The origin of very wide binary stars

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Abstract. A large population of fragile, wide (> 10³ AU) binary systems exists in the Galactic field and halo. These wide binary stars cannot be primordial because of the high stellar density in star forming regions, while formation by capture in the Galactic field is highly improbable. We propose that these binary systems were formed during the dissolution phase of star clusters (see Kouwenhoven et al. 2010, for details). Stars escaping from a dissolving star cluster can have very similar velocities, which can lead to the formation of a wide binary systems. We carry out \( N \)-body simulations to test this hypothesis. The results indicate that this mechanism explains the origin of wide binary systems in the Galaxy. The resulting wide binary fraction and semi-major axis distribution depend on the initial conditions of the dissolving star cluster, while the distributions in eccentricity and mass ratio are universal. Finally, since most stars are formed in (relatively tight) primordial binaries, we predict that a large fraction of the wide “binary stars” are in fact higher-order multiple systems.

1. Wide binary systems in the Galactic field and halo

The large majority of stars are thought to form as part of a binary or multiple stellar system (e.g., Duquennoy & Mayor 1991, Fischer & Marcy 1992, Goodwin & Kroupa 2005, Kouwenhoven et al. 2005, 2007). The general consensus is that most star form in embedded star clusters and loosely-bound associations (e.g., Lada & Lada 2003; Bastian 2011), which initially exhibit a significant amount of substructure (e.g., Allison et al. 2009). Following proto-star formation, the properties of the binary population evolve over time, primarily due to the effects pre-main sequence evolution (Kroupa 1995) and dynamical interactions with other stars (e.g., Heggie & Hut 2003, Marks et al. 2011). Most star clusters dissolve within 10–50 Myr after their formation (see de Grijs & Parmentier 2007, and references therein). The field star population is therefore thought to be the result of a mixture of stars originating from different star clusters (Goodwin 2010).
Over the last decades a significant number of wide (> $10^3$ AU) binary systems have been discovered (see Fig. [1]). In the log-normal period distribution of Duquennoy & Mayor ([1991]), for example, $\sim 15\%$ of the binary systems have a semi-major axis larger than $10^3$ AU. Individual wide binary systems are often identified in proper motion studies, and occasionally combined with parallaxes, radial velocity measurements and background star statistics (e.g., Makarov et al. 2008; Quinn & Smith 2009; Shaya & Olling 2011, and numerous others). The overall properties of the wide binary population can also be obtained statistically (e.g., Longhitano & Binggeli 2010). Wide binary systems are extremely fragile, and those wider than $0.1 – 0.2$ pc are easily destroyed in the Galactic field (see Fig. [1]). This upper limit can be explained by interactions with other stars, molecular clouds, and the Galactic tidal field (e.g., Retterer & King 1982; Jiang & Tremaine 2010). The properties of wide systems in the Galactic field are also used to constrain the properties of hypothesized dark components (e.g., Quinn et al. 2009; Allen et al. 2007; Hernandez & Lee 2008).

Wide binary systems cannot have formed as primordial binaries in star clusters, simply because their orbital separation is comparable to the size of a typical embedded cluster. Moreover, the typical size of a star forming core is $\sim 10^4$ AU (Ward-Thompson et al. 2007), which sets an absolute maximum to the size of a primordial wide binary system. Even if they were somehow able to form, they would be destroyed immediately due to stellar encounters (Kroupa 2001; Parker et al. 2009).

The fact that it is not possible to form primordial binary systems with semi-major axes in the range $10^3$ AU–0.1 pc implies that wide binaries are formed at a later stage, as a result of dynamical interactions between stars. Energy conservation implies that two stars on an initially unbound orbit will remain unbound. Capture is therefore only possible when energy is removed from the system, for example by a third star that is present during the encounter. The formation rate $\dot{N}_B$ of binary systems via three-body encounters is given by

$$\dot{N}_B = 0.75 \frac{G^5 M^5 n^3}{\sigma^9},$$

(Goodman & Hut 1993), where $G$ is the gravitational constant, $M$ is the typical stellar mass, $n$ the stellar number density, and $\sigma$ the velocity dispersion. The value of $\dot{N}_B$ is negligible for stars in the Galactic field and halo. On the other hand, capture is possible in the dense cores of star clusters, but this will never result in the formation of long-lived wide binary systems, due to the crowded stellar environment.

In Kouwenhoven et al. (2010) we proposed that wide binary systems form during the dissolution phase of star clusters. This mechanism can result in a significant population of binary systems (see also Moeckel & Batel 2010; Moeckel & Clarke 2011). In this scenario, an unbound pair of escaping stars can form a binary system when their relative velocity is small.\(^2\) Our $N$-body simulations (see below) result in a population of wide binary systems with semi-major axes comparable to their initial separation, a thermal eccentricity distribution, and a mass ratio distribution resulting from (gravitationally-focused) random pairing of components from the initial mass function.

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1 Following Kouwenhoven et al. (2010), we define systems with an orbital separation in the range $10^3$ AU $\leq a \leq 0.1$ pc as wide binary systems (or wide multiple systems).

2 A large population of comets may also be captured by stars via a similar mechanism, during cluster dissolution (e.g., Eggers et al. 1997; Levison et al. 2010).
2. Method, initial conditions and \(N\)-body simulations

To test our hypothesis that wide binary systems are formed during the dissolution phase of star clusters, we carry out \(N\)-body simulations using the STARLAB package \(\text{[Portegies Zwart et al. 2001]}\). For each star cluster we draw \(N\) stars from a \(\text{Kroupa (2001)}\) mass distribution in the range \(0.1–50 \, M_\odot\). We study the properties of the resulting binary population as a function of the number of member stars \(N\) \((10 \leq N \leq 1000)\), the size \(R\) of the star clusters \((0.1 \, \text{pc} \leq R \leq 1 \, \text{pc})\), and the primordial binary fraction \(B\) \((0\% \leq B \leq 100\%)\). We additionally vary the virial ratio \(Q \equiv E_K/E_p\) of the cluster, where \(E_K\) and \(E_p\) are the kinetic and potential energy of the cluster, respectively. We study the cases \(Q = 1/2\) (cluster in virial equilibrium) and \(Q = 3/2\) (expanding star cluster). We carry out simulations for two different stellar density distributions of the stars: (i) spherical \text{Plummer (1911)} models, and (ii) models with substructured initial conditions with fractal parameter \(\alpha = 1.5\) \(\text{[Goodwin & Whitworth 2004, for details]}\).

Simulations are carried out until the modeled cluster has completely dissolved. At the end of each simulation we determine the properties of the resulting binary population. We identify a pair of stars as a binary system when (i) their binding energy is
negative, and (ii) both stars are each others mutual nearest neighbor. In our analysis we only consider binary systems with a semi-major axis $a \leq 0.1$ pc, as wider pairs are rather easily destroyed due to stellar encounters. We also identify hierarchical multiple stellar systems ($\geq 3$ stars) and impose the Valtonen et al. (2008) stability criterion $a_{\text{out}}/a_{\text{in}} > Q_{\text{st}}$ for multiple stellar systems, where $a_{\text{in}}$ and $a_{\text{out}}$ are the inner and outer orbits of a (sub)system, respectively, and $Q_{\text{st}} \approx 3 - 10$ is a stability parameter which depends on the orbital configuration. For wide higher-order system with (outer) orbital periods of order $\sim 1$ Myr, this corresponds to a stability timescale of several billion years.

3. The wide binary fraction, orbital elements and higher-order multiplicity

A summary of the results of our $N$-body simulations is listed below. For an extensive description of the results we refer to Kouwenhoven et al. (2010). To illustrate the results, we show the orbital properties of a selected sample of the simulations in Figs. 2 and 3.

(a) The wide binary fraction. After cluster dissolution, the wide binary fraction (i.e.,
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Figure 3. Same as Fig. 2 but now for substructured models (fractal parameter $\alpha = 1.5$) with $N = 1000$ and $R = 0.1$ pc, and virial ratios of $Q = 1/2$ (top) and $Q = 3/2$ (bottom); in each case fifty realisations have been simulated.

(b) The semi-major axis distribution. The resulting semi-major axis distribution for wide binary systems is mainly in the range $(0.1 - 1)R$, where $R$ is size of the star cluster at the moment of dissolution. The semi-major axis distribution of the newly formed binaries typically shows two peaks: a dynamical peak at small values of $a$, resulting from three-body interactions, and an dissolution peak of wide binary systems formed during the dissolution phase of the star cluster (this is clearly shown in the left-hand panels in Fig. 3). The ratio of the number of binary stars in the dynamical peak and the dissolution peak depends on the initial conditions of the star cluster (see above).

(c) The eccentricity distribution. The capture process which results in wide binary formation is chaotic. The eccentricity distribution for wide binary systems is therefore expected to be thermal: $f(e) = 2e$ for $0 \leq e < 1$ (Heggie 1975), which is confirmed by the simulations.
(d) **The mass ratio distribution.** The mass ratio distribution for wide binary systems results from gravitationally-focused random pairing (e.g., Kouwenhoven et al. 2009, and references therein) of the individual components. This implies that wide binaries with a high-mass primary star have a small mass ratio, while those with a low-mass binary have a high mass ratio (see Figs. 2 and 3). In addition, the wide binary fraction slowly increases with increasing primary star mass.

(e) **Orientation of the orbits.** The orientation of the stellar spins of the two stars in a wide binary system are randomly aligned. In the case of a wide multiple system, the orbital orientations of the inner orbits are also randomly aligned with respect to each other, and with respect to the orbit of the wide orbit.

(f) **Implications for higher-order multiplicity.** A significant fraction of star form as part of a primordial binary system. Both components of a wide “binary” system are therefore expected to be binary themselves. Recent observations suggest indeed that wide “binary” systems are frequently triple or quadruple systems (Makarov et al. 2008; Mamajek et al. 2010; Faherty et al. 2010; Law et al. 2010). The multiplicity ratios among wide systems can therefore be used to constrain the primordial binary fraction, or more specifically, the binary fraction at the moment of star cluster dissolution (see Fig. 4).

There is an ongoing debate about the wide binary formation mechanism itself. Kouwenhoven et al.
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shows that a pair of (previously unbound) stars can form a wide binary system during the dissolution phase, while the study of Moeckel & Clarke (2011) shows that a small (but transient) population of wide binary systems is always present in a star cluster, and that this wide binary population is frozen in when a star cluster dissolves. It may well be possible that both mechanisms contribute to the formation of the wide binary population in the Galactic field and halo.

4. Summary

Approximately 15% of the known binary systems in the Galaxy have an orbital separation larger than $10^3$ AU. These systems cannot be primordial, simply because their orbital separations are comparable to the size of young embedded clusters. Moreover, if they were able to form in such environments, they would immediately be destroyed by dynamical interactions with other stars. Dynamical capture in the Galactic field or halo is highly improbable due to the low stellar density and high velocity dispersion, and cannot explain the observed wide binary population either.

We propose that wide binary systems form during the dissolution phase of star clusters (see Kouwenhoven et al. 2010, for details). In this scenario, an escaping pair of stars with a small relative velocity can form a wide binary system. N-body simulations confirm this hypothesis, and allow us to predict the prevalence and orbital properties of the wide binary population (§3), and the fraction of triple and quadruple stars among wide systems (see Fig. 4). These predictions can be tested observationally, in particular those for the mass ratio distribution and the higher-order multiplicity.

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