Formation of wide binary stars from adjacent cores

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ABSTRACT

Wide gravitationally bound pairs of stars can be formed from adjacent prestellar cores that happen to move slowly enough relative to each other. These binaries are remnants of the primordial clustering. It is shown that the expected fraction of wide bound pairs in low-density star formation regions can be larger than the fraction of wide pairs in the field. On the other hand, wide binaries do not form or survive in dense clusters. Recent works on the separation distribution of young binaries, summarized here, confirm these expectations. Alternative formation mechanisms of wide binaries such as cluster dissolution or unfolding of triple stars cannot explain the large observed fraction of young wide pairs and therefore are not dominant. The fact that more than a half of wide pairs contain subsystems matches the general multiplicity statistics and does not imply that hierarchical multiplicity and wide binaries are genetically related.

**Key words:** binaries: general; methods: statistical

1 INTRODUCTION

Stars form by fragmentation and collapse of molecular clouds. Dense cores of molecular gas are believed to be the intermediate stage in this process, with each core forming one or several stars and the core mass function being similar to the stellar initial mass function (Alves et al. 2007). Multiple stars form by fragmentation of cores and help to get rid of excessive angular momentum by storing it in the orbital motion (Reipurth et al. 2014).

The typical separation of binaries formed by a fragmenting core is related to its size (on the order of 10^4 AU) and rotation and is somewhere between 10 and 1000 AU (Sterzik et al. 2003), matching the simulations by Lomax et al. (2015). The smallest separation on the order of 10 AU is set by the so-called opacity limit to fragmentation (e.g. Goodwin et al. 2007, Sect. 4.1). Newly formed binaries continue to accrete gas and at the same time migrate, evolving into tighter pairs or even merging (Figure 1).

Stellar pairs with the semimajor axis a of 10^4 AU or wider are known to exist in the field (Makarov et al. 2008). As the typical size of the cores is similar, on the order of the Jeans length, such wide binaries cannot be formed by fragmentation of a single core. Special wide-binary formation mechanisms have been proposed, such as cluster dissolution (Kouwenhoven et al. 2010; Moeckel & Bate 2010) or "unfolding" of more compact dynamically unstable triple systems (Reipurth & Mikkola 2012).

I explore the hypothesis that the components of wide binaries originate from different cores. Owing to the natural clustering of the newly born stars, wide pairs of such stars are very frequent. Some of them happen to be bound accidentally. The estimated fraction of the wide bound pairs is larger than the fraction of wide

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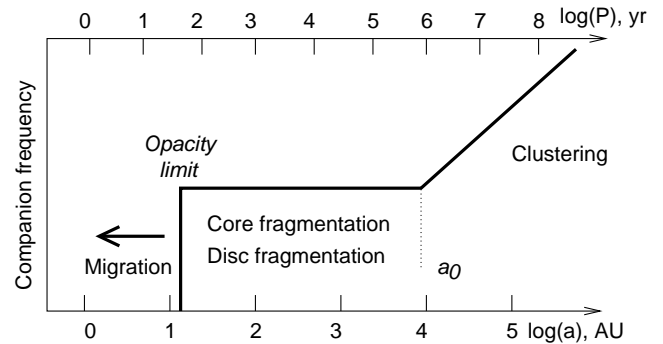
Figure 1. Characteristic scales of binary formation. The thick line shows schematically the number of stellar pairs vs. separation (on the lower axis) or period (on the upper axis). Fragmentation creates pairs with separations from 10 to 10^4 AU, and some of those migrate to smaller separations. At the spatial scales larger than 10^4 AU, the original fractal clustering of stars persists for a long time. The majority of very wide pairs in the clustering regime are not bound, but some are.

pairs in the field and even in the young stellar groups. Recently Joncour et al. (2017) discovered pairs of young stars in Taurus with separations up to 60 kAU and argued that they are remnants of the original clustering.

The idea of wide binaries forming from two independent condensations has a long history. It was invoked by Abt & Levy (1976) to explain the different mass ratio distributions in wide and close solar-type binaries. These distributions were revised by Duquennoy & Mayor (1991), who nevertheless also found statistical differences between wide and close pairs and discussed "independent condensation" of wide binaries. More recent studies have

shown that the mass ratio of solar-type binaries depends on the period weakly, if at all (Raghavan et al. 2010; Tokovinin 2014).

Duchêne & Kraus (2013) discuss "extremely wide systems" in Section 5.5 of their review, defining them as binaries with separation 10 times wider than the (uncertain) empirical mass-dependent upper separation limit (about 10^4 AU for one solar mass). Another way to define wide binaries is by comparing the accretion time with the orbital period. If a protostar of one solar mass is assembled in 10^5 years, the orbital period of a binary with $a > 3$ kAU exceeds the star formation time.

Wide binaries move so slowly that it is extremely difficult or impossible to test observationally whether they are gravitationally bound or just have common spatial motion and distance (Proxima Cen is a good example, Kervella et al. 2017). Frequent occurrence of subsystems further complicates such tests. The term "wide pair" refers here to a pair of related, but not necessarily bound stars, reflecting this observational uncertainty. In contrast, "wide binary" means a bound system.

In Section 2, we show that the clustering and kinematics of young stars allows formation of a substantial number of wide bound binaries. Many of them contain closer subsystems because in a wide orbit there is a sufficient range of allowable stable periods around each component. The observed separation distribution and fractions of wide pairs are reviewed in Section 3; there are many such pairs in sparse environments, while in dense clusters there are few. Section 4 discusses alternative mechanisms of forming wide binaries that has been proposed in the literature. Section 5 is the summary.

2 WIDE BINARIES AND CLUSTERING

2.1 The broken power law

Larson (1995) discussed the distribution of separations between stars in the Taurus-Auriga star-forming region (SFR) by combining the study of the large-scale clustering by Gomez et al. (1993) with the statistics of close binary companions. He found a break in the power law that approximates the density of companions vs. angular separation θ. At projected separations larger than 8250 AU, the density of companions per square degree follows the power law $\Sigma_c = 3.4\theta^{-0.62}$. This corresponds to the logarithmic separation distribution $f(\log s) \propto s^{1.38}$. Larson relates this to the fractal structure of the stellar clustering with a fractal dimension $D \approx 1.4$, inherited from the fractal structure of molecular clouds. On the other hand, at separations between 10 and 8250 AU the surface density of companions in Taurus-Auriga is $\Sigma_c = 0.0064\theta^{-2.15}$, or $f(\log s) \propto s^{-0.15}$. The distribution of $\log s$ is almost flat and matches the Öpik's law for binaries. This range of (small) separations corresponds to binary stars. The total number of *binary* companions is about one per star.

Simon (1997) repeated the Larson's study and extended it to the Ophiuchus and Orion Nebular Cluster (ONC) SFRs. In all SFRs the companion statistics is well represented by the broken power law. The break point in the ONC is found at smaller separation around 400 AU. Simon argues that the transition between the clustering and binary regimes occurs at separation on the order of average projected distance between the stars, i.e. at the confusion limit. Bate et al. (1998) confirm this by simulations and note that the power law at large scales can have multiple origins and does not necessarily mean fractal clustering. For a sparse SFR like Taurus-Auriga, they find that the break in the power law indeed cor-
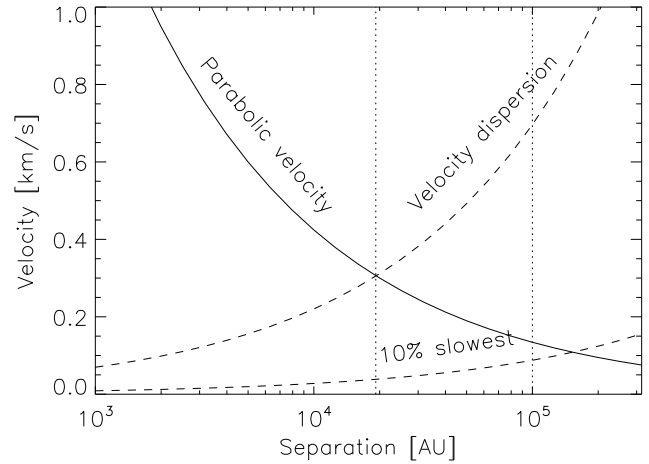
Figure 2. Dependence of the parabolic velocity for a solar-mass binary on its separation and the velocity dispersion in the molecular clouds. The lower curve shows the velocity of the 10% slowest stars, assuming normal distribution. At separation of 10^5 AU (0.5 pc), the dispersion is 5 times larger than the parabolic velocity, but about 15% of star pairs still can be bound if the relative velocity of the cores is normally distributed.

responds to the average spatial separation between the stars which is on the order of the Jeans length.

However, the transition between the clustering and binary regimes is smooth, stars formed in adjacent cores can "fall" to a common centre, interact dynamically, and produce a bound binary if their relative velocity is small enough. We estimate below the fraction of potentially bound wide pairs. Kraus & Hillenbrand (2008) suggested that the binary and clustering regimes are separated by a small region with a constant density of companions where the primordial clustering has been destroyed by motions of the stars. Joncour et al. (2017) explored statistics of wide pairs in Taurus by several alternative methods and found a population of wide pairs with an approximately log-flat separation distribution extending to 60 kAU, with preferentially coeval components.

2.2 Kinematics of cores and binaries

Stars form in groups. The spatial locations of the newly formed stars and their velocities are inherited from the parent molecular cloud. Recent studies have shown that the gas is organized in filamentary structures. The diameters of the filaments are on the order of 0.1 pc, with a remarkably small dispersion around this typical value (André et al. 2014). Prestellar cores form along the filaments in chain-like linear configurations, with typical separations on the order of the filament diameter. Linear configurations correspond to the fractal dimension $D \sim 1$. The number of stars within a distance R grows approximately as R^D. Larson (1995) found $D \approx 1.4$ for the Taurus-Auriga SFR, later Kraus & Hillenbrand (2008) revised it to $D \approx 1$.

Gas motions in molecular clouds are described by the Larson's law, where the typical rms velocity difference between two fragments σ_V is roughly proportional to the square root of their separation s, $\sigma_V(s) \approx (s/1\text{pc})^{1/2}$ [km s^{-1}] (Heyer et al. 2009). On the other hand, the orbital velocity of a binary decreases with its semimajor axis a as $V_{\text{orb}} = 30a^{-1/2}M^{1/2}$ [km s^{-1}], M being the mass sum in solar units and a — semimajor axis in AU. This formula describes the differential velocity in a circular orbit, while the

Table 1. Distribution of projected separations

$\log s$ (AU)	Perseus[a]	Taurus[b]	BPMG[c]	Simulations [d]
$(-0.5, 0)$	. . .	. . .	5	7
$(0, 0.5)$	. . .	. . .	4	23
$(0.5, 1)$	. . .	18	5	35
$(1, 1.5)$	3	17	6	44
$(1.5, 2)$	8	24	5	22
$(2, 2.5)$	5	12	3	24
$(2.5, 3)$	5	18	4	11
$(3, 3.5)$	9	10	7	2
$(3.5, 4)$	13	13	0	5
$(4, 4.5)$	. . .	23	4	2
$(4.5, 5)$	. . .	93	3	0
$N_{\rm tot}$	52	118	49	426

References: [a] Tobin et al. (2016); [b] Joncour et al. (2017); [c] Elliott & Bayo (2016); [d] Bate (2014).

75% of wide pairs are hierarchical multiples. This corresponds to 10.5 hierarchies among the 14 wide pairs in the BPMG.

The field multiplicity model (Tokovinin 2014) does predict a mild correlation between the wide (outer) and close (inner) subsystems by postulating that the field is a mixture of binary-rich and binary-poor populations. Wide binaries come from the low-density SFRs that also have an increased binary fraction, hence a larger fraction of subsystems. Moreover, both Law et al. (2010) and Joncour et al. (2017) note that wide pairs containing subsystems have larger masses and larger binding energies compared to pure wide binaries, helping them to survive. The environment effect and the binding-energy argument may be sufficient for explaining the fraction and period distribution of hierarchies in the field without assuming special formation mechanisms of wide binaries related to hierarchical multiplicity.

3 OBSERVED FREQUENCY OF WIDE PAIRS

3.1 Low-density SFRs

Binarity of very young protostars in the Perseus SFR has been recently explored by Tobin et al. (2016) using high-resolution observations at centimeter wavelengths. Their resolution limit corresponds to the projected separation $s \sim 15$ AU. The distribution of s for Class 0 and Class I sources from their Tables 3 and 4 is reproduced here in Table 1 as the number of pairs per 0.5 dex separation bin. The last line of this Table gives the total size of the sample, allowing us to compute the companion frequency. The age of all sources is less than 0.5 Myr, the majority of the Class 0 sources are younger than $\sim$160 Myr.

Table 1 also gives the latest binary statistics in Taurus based on the Table C1 from Joncour et al. (2017). I selected from their catalogue 142 stars with mass above 0.3 $\mathcal{M}_\odot$ observed with high angular resolution, and computed the number of pairs in each separation bin, counting each pair only once. To match the common convention, 24 pairs of catalog entries within 10 kAU of each other are considered as binary systems, reducing the sample size to 118 (this adjustment affects only the normalization of the curve). The full broken line without error bars in Figure 3 is a good match to the broken power law of Simon (1997). Kraus et al. (2011) also studied the separation distribution in Taurus, but only out to 5 kAU, avoiding the clustering regime.

Young moving groups have ages between 10 and 100 Myr;
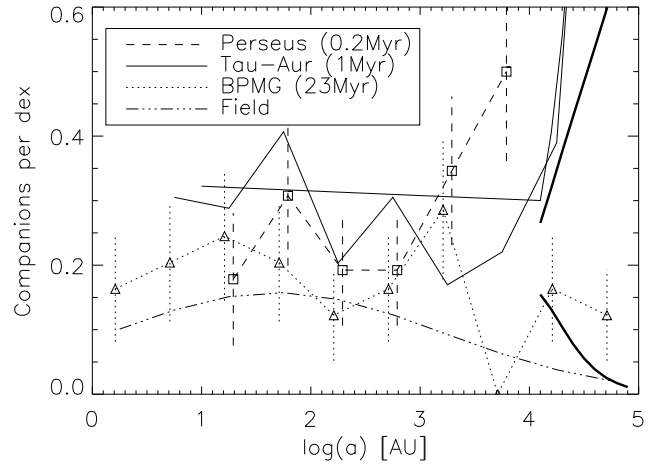
Figure 3. Distributions of projected separations in the Perseus SFR (dashed line, Tobin et al. 2016), Taurus-Auriga (two-segment and broken full lines, Simon 1997; Joncour et al. 2017), BPMG (dotted line, Elliott & Bayo 2016), and the field (dash-dot line, Raghavan et al. 2010). Companion frequency per decade of separation is plotted on the vertical axis. The thick solid lines at $\log a > 4$ are the clustering distributions scaled down according to the expected proportion of wide bound pairs under the assumptions of Gaussian (upper) or Maxwell (lower) velocity distributions.

the age of the β Pictoris moving group (BPMG) is 23 Myr (Mamajek & Bell 2014). Elliott & Bayo (2016) studied the binary statistics in this group using a variety of techniques. The sample size is 49, the companion frequency is about one. Data from their Table 2 are used for computing the histogram given in the fourth column of Table 1. Kraus & Hillenbrand (2009) derived a similar logarithmically flat separation distributions in the range $5 < s < 5000$ AU for binaries in both Taurus-Auriga and Upper Scorpius SFRs.

Binary statistics of the older field stars of approximately one solar mass is well studied (Raghavan et al. 2010; Tokovinin 2014). The distribution of periods and separations is approximately log-normal, with the median period of 10^5 days, logarithmic period dispersion of 2.3, and companion fraction about 0.60. At $s > 3$ kAU, the frequency of companions declines approximately as a power law $f(s) \propto s^{-1.5}$ (Tokovinin & Lépine 2012); the power law fits the data as well as the log-normal model. About 2% of solar-type stars in the field have companions with $s > 10^4$ AU. Figure 3 plots the fraction of companions per decade of separation. The field distribution is shown by the dash-dot line, while the full line is the broken power law for Taurus-Auriga (data from Simon 1997). The clustering power law scaled down according to the expected fraction of bound pairs (thick solid lines) shows the frequency of potentially bound wide pairs originating from adjacent cores under two assumptions (normal or Maxwell distributions of the relative velocity).

In the youngest Perseus SFR there are many pairs with separations of $\sim 10^3$ AU and wider, while at smaller separations the numbers are approximately constant, within the errors (a log-uniform distribution). A similar upturn in the separation distribution of protostars at $s > 10^{3.5}$ AU has been found earlier by Conneley et al. (2008). In the older Taurus-Auriga SFR, the upturn occurs at separations $s > 10^4$ AU, while in the BPMG the distribution is approximately flat out to 10^5 AU (note however the large statistical error bars).

The multiplicity fraction depends on the mass of the primary
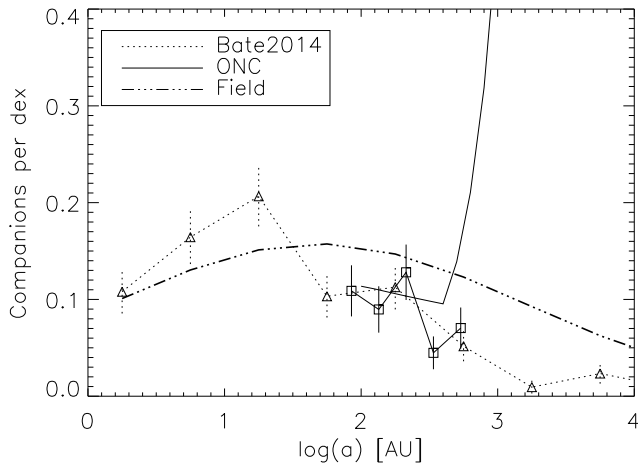
Figure 4. Distributions of projected separations in the ONC (full lines), in a simulated dense cluster (dotted line), and in the field.

component (Duchêne & Kraus 2013). Data on the young associations plotted in Figure 3 refer to a mixture of masses, mostly below one solar, while the masses in Perseus are not known and these protostars are still accreting. The comparison of the multiplicity fraction with the field (masses around one solar) should take this into account. The histograms show that the multiplicity fractions in Taurus, BPMG and Perseus are larger than in the field even at moderate separations $s \sim 10^2$ AU, as in other sparse SFRs (Kraus & Hillenbrand 2009; King et al. 2012). Such binaries are not disrupted dynamically and survive in the field. At the same time, sparse SFRs produce most (or all) wide binaries. Not surprisingly, those wide binaries often contain subsystems.

3.2 Dense SFRs

In dense regions, wide binaries cannot form or survive, owing to dynamical interactions with their neighbors. The typical distance between stars is less than the core size or the Jeans length, so the concept of core becomes questionable in these conditions. Protostars move in a common gas cloud while accreting and interacting dynamically. Bate (2014, and references therein) made large hydro-dynamical simulations of the collapse of a dense turbulent cloud containing 500 $M_\odot$ of gas. Simulations cover 0.3 Myr, until a substantial fraction of the gas is accreted. Although the filamentary structure and fractal-like clustering of newly formed stars develop initially, the subgroups subsequently merge, with violent dynamical interactions between the stars and continuing accretion. Citing Moeckel & Bate (2010), "..the stars form in a structured fashion, with smaller sub-clusters merging to form a final cluster consisting of a tightly bound core with radius ≈0.05 pc surrounded by an expanding halo of ejected stars." We provide in Table 1 the distribution of the semimajor axes from (Bate 2014) that drops sharply at $a > 1$ kAU. Subsequent dynamical evolution of the cluster may curtail this distribution even further (Kaczmarek et al. 2011). However, Moeckel & Bate (2010) argue that after the gas dispersal the cluster expands and does not destroy the binaries that have already formed in a denser environment. The multiplicity fraction in the expanding cluster stays approximately constant, except in its outer halo where it is ∼2 times less.

Figure 4 plots the separation distribution for the high-density SFR, namely the ONC. Squares and full line correspond to the Figure 7 of Reipurth et al. (2007), who studied the binarity in the sep-

aration range from 67.5 to 675 AU in a sample of 781 stars outside the Orion Trapezium. The broken power law is based on the Simon (1997) fit to the companion statistics in the Trapezium. It is reduced by a factor 2 to match approximately the binary fraction found by Reipurth et al. Such adjustment is justified by the large errors of the power-law fits in (Simon 1997) and by the larger primary mass (hence higher multiplicity) in the Trapezium sample. Bate et al. (1998) convincingly show that the break point in the power-law fits is related to the average star density, which is high in the Trapezium. We do not see the sharp upturn in the separation distribution of binaries outside the Trapezium because the stellar density there is much less, and because the contribution of neighbouring stars has been subtracted from the histogram.

For comparison, we plot in Figure 4 the separation distribution of binaries resulting from the large hydro-dynamical simulations by Bate (2014) (see Table 1). The simulated cluster roughly matches the ONC in density. Note the sharp drop of binary frequency at separations beyond 300 AU. There are still a few soft binaries with $s > 10^3$ AU that will likely be disrupted within the cluster, while new wide binaries will appear in its expanding halo (see Section 4.2).

At separations around 100 AU, the companion frequency in the ONC and in the simulated cluster is less than for the solar-field dwarfs. This statistics refer to primary stars of less than one solar mass, hence such difference is expected. Of importance here is the fast drop in the number of pairs wider than ∼300 AU, compared to the separation distribution in the field and in the low-density SFRs. Reipurth et al. (2007) further discuss the paucity of wide pairs in the ONC.

4 ALTERNATIVE FORMATION MECHANISMS OF WIDE BINARIES

4.1 Unfolding

Reipurth & Mikkola (2012) suggested that very wide binaries are formed by ejections from more compact unstable triples. They call this "unfolding" of triple systems into extreme hierarchical architecture. In this mechanism, the outer orbits are very eccentric because the angular momentum of the wide pair is derived from the initially more compact system. Although the ratio of semimajor axes in unfolded triples can be large, they are still only marginally stable because the tertiary and the binary approach each other at the periastron of the eccentric outer orbit.

The unfolding time is on the order of $P/2$. The authors note that "Many wide systems have not unfolded fully at 1 Myr, and the most extreme wide systems will take tens to hundreds of million years to unfold, and they are thus more protected against disruption by passing stars." In young associations such as Taurus-Auriga (age ∼1 Myr), there should be no binaries with $s > 10^4$ AU formed by this mechanism. In reality, young SFRs contain many wide pairs (including unbound ones), but their fraction progressively *decreases* with age instead of increasing.

In the simulations by Reipurth & Mikkola (2012), decaying triple systems generate about 2% of wide ($a > 10^4$ AU) binaries per system, matching approximately the frequency of wide pairs in the field. However, not all cores fragment into triple or quadruple stars, and not all triples are unstable, so in a realistic situation the frequency of "unfolded" wide binaries produced by this mechanism is too small even for the field, and much smaller than in young groups such as BPMG.

Another strong prediction of the unfolding scenario is the high eccentricity of the outer orbits, the majority with $e > 0.9$ for $a > 10^4$ AU. There should be a correlation between the outer semimajor axis and the outer eccentricity. The eccentricities of very wide binaries can be determined statistically by accurate measurement of the relative motion (Tokovinin & Kiyaeva 2016), soon to be available from *Gaia*. However, large incidence of subsystems implies the need to account for their motion, making such future study quite challenging.

The triple system α Cen A,B (HIP 71683 and 71681) and Proxima Cen (HIP 70890) is an excellent test case for the ejection scenario. Being the nearest, it should be typical of other similar systems (rather than exceptional). It is bound, given its age. The projected separation of Proxima is $s_{proj} = 10.7$ kAU, the total separation in space is $s = 15$ kAU, and the parabolic velocity is $V_{par} = 0.51$ km s^{-1}. Wertheimer & Laughlin (2006) calculated the binding energy of the wide pair AB,C and found that it can be either positive or negative with roughly equal probability. The latest study by Kervella et al. (2017), however, shows that the triple system is bound and that the eccentricity of the outer orbit is moderate, 0.42. Therefore this triple system has not been formed by unfolding. Interestingly, the outer and inner orbits are inclined by only 29°. The outer orbit thus has a large angular momentum and it is roughly aligned with the inner orbit.

4.2 Cluster dissolution

Moeckel & Bate (2010) show that after 10 Myr of dynamical evolution of the dense simulated cluster, several wide binaries with $10^4 < s < 10^5$ AU are formed in its expanding halo. These binaries are wider than the original cluster size of 10^4 AU, and half of them are triple or higher-order multiples. There were 15 ± 7 binaries with $s > 10^4$ AU, or 1.7% for a total of 900 stars in that cluster. Kouwenhoven et al. (2010) estimate that, on average, one cluster produces one wide binary with $s > 10^4$ AU. The frequency of such pairs in the field is ∼2%. If all field wide pairs were formed by the cluster dispersal mechanism, a typical cluster should contain ∼50 stars.

On the other hand, the frequency of pairs with $s > 10^4$ AU in the BPMG is 7/49=0.14±0.05, significantly larger than in the field. Such a large fraction of wide pairs cannot be explained by either cluster dissolution or by the unfolding mechanisms. Joncour et al. (2017) reached the same conclusion regarding wide pairs in Taurus.

4.3 Entrapment

Makarov (2012) considered formation of very wide ($s \sim 1$ pc) pairs from unrelated stars that are accidentally "entraped" into common motion in the Galactic potential. In principle, such pairs can survive for a long time. However, their motion is chaotic (not Keplerian) and they can dissolve as easily as they were formed. Makarov estimates that this mechanism is too inefficient for explaining wide pairs in the field. Moreover, wide binaries are more readily disrupted by passing stars or molecular clouds than by the smooth Galactic potential, so the large Jacoby radius of ∼1.8 pc is not relevant for their survival (Weinberg et al. 1987).

5 SUMMARY

The separation distribution of stellar pairs in the low-density SFRs is nearly uniform (logarithmically) up to 10^4 AU and increases at larger separations. This upturn is associated with the initial fractal clustering of prestellar cores. It disappears progressively with increasing age, leaving a smoothly declining separation distribution in the field (Figure 3). Young moving groups such as BPMG (age 23 Myr) represent an intermediate case, with 14% of stars having companions wider than 10^4 AU. This large fraction of wide pairs does not match such proposed formation mechanisms as cluster dissolution or unfolding of unstable triples. However, it can be explained easily as a remnant of the clustering, where a fraction of adjacent cores happen to be gravitationally bound. It is shown that the gas kinematics allows for a large enough fraction of bound core pairs if the motions are highly anisotropic and the resultant velocity difference between the cores is distributed almost normally, rather than by the Maxwell-Bolzmann law.

Stars in the field come from different environments. The frequency of wide pairs in the field therefore can indicate what fraction of the field stars were formed in the low-density SFRs like Taurus-Auriga and BPMG, and what fraction comes from larger and denser clusters (Patience et al. 2002; Reipurth et al. 2007).

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