The formation of very wide binaries

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Abstract. Over the last decades, numerous wide (> 1000 AU) binaries have been discovered in the Galactic field and halo. The origin of these wide binaries cannot be explained by star formation or by dynamical interactions in the Galactic field. We explain their existence by wide binary formation during the dissolution phase of young star clusters. In this scenario, two single stars that leave the dissolving cluster at the same time, in the same direction, and with similar velocities, form a new, very wide binary. Using \textit{N}-body simulations we study how frequently this occurs, and how the orbital parameters of such binaries depend on the properties of the cluster from which they originate. The resulting wide binary fraction for individual star clusters is $1 - 30\%$, depending on the initial conditions. As most stars form as part of a binary or multiple system, we predict that a large fraction of these wide “binaries” are in fact wide triple and quadruple systems.

1 Observations and origin of wide binaries

Observations have indicated that the majority of the stars form in star clusters (e.g., \cite{LadaLada2003}) and as part of a binary system (e.g., \cite{DuquennoyMayor1991}). Surveys for binarity have indicated that a significant number of binaries have orbital separations that are comparable with the typical size of star clusters in which they are thought to have formed. These wide binaries are usually identified as common proper motion pairs (e.g., \cite{WassermanWeinberg1991, ChanameGould2004, LepineBongiorno2007, Makarov2008, QuinnSmith2009, LonghitanoBinggeli2009}) or by employing statistical methods (e.g., \cite{BahcallSoneira1981, Garnavich1988, Gould1995, LonghitanoBinggeli2009}). The wide binary fraction in the separation range $10^3$ AU $< a < 0.1$ pc is of order 15\% (\cite{DuquennoyMayor1991, Poveda2007}), with a drop-off at around 0.1 – 0.2 pc, which corresponds to the stability limit for wide binaries in the Galactic field. In the Galactic halo, where the stellar density is smaller, wide binaries with separations of up to several parsecs are known (\cite{ChanameGould2004}). The origin of these wide binaries in the field

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and halo has long been a mystery. Below, we discuss four potential formation theories of wide binaries:

- **Clustered star formation.** This mode of wide binary formation is excluded, given the compact nature of the embedded clusters (< 1 pc). Even if it were possible to form such a wide binary via the star formation process, it would immediately be destroyed by dynamical interactions with other cluster stars. Hence, clustered star formation is not a viable option.

- **Diffuse star formation.** Although this may be a possible formation mechanism for some wide binaries, diffuse (or isolated) star formation is rare, and it is therefore difficult to account for a the large number of wide binary systems in the Galactic field.

- **Dynamical capture.** Binary formation by dynamical capture is theoretically possible. This mechanism requires a third star to remove kinetic energy from the system, such that the binding energy of the two remaining stars becomes negative. It requires the three stars to be at the same place at the same time, with fine-tuned velocities and impact angles. In the Galactic field, this combination of parameters is extremely unlikely, given the stellar density and velocity dispersion in the field (Goodman & Hut 1993). Therefore, this possibility of forming wide binaries is ruled out. Note that binary formation by dynamical capture is possible in star clusters, as the density is higher and the velocity dispersion lower. However, this does not result in *wide binaries*, as these are immediately destroyed after their formation in young, dense star clusters.

- **Formation during star cluster dissolution.** The vast majority of star clusters are short-lived, and dissolve into the field star population quickly after their formation. Two unbound stars that are close in phase-space may form a wide binary system when a young star cluster dissolves. We have tested this possibility using *N*-body simulations, and find that this process results in a wide binary fraction of 1–30%, depending on the initial conditions of the star cluster (Kouwenhoven et al., 2009, in prep). Wide binary formation during the star cluster dissolution phase is therefore a viable mechanism for the formation of the observed wide binary population.

2  *N*-body simulations and results

Our hypothesis that a significant number of wide binaries form during the star cluster dissolution process, can easily be tested using *N*-body simulations. We therefore carry out star cluster simulations using the STARLAB package (Portegies Zwart et al. 2001), and study how the resulting wide binary population depends on the initial conditions of a star cluster. We draw *N* single stars from the Kroupa (2001) mass distribution in the mass range 0.1\(M_\odot\) < \(M\) < 50\(M_\odot\). We perform simulations of clusters starting out from a Plummer (1911) morphology, and substructured clusters with a fractal dimension of 1.5, following the prescriptions of Goodwin & Whitworth (2004). By varying the initial
cluster mass, size, and morphology, we study how the properties of the wide binary population depend on these, and obtain the following results:

1. The binary fraction among the dissolved stellar population ranges between $F = 1\%$ and $30\%$, depending on the cluster properties. The binary fraction, in this case, is measured as $F = (B + T + \ldots)/(S + B + T + \ldots)$, where $S$, $B$, and $T$ denote the number of single stars, binary systems, and triple systems in the cluster.

2. More massive star clusters result in smaller binary fractions than low-mass clusters. Clusters with a spherical, smooth stellar density distribution form fewer wide binaries than substructured clusters of the same size and mass.

3. The typical semi-major axis $a$ of a newly formed binary is comparable to the initial size $R$ of the star cluster in which it was born (the reason for this being that $R$ is the only size scaling that is present in the initial cluster). The resulting semi-major axis distribution is generally bimodal, consisting of a dynamical peak with binaries formed by dynamical interactions in the cluster centre, and a dissolution peak with binaries formed during the cluster dissolution phase.

4. The formation of wide binaries during the star cluster dissolution phase is a random process, resulting in a thermal eccentricity distribution, a (gravitationally-focused) randomly-paired mass ratio distribution, and random alignments between the orbital spin vector and the stellar rotation axes.

5. Star clusters with a non-zero primordial binary fraction form wide triple and quadruple systems, i.e., the two components that make up the newly formed wide “binary” are in fact primordial binaries, rather than single stars. The ratio of triple to quadruple systems among very wide orbits is therefore indicative of the primordial binary fraction. Given that the primordial binary fraction is large, we predict a high frequency of triple and quadruple systems among the known wide “binary” systems.

3 Summary

Approximately $15\%$ of the binary systems in the Galactic field have separations in the range $10^3$ AU < $a$ < 0.1 pc. Their origin cannot be explained by star formation or by dynamical capture in the Galactic field. We have carried out $N$-body simulations to test the hypothesis that these wide binaries are formed during the dissolution process of young star clusters, where two stars happen to fly off in the same direction and form a new, wide binary (Kouwenhoven et al., 2009, in prep).

Our simulations indicate a binary fraction of $1 - 30\%$ in the separation range $10^3$ AU < $a$ < 0.1 pc, depending on the initial conditions of the star clusters. Clusters with more substructure and with a smaller cluster mass result in a higher wide binary fraction. The resulting separation distribution is generally
bimodal, and has a \textit{dynamical peak} of close binaries formed via dynamical interactions in the cluster, and a \textit{dissolution peak} consisting of wide binaries formed during the dissolution process of the star cluster.

For star clusters with a high primordial binary fraction, these primordial binaries pair up into wide systems. Given that most stars form as part of a binary system, we predict that most observed wide “binaries” are in fact wide triple and quadruple systems. The ratios between wide binary, triple, and quadruple systems are therefore indicative of the primordial binary fraction.

\textbf{Acknowledgments.} MBNK was supported by the Peking University Hundred Talent Fund (985), the Peter and Patricia Gruber Foundation through the PPGF fellowship, and by PPARC/STFC under grant number PP/D002036/1. RJP acknowledges support from STFC.

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