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The theory of multiple star formation in the Gaia era

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Abstract. I review the current state of multiple star formation theory. I explain that whereas purely hydrodynamical models do an excellent job at reproducing observed multiple star statistics, it is found difficult to match such statistics using models that include realistic magnetic flux levels. This difficulty relates to the low level of fragmentation in such models. If one instead uses the observed level of initial fragmentation in star forming clouds as an initial condition, it is still possible to test models of further evolution (involving orbital reconfiguration within high level multiple systems and interaction between such groupings and any wider cluster environment) using *Gaia*. I highlight the case of wide binary stars where *Gaia* can play a key role in distinguishing rival formation theories via constraining eccentricity distributions. I however caution that proper motion data needs to carefully model the distortions introduced by unresolved inner binaries within wide pairings, whose presence is not only expected theoretically but well established observationally. This not only affects experiments that attempt to model the origin of wide binaries but also those constraining alternative gravity theories using wide binary kinematics.

Key words. Binaries: general – stars: formation astrometry

1. Introduction

Models of multiple star formation are traditionally divided into those involving the mutual capture of initially unbound stars and those that involve fragmentation of bound gas into multiple components. Capture scenarios divide into those where the excess kinetic energy of an initially unbound pair is transferred to a third star and those where it is dissipated either via tides in the stellar envelope (Fabian et al. 1975) or in extended star-disc interactions (Clarke &Pringle 1991a,b). Capture is generically easier within relatively small N systems where less energy needs to be removed in order to achieve a gravitationally bound outcome and where pure N-body interactions generate a significant binary fraction (van Albada et al. 1968; McDonald & Clarke 1993).

As far as fragmentation is concerned, models are distinguished according to the stage of collapse at which splitting occurs. In general, the relative amplitude of density perturbations relative to the background grows only algebraicially in time within a collapsing medium (Hunter 1962). Therefore, fragmentation requires either large amplitude initial perturbations or else the slow-down of collapse, usually associated with the growing importance of centrifugal effects. These two possibilities are currently often designated 'turbulent fragmentation' (Offner et al. 2010) or 'disc fragmentation' although it is worth stressing that these labels are only indicative and there is a continuum of outcomes as a function of initial amplitude and importance of rotational support.

Finally, 'fission' models involve the formation of a single star which spins up due to the accretion of high angular momentum material and breaks into two entities. Although this possibility was once a popular candidate for forming the closest spectroscopic binaries, hydrodynamical simulations instead find that, for compressible gas, angular momentum is efficiently removed via spiral features and fission does not occur (Tohline 2002).

Further complications arise in mapping observed binaries on to formation modes when it is borne in mind that the mass ratios and orbital elements of proto-binaries evolve as a result of accretion of gas, star-disc dynamical interaction, interactions within triple (or higher order multiple) systems and, for the closest binaries, tidal interaction. The complexity interplay between these processes mean that since the 1980s the study of binary formation has been largely a numerical one. Following pioneering calculations of the fragmentation of isolated clouds cores (Larson 1978; Boss & Bodenheimer 1979; Boss 1991; Chapman et al. 1992), since the early 2000s it has become possible to simulate multiple star formation in the context of star-cluster formation. The most basic class of such simulations (which include only thermal pressure, gravity and an initially 'turbulent' supersonic velocity field; Larson 1981) have been exhaustively compared with observed binary statistics and, in broad terms, do an excellent job at reproducing observed systems (Bate,Bonnell & Bromm 2002a; Bate, Bonnell & Bromm 2002; Bate 2009a, 2012). Such calculations are generically associated with the creation of small N clusters and imply an important role for few-body interactions, as well as gas dynamical processes, in binary star formation (Delgado et al. 2003, 2004; Goodwin et al. 2004a,b). Models predict a binary fraction that increases with primary mass (consistent with the enhanced ability of a massive star to hold on to its companions in a multi-star environment), a tendency for low mass stars to be associated with more compact binaries (again for survival reasons) and a high fraction of higher order multiple systems. In such calculations the planes of circumstellar discs (or of binaries within multiple systems) become increasingly misaligned with each other, and with the (outer) binary plane in the case of wider systems. These predictions match well with observed binary statistics (see e.g. Bate 2009a).

It is evident, however, that these simplest calculations omit important physics. Firstly it is necessary to include radiative feedback from star formation on the thermodynamics of surrounding gas (Bate 2009b, 2012; Offner et al. 2009, 2010; Krumholz et al. 2012). Lomax et al. (2015) demonstrated that the inclusion of this effect does not affect the properties of the binary population produced but does reduce the over-all incidence of binaries to a value well below that observed. This is a consequence of fragmentation being suppressed in the warmer conditions that prevail when feedback is included. On the other hand, they showed that if the energy associated with stellar assembly is released intermittently (as required in order to match the observed protostellar luminosity function; Stamatellos et al. 2011), the binary fraction is restored to an observationally acceptable level.

The presence of magnetic fields in star forming gas presents a much less tractable problem for binary star formation. Magnetic field strength in star forming gas, measured via Zeeman polarimetry, is generally expressed in terms of μ, the mass to flux ratio normalised to the minimum ratio required for gravitational collapse (Mouschovias & Spitzer 1976). Such data demonstrates that the majority of dense star forming gas is *super-critical*, i.e. capable of collapse without requiring magnetic field decoupling from the gas by non-ideal MHD effects such as ambipolar diffusion (Crutcher 2012). Nevertheless, μ is not in general very large (mainly in the range $1 - 20$) which implies that the magnetic field, while not preventing collapse, is nevertheless of some dynamical importance.

The last decade has seen a number of collapse calculations using observationally motivated μ values in this range and all these find that a strong magnetic field (lower end of the observed range of μ) is problematical for multiple star formation (Kudoh & Basu 2008; Hennebelle & Teyssier 2008; Hennebelle et al. 2011; Commercon et al. 2011; Boss & Keiser 2014; Lewis & Bate 2017). Indeed, Hennebelle & Teyssier (2008) pointed to a 'fragmentation crisis': magnetic braking acts so as to suppress disc formation and hence the formation channel for multiple star formation associated with the slowing of collapse by centrifugal support. Magneto-hydrodynamical simulations of cluster formation also point to a suppression of fragmentation by strong fields, which instead favour the formation of a single massive star fed by magnetically dominated filaments (Myers et al. 2013). Extensive simulations suggest that binary fragmentation is somewhat assisted by the inclusion of non-ideal MHD effects (Wurster et al. 2017) and by rapid core rotation (Wurster & Bate 2019); the overwhelmingly dominant effect determining whether binaries are formed is however the magnitude of the magnetic field. While recent calculations succeed in forming binaries in moderately magnetised cores (μ of $10-20$ or above), it is nevertheless hard to square the common incidence of binaries with the distribution of observed distribution of μ values.

In addition to this fundamental difficulty, the computational expense of magneto-hydrodynamical calculations, combined with the low probability of a binary outcome, means that it is currently impossible to compare the observed properties of binary stars with the results of MHD calculations. This difficulty has paused progress in the direct comparison of simulation data with observations. In the rest of this contribution I therefore bypass questions of initial fragmentation and use as a starting point the observed fragmented state of the youngest star forming regions and ask how recent observational datasets can clarify their subsequent evolution.

2. The evidence for dynamical decay of small N groups

Binary formation simulations that succeed in reproducing observed binary statistics (i.e. the pure hydrodynamical models discussed in the previous section) involve an evolutionary sequence wherein the fundamental unit of star formation is the small N grouping (Larson 1995). Such groupings may spawn a mixture of sub-systems which may or may not be initially hierarchically organised. Subsequently system architecture evolves due to a mixture of few-body dynamics, accretion and gas mediated orbital evolution. In this section we enquire whether there is observational evidence for this scenario. This examination of the structure and kinematics of young stellar systems is obviously a topic in which *Gaia* will have the capability to play a leading role.

Circumstantial evidence in favour of an origin within such groupings is obtained from the high fraction of (stable, hierarchical) higher order multiple systems in main sequence stellar populations. The most complete census of higher order multiplicity is that of Tokovinin (2014) where within a volume limited sample of 4847 F-G type stars, the fraction of systems with $N > 2$ components is 13% compared with 33% in pure $N = 2$ binaries. This implies that $\sim$ 28% of all binaries contain additional components. (Note that this latter fraction is much higher (of order 50 %) if only wide (common proper motion) binaries are considered: see Riddle et al. 2015; Halbwachs et al. 2017).

It is very unlikely that the present census of higher order multiples represents that of systems at birth. The reason for this is that the distribution of periods of inner and outer pairs within multiple star systems fills the available parameter space that is bounded (in the limit of low period ratio) by considerations of dynamical stability (Tokovinin 2014). The existence of multiples whose period ratio lies just on the 'stable' side of this limit suggests that there are likely to have been many more which were formed or evolved beyond this limit and which underwent orbital reconfiguration into a mixture of binaries and singles. Main sequence multiplicity statistics do not however on their own allow one to constrain the fraction of systems which underwent this dynamical history.

More direct evidence is however provided by looking at the reconfiguration of multiple systems throughout the pre-main sequence stage. Connelley et al. (2008) demonstrated an anti-correlation between the infrared spectral indices of young stars (an indicator of age) with binary fraction on scales of 1000 au and Chen et al. (2013) further noted a strong decline in both the multiplicity fraction (i.e. fraction of non-single systems in a sample) and the companion star fraction (average number of stars per system) between the earliest (Class 0) and subsequent (Class I) protostellar phase. Concerns about inhomogeneous resolution across this sample have been subsequently allayed by the larger VLA survey of Tobin et al. (2016) which achieved a uniform resolution of 15 au across the sample. The decline in companion star fraction is particularly marked - in the sample of Tobin et al. (2016), 10/30 of Class 0 systems were higher order multiples while the same figure for the Class I systems was 0/26.

If this decline in companion star fraction is a result of orbital configuration in unstable multiples (and it is hard to posit an alternative explanation given the small probability of stellar mergers) then the stars released from the small N grouping should, in some cases, still be in the vicinity (Reipurth & Clarke 2001). There seems to be some evidence to support this. Connelley et al. 2008 noted that all protobinaries in their sample with separations < 200 au were accompanied by neighbours within $\sim$ 25000 au, this distance being of the order of the expected distance traveled by a star ejected from a $\sim$ 100 au scale multiple system. Joncour et al. (2017) have subsequently found evidence for a similar effect in somewhat older (Class II and Class III) T Tauri stars in Taurus auriga, where binary stars have an excess fraction of nearest neighbours on scales < 10000 au compared with single stars. This finding admits several interpretations, among which is the hypothesis that these neighbours are members of the original grouping that have become unbound, or very weakly bound, as a result of dynamical interactions. Note that typical errors on proper motions in Taurus from *Gaia* DR2 are $\sim$ 0.1 mas yr^{-1} which equates with a typical relative velocity error of around 0.2 km s^{-1} (Lindegren et al. 2018); at face value, this accuracy is marginally sufficient to establish whether pairs on a 10^4 au scale are bound or unbound. However, there is an important caveat with regard to proper motion data in a situation where there is a high fraction of multiple star systems which are unresolved by *Gaia* but whose period is considerably longer than the duration of the proper motion experiment. In the case of unresolved unequal mass binaries, the non-linear relationship between stellar mass and luminosity results in an effective velocity of the binary photocentre with respect to its centre of mass (see Sect. 4) and this can introduce an error in the relative proper motion (with respect to a distant neighbour) which exceeds the formal astrometric error.

The system where there is the best evidence for a multiple star system disintegrating into widely separated components is the HV Tau and DO Tau system, whose separation on the sky is $\sim$ 10^4 au and where the relative sky motion from *Gaia* DR2 (formally 0.82 ± 0.24 km s^{-1}) implies it is somewhat unbound. Crucially, in this system the large scale distribution of thermal dust emission imaged by Herschel implies that the HV/DO system is enclosed in a large scale envelope with a morphology strongly suggesting a tidal interaction between these components (Howard et al. 2015). Currently discs are observed in both HV Tau and DO Tau (of radii respectively 75 and 50 au; Kwon et al. 2015; Stapelfeldt et al. 2003), and there is evidence (from the wavelength independence of the disc size) that the former disc has a sharp edge (Monin & Bouvier 2000). HV Tau is itself a triple system with inner and outer components of separation 10 and 550 au (Simon et al. 1996; Duchene et al. 2010) . Winter et al. (2018) have shown via a suite of hydrodynamical models of interacting three star systems (HV Tau AB, HV Tau C and DO Tau) that the current system kinematics, disc properties and morphology of extended Herschel emission can be simultaneously matched in a scenario where HV Tau and DO Tau formed together as a bound system on a scale of $\sim$ 5000 au and, around 0.1 Myr ago, underwent a close interaction (on scale $\sim$ 300 au) involving a nearly perpendicular collision between their respective discs. The hardening of the HV AB - HV C system in the encounter injected relative energy into the orbit of DO Tau, ejecting it into its current weakly bound/unbound orbit. The wealth of dynamical and morphological constraints is quite constraining of the system's orbital history. Note however that, as mentioned above, the *Gaia* DR2 relative proper motion of the HV and DO components is relatively poorly constrained owing to the close binary components in HV Tau.

3. Ultra-wide binaries

Very long period binaries receive special attention for a variety of reasons although their designation is not generally consistently applied across different surveys. Pairs with separation of order the Jacobi radius ($\sim 3 \times 10^5$ au for a solar mass system) are subject to perturbations associated with stellar encounters and the Galactic tide (Jiang & Tremaine 2010). Closer pairs (with separations of order $5 - 10 \times 10^3$ au) are instead of interest because, while being largely immune from environmental effects, they are already in a regime of relatively low gravitational acceleration, comparable to that experienced in the outer regions of spiral galaxies where modified gravity (MOND) theories have been invoked to explain flat rotation curves without recourse to dark matter (see e.g. Scarpa et al. 2017; Pittordis & Sutherland 2018, 2019) for studies exploring the constraints that wide binaries can place on MOND type theories). On the other hand, there is substantial interest in understanding the formation scenario for the widest pairs since they appear to flout the fundamental conservation of angular momentum for star forming gas. If the ratio of rotational energy to gravitational energy is β in an initial star forming core, radius a_{core}, then angular momentum conservation implies that the semi-latus rectum of a roughly equal mass binary is $\sim \beta a_{core}$. If the bulk of angular momentum of the system is instead contained in an object, eccentricity e, containing a fraction f of the total core mass, and if, as is statistically likely, this binary is observed close to apocentre then angular momentum conservation implies that the separation of this pair is $\sim \beta/((1-e)f^2)a_{core}$. Now β is observed to be in the range $0.01 - 0.1$ and $a_{core} \sim 10^4$ au (Goodman et al. 1993). This implies that a very wide binary (with, say, separation 10^5 au $\sim 10 \times a_{core}$) is only consistent with angular momentum conservation if $f \ll 1$ (i.e. the distant companion is a small fraction of the system mass) and/or the orbit is highly eccentric.

This limitation on system parameters applies to situations where the wide binary originates from within a single star forming core and thus to the class of models discussed in the previous section involving orbital reconfiguration of small N groupings. Observationally, however, the mass ratio distribution of wide binaries is found to be approximately flat (Tokovinin & Lepine 2012), which is hard to square with a mechanism that strongly favours low mass outliers. Moreover, it would be a *requirement* of such models that one or more of the wide components are themselves binary systems. As already noted, higher order multiplicity is commonly observed within wide binaries (Riddle et al. 2015; Halbwachs et al. 2017) but this is not universal (see Law et al. (2011) for a demonstration that in the case of wide pairs with an M dwarf primary, the binary fraction of the individual components is the same as it would be for M stars in general and therefore falls short of 100%). It would seem therefore that at least some wide binaries are formed from a mechanism which is not limited by the angular momentum reservoir within a single star forming core.

An attractive additional formation channel for wide binaries is a capture variant which works only in the context of dissolving stellar clusters (we emphasise here that the clusters considered are roughly of order open cluster scale or above and should not be confused with the small N groupings discussed in Sect. 2). Kouwenhoven, M. et al. (2010) and Moeckel & Clarke (2011) performed N-body simulations of populous clusters that undergo stellar dynamical core collapse which is halted by the formation of a small number of three-body capture binaries in the cluster core. From this point onwards, the energy extracted from the (close) binary population in the cluster core drives the expansion of the cluster on its half-mass radius two-body relaxation timescale.

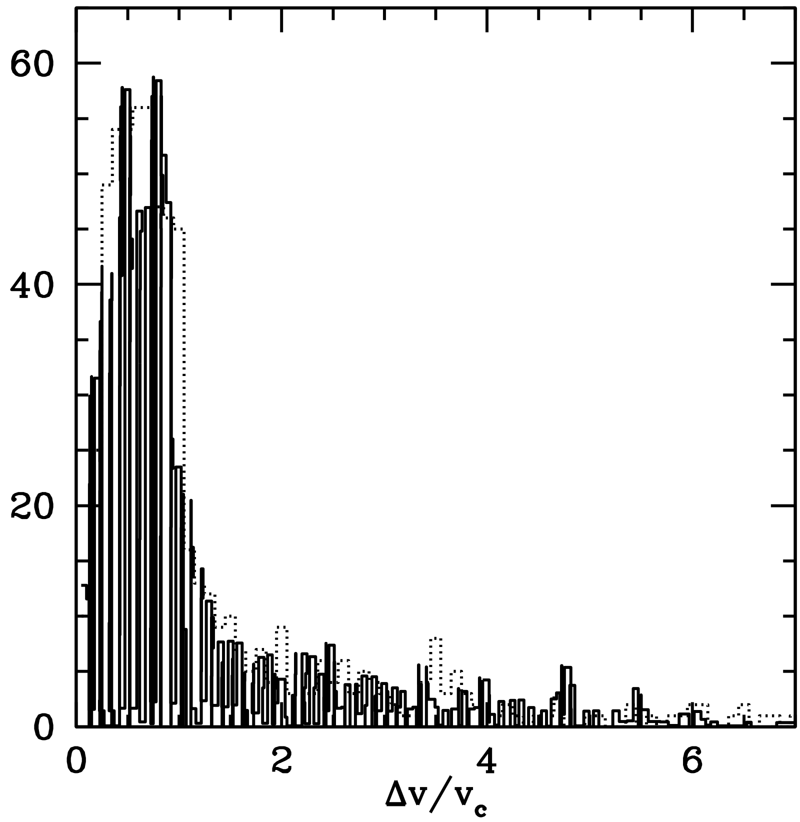

Fig. 1. The distribution of normalised sky velocities (see text) for pairs in the separation range $5,000 - 7000$ A.U. in the *Gaia* DR2 derived sample of Pittordis & Sutherland (2019). This distribution shows a pronounced "shelf" for normalised velocities $> \sqrt{2}$ in contrast to the cut-off predicted by Newtonian gravity in the case of pure binaries. The dashed line shows simulated data for randomly viewed pairs in the same separation range in which 50 % have an inner companion in the range $3 - 100$ A.U., demonstrating the creation of a similar "shelf" at high normalised velocities.

In a cluster that does not expand, its members continually enter weakly bound pairings with their neighbours which are then broken up by interactions with other stars in the vicinity (Heggie 1975). In an expanding cluster, however, where the stellar density is secularly decreasing, there is the possibility that the destruction timescale for a temporary pair forming in the outer part of the cluster becomes longer than the timescale for cluster expansion. In this case, such a pair remains marooned in a permanent liaison with a randomly associated partner. Moeckel & Clarke (2011) designated such objects as 'permanent soft binaries' and demonstrated that the expected number of such objects per cluster is of order one per decade of separation, irrespective of the membership number of the cluster. If one were to turn this round and ascribe *all* wide binaries to this mechanism then, given a notional binary frequency in the decade of separation around 10^4 au of around a few per cent, this would imply a 'typical' cluster membership of order ~ 100.

Since wide binary formation during cluster dissolution is a capture process, it is unsurprising that simulations find that pairs are assembled randomly from the local mass function and therefore the multiplicity of each component reflects the multiplicity of the field; moreover the captured components inherit the thermal equilibrium eccentricity distribution ($f(e) \propto e$; Heggie 1975) from the cluster environment (Kouwenhoven, M. et al. 2010). Thus, in contrast to the alternative formation channel (by orbital reconfiguration within a star forming core), there is no strong preference towards low mass ratio or highly eccentric systems.

Nevertheless, random association from the IMF is at odds with the observed flat mass ratio distribution of wide binaries (Tokovinin & Lepine 2012). However it is here necessary to also fold in the effect of diffusion of binary orbital elements in response to stochastic perturbations by distant encounters in the Galactic field. This effect acts to preferentially to 'lift' or disrupt the orbits of binaries with low mass companions and thus tends to flatten the mass ratio distribution produced by random association, in line with observations (Goodwin & Clarke, in prep.).

Finally it is worth stressing that *Gaia* proper motion data will be able to determine the eccentricity distribution of wide binaries and thus has the capacity to distinguish the two formation channels described here. However, as explained in the following Section, it is necessary that this exercise takes careful account of the distortions introduced by unresolved close binary components within wide pairs.

4. Wide binaries - MOND or multiples?

As noted above, solar type binaries with separations exceeding around 5 000 au are good testbeds for the assessment of alternative gravity theories. Pittordis & Sutherland (2019) collated proper motion data on 24 282 wide pairs and constructed a histogram of the relative proper motion normalised to that of a circular binary of the same apparent separation if it were orbiting in the sky plane. Clearly, if the dynamics were governed by Newtonian gravity, this ratio should always be less than $\sqrt{2}$, this limit corresponding to the case of a face-on marginally bound orbit at pericentre. While the majority of pairs occupy the expected distribution with $g < \sqrt{2}$, there is a pronounced 'shelf' of systems extending up to ratios of ~ 6 (at which point objects are discarded as not having common proper motions). Pittordis & Sutherland use this discrepancy from Newtonian predictions to explore alternative gravity theories.

There is, however, a complication in the assessment of proper motion data, namely that the apparent proper motion of the wide pair is distorted if one of the components is in fact an unresolved multiple. (In the case of this *Gaia* dataset, inner pairs with separations less than 100 au would be unresolved). For unequal mass ratio binaries where the mass luminosity relation is non-linear, there is a well known motion of the centre of light with respect to the binary centre of mass. While this can be detected as a periodic signal in proper motion data for binaries whose period is short compared with the duration of astrometric monitoring, there is an intermediate range of separations (from a few to $\sim$ 100 au) where an inner binary would introduce an extra apparent sky motion in addition to that deriving from the relative motions of the centres of mass of the two wide components.

I have modeled this effect by randomly viewing an eccentric population of wide binaries (projected separation around 5000 au) in which, in a fraction f_{triple} of cases, I assign an inner binary (uniformly distributed in log separation over the range 5 to 100 au and randomly picked from the IMF) to one of the members of the wide pair. I adopt the relationship between G magnitude and stellar mass given in Pittordis & Sutherland (2019) and adopt $f_{triple} = 50\%$, motivated by the findings of Riddle et al. (2015) and Halbwachs et al. (2017) with regard to the frequency of inner pairs in wide binary systems.

The results of this exercise are depicted in the Fig. 1. It should be emphasised that this is not a 'best fit' to the data but illustrates that these simple observationally motivated assumptions about the underlying frequency of close multiple components generate a distribution that well reproduces the 'shelf' seen in the *Gaia* data.

This result implies that the ability of wide binaries to provide a testbed for MOND theories is limited by our capacity to correct for close binary components. The same consideration applies when using proper motion data to assess the origin of wide binaries by deriving their eccentricity distribution (see Sect. 3). Conversely, if Newtonian gravity is accepted, *Gaia* derived kinematic data, as shown in the Fig. 1, has the capacity to constrain the incidence of higher order multiples in wide pairs.

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