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Star–Disc Interactions and Binary Formation

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1. INTRODUCTION

By the time a binary arrives on the main sequence, its dynamics have essentially become those of a simple two–body system, so that its orbital parameters are constants of the motion thereafter. This statement of course needs to be modified under several circumstances, such as where tidal effects, mass exchange or interactions with field stars come into play. For the majority of binaries, however, orbital evolution is all but over by the main sequence. Therefore, in order to explain the distribution of binary orbital parameters one has to look to earlier times (prior to 10^7 years) when the more complicated dynamics can drive the orbital evolution that establishes these parameters.

The main ingredient in this extra complexity during the pre-main sequence stage is the presence of distributed gas in the system. This gas may be distributed around the entire binary and/or around the individual components; since this material is that from which the binary is formed, it is likely to contain a substantial fraction of the system mass at early times. Moreover, if this material contains a significant angular momentum, it cannot settle onto the stars on a dynamical timescale but is instead held up in a centrifugally supported disc, which can be accreted only on the (substantially longer) viscous timescale of the disc. There is abundant observational evidence for such discs around *single* pre-main sequence stars, and the theoretical expectation that most conceivable binary formation scenarios should result in residual gas being deposited in angular momentum supported discs (see contributions by Adams, Boss and Bonnell). It is therefore highly relevant to ask how the orbital evolution of a pre-main sequence binary is affected by the dynamical interactions between the binary and its associated disc(s). A second, and related, question is how the (observed or inferred) distributions of gas around young binaries might be used to place some constraints on the initial binary formation mechanism.

In the present contribution we keep an open mind about the mechanism for binary formation and report on an ongoing project which explores a number of issues relating to the dynamical interactions between discs and young binaries. In Section 2, we consider the role of star–disc interactions in the formation of binaries through capture: we discuss this mechanism in turn in the contexts of large N virialised clusters, in small N (non-hierarchical) clusters and in clusters which collapse from rest (this latter scenario being of possible relevance to the formation of globular clusters). In Section 3 we review some recent work on the dynamical evolution of binaries embedded in circumbinary discs and discuss the relation between the gas distributions around young binaries and their mode of formation. We summarise our findings in Section 4.

2. STAR–DISC CAPTURE

2.1. Large N virialised clusters

The formation of a binary from two initially unbound stars requires the dissipation of some fraction of the energy of their relative orbit. One way in which this might be achieved is if a star passes close to (or through) the disc around another star. Such a mechanism bears a certain resemblance to tidal capture (in that binary orbital energy is converted into heat in the disc/star and radiated); from a practical point of view, the main difference is that the relevant cross section of a disc is up to 10^4 times greater. Larson (1990) estimated that for the case of discs of radius 100 A.U., a large fraction of all stars might be incorporated into binaries through this mechanism during the pre-main sequence phase.

This analysis is probably over–optimistic, however: it requires an unusually high stellar density (10^4 stars per cubic parsec, which is attained only in the densest regions of the Trapezium cluster) and it requires also an optimistic prescription for the efficiency of star–disc energy transfer. Furthermore, it neglects the destruction of discs by encounters in which the velocities are too high for capture, whereas numerical simulations of star–disc encounters indicate a severe pruning and ejection of material from close to and beyond the distance of closest approach (Clarke & Pringle 1992). When this effect is included (by requiring that the *first* star that impacts a disc must be travelling slowly enough to be captured) the binary formation rates are dramatically reduced, leading Clarke & Pringle (1991a) to the conclusion that star–disc capture is *not* a major source of binaries in large N virialised clusters.

2.2. Small N clusters

We turn now to the case of binary formation in small N clusters. This is probably a more realistic initial condition than that discussed above, as the stellar distribution in star forming regions is far from uniform, being characterised by sub-clustering on a variety of scales. Moreover, the existence of hierarchical multiples on the main sequence implies that stars cannot only form as isolated single stars or binaries.

In the case of small N clusters, the formation of binaries is easier than the large N case for two reasons. Firstly, even in the absence of dissipation, binaries can be formed by purely dynamical processes: in this case, the energy lost from the relative orbit of the two stars is transferred as kinetic energy to a third star. Thus, in contrast to the case described above, the star–disc interaction does not have to provide the entire energy loss mechanism but can act in conjunction with the dynamical processes. Secondly, the internal velocity dispersion within small N clusters is reduced compared with the large N case (by definition, two body encounters can never be highly hyperbolic in a small N cluster) so that the destruction of discs by high speed impacts is reduced.

To date, the only calculation of small N cluster evolution with star–disc interactions is that of Clarke & Pringle (1991b). These simulations started from an unstable (equidistant) three–body configuration and allowed the stars to interact gravitationally, with dissipative drag terms introduced for encounters involving star–disc impacts. Two interesting features emerged from these calculations. Firstly, the chaotic nature of small N body dynamics ensures that binaries are formed with a wide range of parameters from a narrow range of initial conditions — evidently an attractive feature, given the large dynamic range of binary properties. Coupled with the orbital shrinkage brought about by interaction with residual gas, this permits the formation of binaries with separations considerably smaller than the radius of the initial mini-cluster. Secondly, the calculations pointed to a new way of forming hierarchical multiples from initally unstable (trapezium) systems. This involves a close encounter between two of the stars whilst the third star is near apocentre of an elongated orbit. If the close encounter is a dissipative one, the orbit of this pair is thereby shrunk, so that the ratio of periods of the outer to the inner binary then exceeds the threshold required for stability. This mechanism should be contrasted with the alternative way of converting a trapezium system into a hierarchical system, in which the orbit of the outer binary is expanded by gravitational encounter with another star in the cluster. This (non-dissipative) mechanism however involves the ejection of large numbers of single stars for every hierarchical system formed, and therefore is in conflict with the large binary fraction observed on the main sequence.

For the case of $N > 3$, and for a spectrum of masses, the calculations have not yet been performed with the inclusion of star–disc interactions. The subject has been fully explored for the case of gravitational encounters only (see Harrington 1974, 1975 ($N=4,5$), van Albada 1968a) and b) ($N=10,24$)) from which it has been concluded that such encounters yield at most one binary per cluster and that this binary usually consists of the two most massive stars in the cluster. If stars are picked at random from some mass function, assembled into N body clusters and then allowed to form binaries according to this prescription one may readily derive analytical expressions for the mass ratio distribution and binary fraction as a function of stellar mass (McDonald & Clarke 1992). Figure 1 demonstrates the results of such an exercise for $N=3$, using a mass function for low mass stars derived by Kroupa *et al.* (1991) (dotted curve). The full curve shows the predicted mass ratio distribution for binaries with a solar mass primary, normalised to the mass function at the high mass end, and this is compared with the observed mass ratio distribution for binaries with G/late F type primaries (Duquennoy & Mayor 1991), normalised in the same way. It is evident that for secondary masses in excess of around $0.5\ \mathcal{M}_\odot$, the predicted mass ratio distribution just follows the mass function. For lower masses, however, there is an increasing divergence between the mass ratio distribution and the mass function, with a decreasing fraction of the lower mass stars ending up as companions to the solar mass primary. This result is simply a consequence of the dynamical bias which selects the second most massive star in the cluster as the companion to the solar mass star: although the lower mass stars are present in the mass function in large numbers, they rarely fulfil this criterion and thus do not often end up as secondaries in such binaries.

It is clear from Figure 1 that the predicted mass ratio distribution is a reasonable fit to the Duquennoy & Mayor data, indicating that one cannot rule out the role of dynamical biasing in small N clusters on these grounds. Moreover, these results sound a warning note about the practice of assuming that the good correspondence between mass function and mass ratio distribution for high mass ratios can necessarily be extrapolated to the case of extreme mass ratios. It is this assumption that has stimulated the search for brown dwarfs as binary

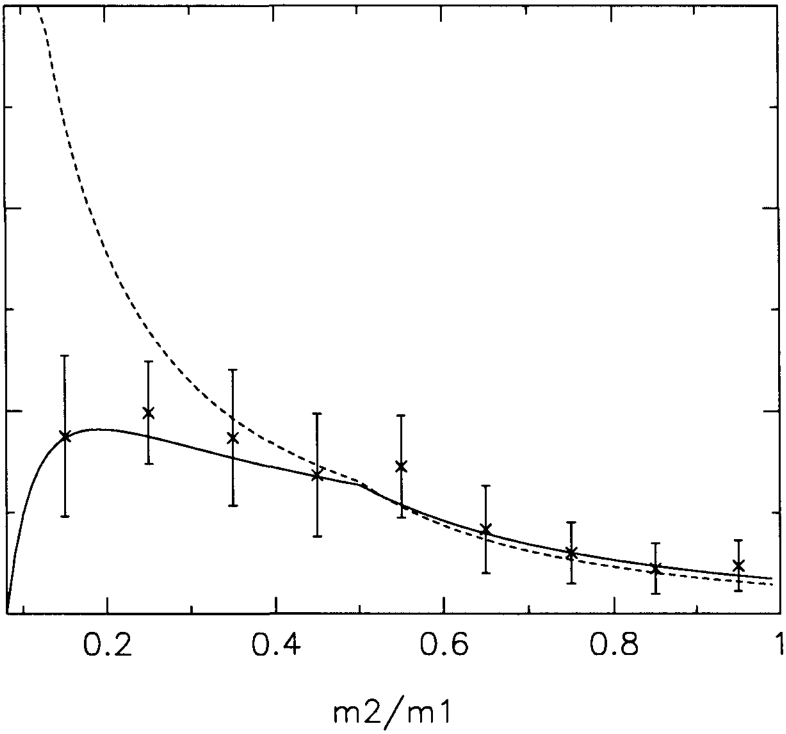

FIGURE 1. Mass ratio distribution for binaries with solar mass primaries: observed distribution of Duquennoy & Mayor (crosses) and predicted distribution for dynamical biasing model with N=3 (solid line). The dotted line is the mass function employed, that of Kroupa *et al.* .

companions to luminous dwarfs, so far, with little success (e.g., Marcy *et al.* 1988, Campbell *et al.* 1988). Although the steep turnover in the predicted mass ratio distribution in Figure 1 at just the hydrogen burning mass limit (0.08 solar masses) is probably fortuitous, these results indicate that one should exercise caution in interpreting a lack of brown dwarf companions: such a finding does *not* imply that brown dwarfs need be scarce (or non-existent) in the field.

A further consequence of this dynamical biasing is that the binary fraction should *decrease* with decreasing stellar mass. This results purely from the fact that for a lower mass star, there is a relatively low probability that such a star is the most massive star of its mini cluster, and therefore ends up as a primary of a binary. Defining the binary fraction (for each mass) as the ratio of the number of systems in which a star of this mass is the primary to this number plus the number of single stars of this mass, we obtain (for N=3 and the mass function described above) a binary fraction of 0.99, 0.83 and 0.47 for dwarfs of masses 1, 0.7 and 0.4 solar masses respectively. These figures decline with an increase in the mean mini-cluster size: for N=5 the corresponding figures are 0.94, 0.63 and 0.19.

2.3. Large N clusters collapsing from rest

The calculations described in Section 2.1 assume that stellar clusters form in approximate virial equilibrium. Whereas this assumption is apparently reasonable in observed star forming regions, where stars form from clumps whose motions are already approximately virialised, it may be argued that the extreme chemical homogeneity of globular clusters requires a much more rapid (dynamical) process of fragmentation and star formation (e.g., Murray & Lin 1989). If this is the case, then stars would have condensed out of the proto-globular cloud on almost radial orbits, and the entire cluster would then have to collapse on a dynamical timescale. A singularity is avoided due to the tangential velocity dispersion generated during the collapse, which eventually becomes sufficient to halt and reverse the collapse: the system 'bounces' and rebounds into a state of approximate virial equilibrium.

Evidently, such a picture of cluster formation has quite different consequences for the dynamics of pre-main sequence stars, and thus for the formation of binaries through star–disc captures. The main difference is that the stars form with a very low initial velocity dispersion; during the collapse, both the density and velocity dispersion rise and the rate of star–disc captures varies as a result of a trade–off between these two effects. Murray *et al.* (1992) computed the rate of star–disc captures during such a collapse, using a simple analytical model, derived by Aarseth *et al.* (1988), for the growth of velocity dispersion during the collapse of a uniform sphere. The binary formation rate rose gradually during the collapse, peaking at the bounce, but being rapidly quenched thereafter due to the destruction of discs in the high density, high velocity dispersion environment of the bounce phase. Such calculations yielded a fraction of hard binaries of a few per cent: it is hard, however, to compare this number in detail with the result of globular cluster binary searches, without a more detailed model of the subsequent orbital evolution, since this fixes the fraction of binaries in a particular period range. Subsequent calculations (Murray & Clarke 1992) have re-investigated the problem using a N-body code, which has the advantage of being able to study non-uniform initial conditions and also of being able to follow the collapse through the bounce phase. These calculations have confirmed the analytical estimates and shown them to be rather insensitive to the initial global density profile: any clumpiness in the initial distribution however drives up the rate of binary formation significantly.

3. STAR–DISC INTERACTIONS & BINARY EVOLUTION

We now turn from the question of the role played by discs in the initial formation of binaries, and address the more general question of how the existence of proto-stellar discs can drive the subsequent orbital evolution of young binaries. The answer to this question probably depends on whether the residual gas is predominantly distributed in discs around the individual stars (circumstellar) or around the entire binary (circumbinary). The former case has not been studied in detail, and we restrict the subsequent discussion to the interaction between binaries and circumbinary discs.

If a binary is formed with a disc around it, it sweeps a cavity in the disc on a dynamical timescale. Subsequently this disc is unable to accrete onto the central binary owing to the tidal barrier set up around the binary: the rim of this cavity is stabilised at the radius at which the torque received from the binary just balances the rate of viscous angular momentum transport in the disc. In practice, the rate of energy and angular momentum transport from binary to disc is such a steeply declining function of radius, that the radius of this rim is very insensitive to the magnitude of the viscosity, and is around twice the binary orbital separation. At this radius, the disc is orbiting more slowly than the binary and hence there is a transfer of energy and angular momentum from binary to disc. This immediately implies that the binary orbital axis is shrunk by the interaction, but the sign of the eccentricity change depends on the ratio in which energy and angular momentum are removed from the binary. Numerical (SPH) simulations of binary–circumbinary disc interactions have demonstrated that the major contribution to the energy and angular momentum transfer between binary and disc is through *resonances* excited at the disc's inner edge (Artymowicz *et al.* (1991). It turns out that the dominant contribution is from an outer Lindblad resonance, for which the angular momentum loss term dominates the energy loss term: consequently, the net effect is that the binary eccentricity *grows* as a result of interaction with its surrounding disc. The magnitude of this effect depends only on the surface density of the disc in the rim region: without a detailed model for the disc viscosity, however, it is not trivial to scale this quantity to the total disc mass. The process is however remarkably effective even in the case of rather modest disc masses: for example, in the case of a disc that contains one per cent of the binary mass within several binary radii, the predicted growth time for the eccentricity is only of order a thousand orbital periods — much less, that is, than the pre-main sequence lifetime of binaries closer than 100 A.U.

What are the potential observational consequences of these results? Firstly, the stability of the disc's inner rim implies that circumbinary discs are long–lived: being unable to accrete on to the central binary, they should persist throughout the pre-main sequence lifetime of the binary and their eventual dispersal must result from some additional energy input (e.g., from stellar winds). As a result, if binaries form accompanied by bound material of high specific angular momentum, this material must remain in circumbinary orbit: the detection (or otherwise) of circumbinary discs therefore places constraints on the initial formation mechanism of the binary, since different theroretical models (when sufficiently developped) will predict differing fractions of the binary mass deposited in circumbinary orbit. (It should be stressed, at this point, that it is only circumbinary material of sufficiently high specific angular momentum that can form a circumbinary disc: material raining in on more radial orbits can be accreted by the binary on a dynamical timescale). A second consequence of the stability of the inner rim of the circumbinary disc is that the binary within is starved of material accreting on to the stellar surfaces. If the binary forms with discs around the individual stars, then accretion will continue on to the stellar surfaces from these discs, but once they are exhausted (that is after a viscous timescale), the lack of replenishment from the circumbinary disc means that accretion ceases. It is tempting to speculate that the apparent paucity of spectroscopic binaries among Classical T Tauri Stars (Mathieu *et al.* 1989) might be attributed to this effect: in such close systems, the small discs around the individual stars are soon exhausted so that these objects are unlikely to display the spectral signatures of material at small radii.

If the resonant interaction between binary and disc is as efficient as suggested by Artymowicz *et al.* (1991), this has important consequences for binary formation. The relatively modest disc masses required imply that one might invoke this mechanism to explain the eccentricity distribution of all binaries, even if binaries were to have formed initially on low eccentricity orbits (like planets). The form of the eccentricity–period diagram (e.g., Duquennoy & Mayor 1991) however argues against this interpretation, since one would then expect the closer systems to be the most dynamically evolved and therefore to have higher mean eccentricities. A direct observational test would be provided by the discovery of an eccentric spectroscopic binary with a circumbinary disc, since it would then be possible to measure the precession of periastron predicted by the theory of binary–disc resonant coupling. It is frustrating, in this respect, that GW Ori, the only spectroscopic binary with evidence for a circumbinary disc is on an alomost circular orbit (see contribution by Mathieu).

4. SUMMARY

We have discussed a number of aspects of the dynamical interactions between young binaries and their associated discs. We conclude that star–disc capture is not a significant source of binaries in large N, virialised clusters but may play an important role in small N clusters or in clusters collapsing from rest. Models for the collapse and violent relaxation of globular clusters suggest that star–disc interactions alone may provide a primordial hard binary fraction of a few per cent. In the case of binary formation in small N clusters, we show that dynamical biasing (in which the two most massive stars in a cluster pair up) is consistent with observed mass ratio distributions, provided that N is small (3–5). We note that dynamical biasing predicts a decreasing binary fraction with decreasing stellar mass, and also predicts that very low mass objects should be under–represented in binaries compared with their presence in the field mass function. This latter point should be borne in mind when interpreting the results of spectroscopic searches for brown dwarf companions to luminous stars.

We also consider the dynamical interaction between binaries and gas in circumbinary orbit, reviewing the consequences of recent numerical work suggesting that such interactions should be highly efficient in generating binary eccentricity. We point out that the inability of such discs to accrete onto the central binary implies that they should be long lived, and their presence (or otherwise) thus provides important fossil evidence about the initial conditions of binary formation.

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6. DISCUSSION

ZINNECKER: Infrared images have not revealed many cases of triples with roughly equidistant component separations (these images can resolve typical linear separations $\geq$150 AU). Is this a problem for the predictions of your models of binary and multiple system formation? Have triples already become hierarchical by the time we see pre-main sequence stars in the IR?

CLARKE: At $\sim$100 AU, the dynamical timescale is only $\sim 10^3$ yr, so one would not expect to see dynamically unstable configurations on this spatial scale.

ABT: From what we know observationally, disks around B and A type stars, even field stars, come and go on time scales of decades. So if one is destroyed, other low–mass disks will form.

CLARKE: This star-disk capture scenario really needs the massive disks resulting from accretion. I doubt that the mass replenished from the star could ever be significant in capturing companions.

POVEDA: Have you determined the distribution of binary separations that come out as the result of the stellar intruder dissipating its energy while interacting with the disk?

CLARKE: We have only determined the initial separations at capture. In addition, there is the secular evolution of the binary due to interaction with residual gas over many orbits. Since the nature of this interaction is still under investigation, we are unable to present a final distribution of separations at present.

SIMON: Could you specify the parameters that enable the disk capture process to work as a binary formation process in small N systems? If I calculate the capture time for systems with $N = 100$ pc^{-3}, $V = 1$-2 km/s, and disk radius of $\sim$100 AU (which should be characteristic of one of the Taurus molecular cloud condensations), I get capture times of order 10^9 yr.

CLARKE: One can't use that kind of 'cross section' calculation for small N systems (say N $<$ 10) since they are dynamically unstable configurations, which decay over ~N dynamical times. The distances of closest approach during this process occupy a wide range (owing to the chaotic nature of the dynamics), but tend to be within an order of magnitude of the radius at which the mini-cluster's collapse is halted by rotation. This radius is determined by the initial size and rotation of the parent cloud core. Obviously, wherever the distance and closest approach is less than the disk radius, there is the possibility of star-disk capture.

CHEN: As far as the near-IR excess goes, remember what is removed is the gas. All we need is a small amount of dust around the star. Some residual material in a halo structure will be sufficient. My question is: you mentioned that in the capture scenario the disrupted disk material becomes unbound. Since the energy comes from the kinetic energy of the intruder, doesn't the result depend strongly on the initial impact velocity?

CLARKE: I agree with your comment. Although we find that much mass becomes unbound, there is always residual gas left around the individual components, and where the binary and disk planes are not aligned, the remnant structure is highly warped and flared; ideal for re-processing photons. Concerning your question; most encounters relevant to star forming regions are strongly gravitationally focused, so the trajectories are always close to parabolic and the magnitude of the impact velocity is approximately constant. The results are, of course, sensitive to the inclination of impact, as our simulations show, but we find that the efficiency of unbinding material is high for all inclinations.