understanding of these different timescales must be sought in activity cycles of the driving sources of the outflows. Orbital evolution of companions of the driving

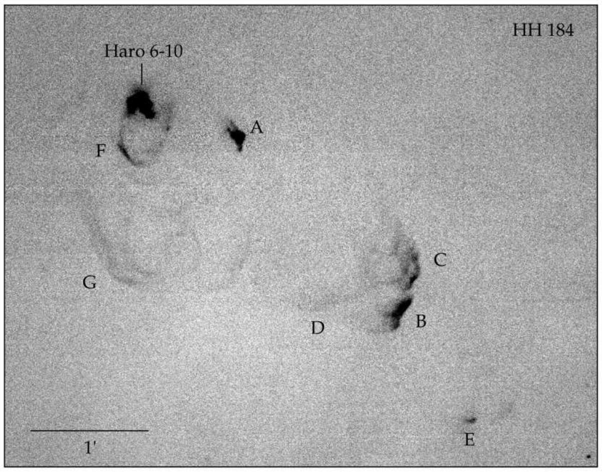

Fig. 6. The small group of HH objects near the young binary Haro 6-10 form two independent flows, one to the south-west (A-E) and another to the SSE (F-G). From Devine et al. (1999).

stars offers an attractive way to explain the range of timescales observed in HH flows.

Dynamical interactions will transform a non-hierarchical triple system into a hierarchical one, in the process ejecting a member (into either a bound or an unbound orbit). The binary system that is formed in this dynamical process is highly eccentric, and given that the triple disintegration is likely to take place while the stars are still actively accreting gas from an infalling envelope, it follows that the circumstellar disks will interact on an orbital timescale, which will lead to shrinkage of the orbit (e.g. Artymowicz & Lubow 1996). These interactions are again likely to cause cyclic variations in the accretion rate, with consequent pulses in the outflow production, and the giant HH flows may therefore represent a fossil record of the birth and early evolution of binary systems (Reipurth 2000). More specifically, the giant HH bow shocks may result from close triple encounters; once the third member of a triple system has been ejected, no further giant bow shocks will be produced. As the orbit of the resulting binary evolves, periastron passages with ensuing disk disturbances will occur with increasing frequency, initially on timescales of many hundreds of years, but eventually measured in decades. Once the semi-major axis becomes smaller than approximately 10 AU the circumstellar disks are so seriously truncated that jet activity soon after begins to die out.

The case of the T Tauri star Haro 6-10 offers an interesting example of these processes. Haro 6-10 drives a giant HH flow, HH 410, which stretches over 1.6 pc along a well defined flow axis (Devine

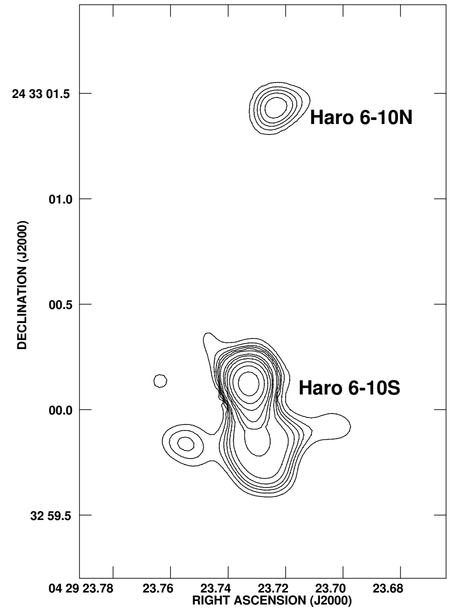

Fig. 7. A high resolution 3.6 cm radio continuum VLA map of Haro 6-10 shows that it is a compact triple system. The southern companion to Haro 6-10S drives a small bipolar radio jet along an east-west axis. ¿From Reipurth et al. (2004).

et al. 1999). Closer to the source there is a small group of HH objects, known as HH 184. The various knots are labeled in Fig. 6. The main flow axis of the giant HH flow is defined by a line through the star and knot E. But as we approach the star, the knots B, C, and A deviate increasingly from the principal flow axis, while to the south-east knots G and F appear to form a separate, independent flow. It is noteworthy that the ratio of the projected distances of knots A and B from the star is almost exactly the ratio of the distances to knots F and G. It thus appears that the events that formed knots A and B were contemporaneous with events forming F and G. This synchronism, as well as the gradual axis changes, are well understood in terms of the knots being formed at the periastron passages of a binary system. When the binary components and their disks get close enough to perturb each other significantly, simultaneous outbursts take place. The tidal forces may warp the disks, and thus create the observed gradual changes of the outflow axes.

The visible young star Haro 6-10 indeed has an embedded infrared companion about 1 arcsec to the north. Furthermore, new high-resolution VLA maps have revealed what appears to be an even closer third component 0.27 arcsec to the south (Reipurth et al. 2004). Fig. 7 shows that the third component drives a separate small radio jet. The giant HH 410 bow shocks are about 6000 yr old, and if the infrared companion to the north was ejected from the system at that time, it is drifting away with a projected velocity of 0.15 km s^{-1}, consistent with the theoretical calculations presented in Sect. 2.

Altogether, in this review, we have argued that seemingly disparate phenomena like the birth of binaries, Herbig-Haro jets, and the formation of brown dwarfs, are in fact all aspects of the same underlying phenomenon, namely the evolution and break-up of small multiple systems of newborn stars.

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REFERENCES

Allen, C., & Poveda, A. 1974, in The Stability of the Solar System and of Small Stellar Systems, ed. Y. Kozai (IAU Symp. No. 63) (Dordrecht: Reidel), 239
Armitage, P. J., Clarke, C. J., & Palla, F. 2003, MNRAS, 342, 1139
Artymowicz, P., & Lubow, S. H. 1996, ApJ, 467, L77
Bate, M. R. 2004, this volume
Bate, M. R., Bonnell, I. A., & Bromm, V., 2002a, MNRAS, 332, L65
Bate, M. R., Bonnell, I. A., & Bromm, V., 2002b, MNRAS, 336, 705
Bate, M. R., Bonnell, I. A., & Bromm, V., 2003, MNRAS, 339, 577
Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 1997, MNRAS, 285, 201
Bonnell, I. A., Clarke, C. J., Bate, M. R., & Pringle, J. E. 2001, MNRAS, 324, 573
Boss, A. P. 2001, ApJ, 551, L167
Briceno, C., Luhmann, K.L., Hartmann, L., Stauffer, J. R., & Kirkpatrick, J. D. 2002, ApJ, 580, 317
Clarke, C. J., & Pringle, J. E. 1991, MNRAS, 249, 588
Delgado-Donate, E. J., Clarke, C. J., & Bate, M. R., 2003, MNRAS, 342, 926
Delgado-Donate, E. J., Clarke, C. J., & Bate, M. R., 2004a, MNRAS, 347, 759
Delgado-Donate, E. J., Clarke, C. J., Bate, M. R. & Hodgkin, S. T., 2004b, MNRAS, submitted
Devine, D., Reipurth, B., Bally, J., & Balonek, T. J. 1999, AJ, 117, 2931
Durisen, R., Sterzik, M., & Pickett, B. 2001, A&A, 371, 952
Elmegreen, B. C. 1999, ApJ, 522, 915
Ghez, A. M., Neugebauer, G., & Matthews, K. 1993, AJ, 106, 2005
Gizis, J. E., Kirkpatrick, J. D., Burgasser, A., Reid, I. N., Monet, D. G., Liebert, J., & Wilson, J. C. 2001, ApJ, 551, L163
Goodwin, S., Whitworth, A., & Ward-Thompson, D. 2004, A&A, submitted
Hodgkin, S. T., Pinfield, D. J., Jameson, R. F., Steele, I. A., Cossburn, M. R., & Hambly, N. C. 1999, MNRAS, 310, 87
Jameson, R. F., Dobbie, P. D., Hodgkin, S. T., & Pinfield, D. J. 2003, MNRAS, 335, 853
Joergens, V., & Guenther, E. 2001, A&A, 379, L9
Klessen, R. 2001, ApJ, 556, 837
Klessen, R., Heitsch, F., & Mac Low, M. 2000, ApJ, 535, 887
Köhler, R., & Leinert, C. 1998, A&A, 331, 977
Kroupa, P., & Bouvier, J. 2003a, MNRAS, 346, 343
Kroupa, P., & Bouvier, J. 2003b, MNRAS, 346, 369
Larson, R. B. 2002, MNRAS, 332,155
Lin, D. N. C., Laughlin, G., Bodenheimer, P., & Rozyczka, M. 1998, Science, 281, 2025
Liu, M. C., Najita, J., & Tokunaga, A. T. 2003, ApJ, 585, 372
Lucas, P. W., Roche, P. F., Allard, F., & Hauschildt, P. H. 2001, MNRAS, 326, 695
Marcy, G. W., Cochran, W. D., & Mayor, M. 2000, in Protostars and Planets IV, eds. V. Mannings, A. P. Boss, & S. S. Russell, (Tucson: Univ. of Arizona Press), 1285
Martín, E. L., Brandner, W., & Basri, G. 1999, Science, 283, 1718
McDonald, J., & Clarke, C. J. 1993, MNRAS, 262, 800
McDonald, J., & Clarke, C. J. 1995, MNRAS, 275, 671
Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150
Muench, A. A, Alves, J. A., Lada, C. J., & Lada, E. A. 2001, ApJ, 558, L51
Papaloizou, J. C. B., & Terquem, C. 2001, MNRAS, 325, 221
Preibisch, T., Stanke, T., & Zinnecker, H. 2003, A&A, 409, 147
Reipurth, B. 2000, AJ, 120, 3177
Reipurth, B., & Zinnecker, H. 1993, A&A, 331, 977
Reipurth, B., & Clarke, C. J. 2001, AJ, 122, 432
Reipurth, B., & Bally, J. 2001, Ann. Rev. Astron. Astrophys. 39, 403
Reipurth, B., Rodríguez, L. F., Anglada, G., & Bally, J. 2004, AJ, in press
Sterzik, M., & Durisen, R. 1998, A&A 339, 95
Sterzik, M., & Durisen, R. 2003, A&A 400,1031
Tokovinin, A. A. 2004, this volume
van Albada, T. S. 1968, Bull. Astron. Inst. Netherlands, 19, 479

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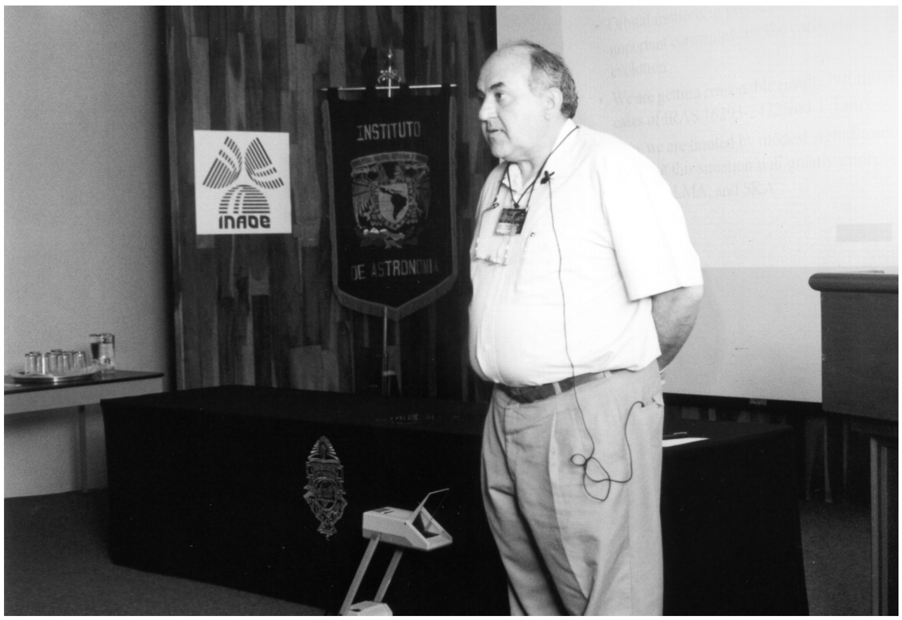
DISCUSSION

Tokovinin – It may well be true that in a typical triple the tertiary component is the least massive one (like in 4 out of 5 nearby triples). Such systems are missing from current catalogs, so observers need to make an effort to recover those triples.

Scarfe – Quite often, in the triple systems Frank Fekel and I have observed the distant companion is the most massive star. Regrettably, the number of systems for which we can say this with certainty is still small!



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Mauri Valtonen, Arcadio Poveda and Hans Zinnecker.