Article:

Kouwenhoven, M.B.N., Goodwin, S.P., Parker, R.J. et al. (3 more authors) (2010) The origin of very wide binary systems. Proceedings of the International Astronomical Union, 5 (S266). pp. 438-441. ISSN 1743-9213

https://doi.org/10.1017/S1743921309991633

Star clusters: basic galactic building blocks
Proceedings IAU Symposium No. 266, 2010
R. de Grijs & J. R. D. Lépine, eds.

DOI: 00.0000/X000000000000000X

The origin of very wide binary systems

M. B. N. Kouwenhoven,[1,2] S. P. Goodwin,[2] Richard J. Parker,[2] M. B. Davies,[3] D. Malmberg[3] and P. Kroupa[4]

[1]Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Lu 5, Hai Dian District, Beijing 100871, P. R. China
email: kouwenhoven@kiaa.pku.edu.cn

[2]University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK

[3]Lund Observatory, Box 43, SE-221 00, Lund, Sweden

[4]Argelander Institute for Astronomy, University of Bonn, Auf dem Hügel 71, 53121, Bonn, Germany

Abstract. The majority of stars in the Galactic field and halo are part of binary or multiple systems. A significant fraction of these systems have orbital separations in excess of thousands of astronomical units, and systems wider than a parsec have been identified in the Galactic halo. These binary systems cannot have formed through the 'normal' star-formation process, nor by capture processes in the Galactic field. We propose that these wide systems were formed during the dissolution phase of young star clusters. We test this hypothesis using N-body simulations of evolving star clusters and find wide binary fractions of $1-30\%$, depending on initial conditions. Moreover, given that most stars form as part of a binary system, our theory predicts that a large fraction of the known wide 'binaries' are, in fact, multiple systems.

Keywords. binaries: general, stars: formation, stellar dynamics, methods: N-body simulations

1. Observations and formation of very wide binary systems

Numerous wide (10^3 AU$-$0.1 pc) binary systems are known to exist in the Galactic field and halo (e.g., Close et al. 1990; Chanamé & Gould 2004). These binaries are usually detected as common-proper-motion pairs (e.g., Wasserman & Weinberg 1991; Lépine & Bongiorno 2007) or through statistical methods (e.g., Bahcall & Soneira 1981; Garnavich 1988). Approximately 15% of the wide binaries in the field have a semi-major axis in the range 10^3 AU $< a <$ 0.1 pc (Duquennoy & Mayor 1991; see also Poveda et al. 2007). The origin of these wide binaries cannot be explained by star formation or by dynamical interactions in the Galactic field, and has long been a mystery.

The majority of stars are known to form in embedded clusters (Lada & Lada 2003). Wide binary systems cannot have formed through clustered star formation, simply because their semi-major axis is comparable to the size of a typical embedded cluster. Even if it were possible to form wide binaries in star clusters, they would immediately be destroyed by dynamical interactions. Although most stars are believed to have formed in star clusters, a fraction ($< 10-30\%$) may form through diffuse (isolated) star formation. However, this fraction makes it difficult to account for the $\sim 15\%$ wide binaries in the Galactic field. If wide binaries are formed through diffuse star formation, then the majority of stars formed in this process must form a wide binary, implying a star-formation process that is fundamentally different from that of clustered star formation.

Binary systems of any separation may also form through dynamical capture processes. To form a binary system from two interacting stars, a third star should be present to serve as energy sink. Each of the three stars should be at the same location at the same time, and should have precisely those velocities and impact angles that allow the formation of

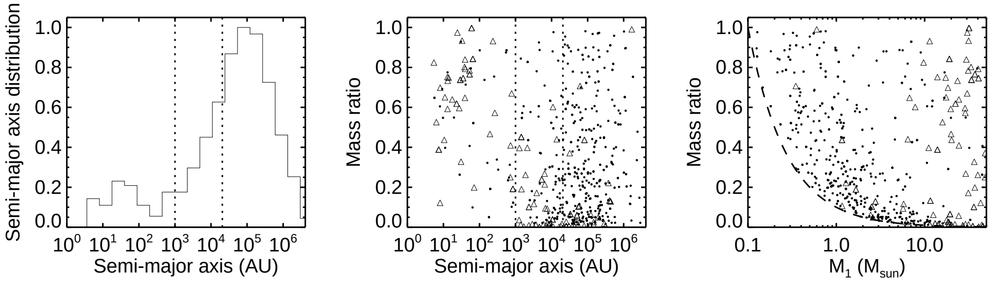

Figure 1. The binary population resulting from a Plummer model with $N = 1000$ and a virial radius of 0.1 pc (50 runs), showing the semi-major-axis distribution *(left)*, the correlation between mass ratio q and semi-major axis a *(middle)* and between primary mass and mass ratio (right). Binary and multiple systems are indicated with circles and triangles, respectively. The vertical dashed lines indicate $a = 10^3$ AU and $a = 0.1$ pc, respectively, the semi-major-axis range we consider in our analysis. The dashed curve in the right-hand panel indicates the minimum mass ratio $q_{\rm min}(M_1) = M_{\rm min}/M_1$ (Kouwenhoven et al. 2009).

a new binary system. These conditions are extremely rare in the Galactic field, resulting only in a handful of binaries over the lifetime of the Galaxy (Goodman & Hut 1993). Note that binaries can form through the capture process in the cores of star clusters through this process. However, wide binary systems cannot form in these environments, simply because they have a semi-major axis comparable to (or even larger than) star cluster cores.

We propose that wide binaries are formed during the dissolution of young star clusters (Kouwenhoven et al., in prep). Young clusters generally have a short lifetime and dissolve into the field stellar population within typically 20 Myr (e.g., Mengel et al. 2005; Bastian et al. 2005; de Grijs & Parmentier 2007). During this dissolution process, two stars may escape the cluster in the same direction, with similar velocities. Although initially unbound, these two stars may form a new binary system after having left the gravitational potential of the cluster. In this process, the separation between the two stars is typically on the order of the size of their natal cluster at the time of dissolution, i.e., of order a parsec.

2. N-body simulations and results

It is theoretically possible to form a wide binary in the star cluster dissolution phase and it is important to find out whether this process happens frequently enough to account for the observed wide binary population. To this end, we carry out N-body simulations of evolving star clusters using the STARLAB package (Portegies Zwart et al. 2001). We randomly draw N single stars from the Kroupa (2002) initial mass function in the mass range $0.1-50$ $M_\odot$. The stars are given positions and velocities according to two models, (i) the spherical and homogeneous Plummer (1911) model and (ii) a fractal stellar distribution with fractal dimension 1.5, following the prescriptions of Goodwin & Whitworth (2004). The simulations are run until the star cluster is completely dissolved. We only consider the wide binary population in the semi-major-axis range 10^3 AU $< a <$ 0.1 pc, where the upper limit roughly corresponds to the stability limit in the Galactic field. We find the dependence on initial conditions by varying the cluster mass, size and morphology. Our main results are the following.

(a) The resulting wide binary fraction is $1-30\%$, depending on the initial properties of the star cluster. The wide binary fraction increases strongly with increasing initial substructure of the cluster, and decreases with increasing cluster mass.

(*b*) The dissolution of star clusters results in a binary population with a bimodal semi-major-axis distribution. At small separations, we find a *dynamical peak*, consisting of binaries formed dynamically in the centre of the star cluster. At large separations, we find a *dissolution peak*, which contains the binary systems formed during the dissolution process of the star cluster. As an example, we show in Figure 1 the binary population resulting from a star cluster with $N = 10^3$ single stars and an initial radius of 0.1 pc. The resulting semi-major axis scales linearly with the initial size of the star cluster.

(*c*) Wide-binary formation is a process where two random stars encounter each other. When two stars are nearby in phase space, their mutual gravitational attraction (i.e., their combined mass) determines whether they form a new binary. The resulting mass-ratio distribution can therefore be characterised by gravitationally focused random pairing (e.g., Gaburov et al. 2008). The resulting eccentricity distribution is thermal (e.g., Heggie 1975) and there is no correlation between the orbital orientation and the stellar rotation vectors.

3. Implications for higher-order multiplicity

In the previous section we described simulations of star clusters that initially consist of single stars only. In reality, however, most stars (possibly even all stars) are formed as part of binary or multiple systems (e.g., Duquennoy & Mayor 1991; Fischer & Marcy 1992; Kroupa 1995; Kouwenhoven et al. 2005, 2007; Zinnecker & Yorke 2007). To first order, primordial binaries with separations much smaller than those of wide binaries can be dynamically approximated as single stars. Therefore, for a star cluster with primordial binaries we expect to find approximately the same wide-binary population as described above. But in this case, the wide 'binaries' are, in fact, wide triple or quadruple systems, where one or both of the subsystems consists of a primordial binary. Our N-body simulations of clusters with primordial binaries show that this is indeed the case. The ratio between the newly formed wide binaries, triples and quadruples, is a function of the primordial binary fraction. For example, for a primordial binary fraction of 50%, we expect a binary:triple:quadruple ratio of 1:2:1. By accurately measuring the multiplicity of wide-binary systems, we can therefore constrain the primordial binary fraction.

4. Summary

A significant fraction of the stars in the Galactic field and halo are part of wide ($a > 10^3$ AU) binary systems. The origin of these binary systems cannot be explained by clustered star formation, nor by dynamical capture in the Galactic field and halo. We propose that these binaries are formed during the dissolution process of young star clusters, where two initially unbound stars escape in a similar direction and form a bound wide binary (Kouwenhoven et al., in prep). We test this hypothesis using N-body simulations and find that we are able to reproduce wide-binary fractions of $1-30\%$ (in the semi-major-axis range 10^3 AU $< a <$ 0.1 pc), depending on the initial conditions. Moreover, as most stars form as part of a binary system, we predict that a large fraction of the known wide 'binaries' are, in fact, triple or quadruple systems, and the ratio of wide binary, triple and quadruple systems therefore provides an indication of the primordial binary fraction.

Acknowledgements

MBNK was supported by the Peter and Patricia Gruber Foundation through a PPGF fellowship, the Kavli Foundation, the Peking University One Hundred Talent Fund (985) and by STFC (grant PP/D002036/1). RJP acknowledges support from STFC.

References

Bahcall, J. N., & Soneira, R. M. 1981, *ApJ*, 246, 122
Bastian, N., Gieles, M., Lamers, H. J. G. L. M., Scheepmaker, R. A., & de Grijs, R. 2005, *A&A*, 431, 905
Chanamé, J., & Gould, A. 2004, *ApJ*, 601, 289
Close, L. M., Richer, H. B., & Crabtree, D. R. 1990, *AJ*, 100, 1968
Fischer, D. A., & Marcy, G. W. 1992, *ApJ*, 396, 178
de Grijs, R., & Parmentier, G. 2007, *ChJA&A*, 7, 155
Duquennoy, A., & Mayor, M. 1991, *A&A*, 248, 485
Gaburov, E., Gualandris, A., & Portegies Zwart, S. 2008, *MNRAS*, 384, 376
Garnavich, P. M. 1988, *ApJ* (Letters), 335, L47
Goodman, J., & Hut, P. 1993, *ApJ*, 403, 271
Goodwin, S. P., & Whitworth, A. P. 2004, *A&A*, 413, 929
Heggie, D. C. 1975, *MNRAS*, 173, 729
Kroupa, P. 2001, *MNRAS*, 322, 231
Kouwenhoven, M. B. N., Brown, A. G. A., Zinnecker, H., Kaper, L., & Portegies Zwart, S. F. 2005, *A&A*, 430, 137
Kouwenhoven, M. B. N., Brown, A. G. A., & Kaper, L. 2007, *A&A*, 464, 581
Kouwenhoven, M. B. N., Brown, A. G. A., Goodwin, S. P., Portegies Zwart, S. F., & Kaper, L. 2009, *A&A*, 493, 979
Kroupa, P. 1995, *MNRAS*, 277, 1491
Lada, C. J., & Lada, E. A. 2003, *ARA&A*, 41, 57
Lépine, S., & Bongiorno, B. 2007, *AJ*, 133, 889
Mengel, S., Lehnert, M. D., Thatte, N., & Genzel, R. 2005, *A&A*, 443, 41
Poveda, A., Allen, C., & Hernández–Alcántara, A. 2007, in: W. I. Hartkopf, E. F. Guinan and P. Harmanec (eds.), *Binary Stars as Critical Tools and Tests in Contemporary Astrophysics*, Proc. IAU Symp. 240, p. 417
Plummer, H. C. 1911, *MNRAS*, 71, 460
Portegies Zwart, S. F., McMillan, S. L. W., Hut, P., & Makino, J. 2001, *MNRAS*, 321, 199
Wasserman, I., & Weinberg, M. D. 1991, *ApJ*, 382, 149
Zinnecker, H., & Yorke, H. W. 2007, *ARA&A*, 45, 481