The Formation of Binary Stars
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Fun for Two

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Abstract. We performed populations synthesis calculations of single stars and binaries and show that binary evolution is extremely important for Galactic astronomy. We review several binary evolution models and conclude that they give quite different results. These differences can be understood from the assumptions related to how mass is transfered in the binary systems. Most important are 1) the fraction of mass that is accreted by the companion star during mass transfer, 2) the amount of specific angular momentum which is carried away with the mass that leaves the binary system.

1. Introduction

Binaries are characterized by "the union of two stars, that are formed together in one system, by the laws of attraction" (Herschel 1802). They form the basic building blocks of the Milky Way as galaxies are the building blocks of the Universe. In the absence of binaries many astrophysical phenomena would not exist and the Galaxy would look completely different over the entire spectral range. A considerable fraction of the astrophysical community would be unemployed, Doppler (1842) would not have written his famous paper, Herschel's nearest neighbor distribution of field stars would look different. Even life as we know it would not have evolved in the Universe as Type Ia supernovae, which enrich the interstellar medium with elements required to enable life, would not occur.

2. Galaxy Models without Binaries

Let's assume that the Galaxy contains only single stars and that the evolution of a single star passes through three stages; main-sequence (ms), giant (gs) and remnant, which again we subdivide into white dwarf (wd) and neutron star (ns), black holes are neglected here. Table 1 presents the distribution of

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stars over these subtypes at different times during the lifetime of the Galaxy if all stars were born at the same time (columns 2–5) and if the star formation was constant for the last 10 Gyr (column 6). We assumed that the initial mass function is given by the distribution proposed by Scalo (1986) between 0.1 $M_\odot$ and 100 $M_\odot$. Calculations were performed with the SeBa population synthesis code (Portegies Zwart & Verbunt 1996, see the starlab software tool set `http://www.sns.ias.edu/~starlab`).

Table 1. Stellar types and total mass as a function of time. Calculation are performed with 10^5 stars, but the numbers are rescaled to 100 stars. The first column gives the stellar type followed by the normalized number of stars of that type at zero age, 100 Myr, 1 Gyr and 10 Gyr after formation. The last column gives the stellar population if the star formation rate was constant over 10 Gyr. The bottom line gives total mass in $M_\odot$.

time [Myr]	0	100	1000	10000	0–10000
ms	100	99.03	94.98	86.24	90.14
gs	0	0.22	0.52	0.85	0.80
wd	0	0.41	4.16	12.57	8.72
ns	0	0.34	0.34	0.34	0.34
mass [$M_\odot$]	61.6	55.3	46.8	40.1	42.9

At all times the stellar population is dominated by main sequence stars (of which the majority lives longer than 10 Gyr), followed by white dwarfs and giants. The $\sim$ 14% of the stars which evolve reduces the total mass with $\sim$ 35%. The population of neutron stars builds up within a couple of 10 Myrs and remains constant at later times.

3. Galaxy Models with Binaries

If we fill the Galaxy with binaries things become more interesting and considerably more complicated (see Table 2).

Except for the initial mass function we now have to select the mass of the secondary star, the orbital period and the ellipticity of the binary system. In our numerical experiment these were all selected following model *A* of Portegies Zwart & Verbunt (1996). The initial conditions are representative for the G-dwarfs in the solar neighborhood (Duquennoy & Mayor 1991), which are well established. The orbital elements and masses of the two stars for binaries with other spectral types are still ill known and recent work is painfully sparse.

Instead of evolving single stars we now have to evolve two stars synchronously. And at the same time account for the effects of their evolution on the orbital parameters of the binary system. Furthermore the evolution of each star may be affected by its companions' evolution, i.e. through tidal effects and mass transfer.

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Table 2. Stellar types from population synthesis of 10^5 binaries. All stars are born in binaries and they are evolved in time with SeBa. For binaries the two stellar types are enclosed by parenthesis, a bracket indicates that the star is transferring mass to its companion.

time [Myr]	0	100	1000	10000	0 – 10000
ms	0	0.07	0.02	0.01	0.02
gs	0	0.03	0.10	0.11	0.08
wd	0	0.09	0.76	2.68	1.90
ns	0	0.45	0.46	0.46	0.51
(ms, ms)	100	98.60	94.47	84.27	89.07
(ms, gs)	0	0.18	0.47	0.77	0.63
(ms, wd)	0	0.15	1.80	5.97	4.01
(ms, ns)	0	0.01	0.00	0.00	0.00
(gs, gs)	0	0.01	0.01	0.02	0.01
(gs, wd)	0	0.04	0.16	0.27	0.23
(gs, ns)	0	0.00	0.00	0.00	0.00
(wd, wd)	0	0.03	1.04	3.72	2.47
(wd, ns)	0	0.02	0.02	0.01	0.02
(ns, ns)	0	0.00	0.00	0.00	0.00
[ms, ms]	0	0.51	0.71	1.41	0.96
[gs, ms)	0	0.00	0.02	0.01	0.01
[ms, wd)	0	0.00	0.00	0.06	0.03
mass [$M_\odot$]	96.9	87.8	76.3	64.9	69.6

Table 2 shows the distribution of binaries over the various subtypes at several moments in time (as in Table 1). The single stars originate from binaries which are broken up or have coalesced. We keep the same simple subtypes as before and write a binary as the two stars enclosed with parenthesis following the notation introduced by Portegies Zwart & Verbunt (1996). The number of possible outcomes is much larger than for the evolution of a population of single stars.

The total mass in binaries is slightly higher than 1.5 times the total mass in single stars (see Table 1), as one would expect from a flat mass ratio distribution. This is because we limit the masses of the primary and secondary stars to $> 0.1\,M_\odot$.

As expected, main-sequence binaries are most common but at later age a considerable fraction of binaries contain at least one white dwarf. Note that the fraction of single stars produced from the evolution of binaries is small and the majority of these are white dwarfs. Most of the single white dwarfs are the result of a merger in the common envelope phase after the formation of the first white dwarf.

The simple representation used here is insufficient to describe the evolution of binary stars in detail. It neglects interesting information about the distributions of masses, mass ratios, orbital period and eccentricities and it lacks detailed information to, for example, distinguish blue stragglers from main sequence stars or identify low mass carbon-oxygen white dwarfs (see for example Nelemans et al. 2000). It shows, however, that the possible outcomes of the evolution of a population of primordial binaries are vastly larger than for single stars.

4. Binary Evolution

There are many binary population synthesis programs available which claim to be able to evolve any binary in time. This industry was started in the early eighties by Kornilov & Lipunov (1983), Iben & Tutukov (1984) followed by Dewey & Cordes (1987) and continues to the present time.

We will show an evolutionary sequence produced by three of these programs together with the fully conservative case which is easily computed by hand. We can not present the evolution of more scenarios or those produced by other models because most publications do not provide sufficient information to follow the complete evolution of a particular binary system. In Table 3 we show one evolutionary track of one of the rare comparisons which can be made.

Table 3 shows that various groups obtain quite different results from identical initial conditions (see also Verbunt 1996, who performed a similar comparison between two models). The conservative case is most radically different, indicating that all groups agree that the evolution of such a binary should proceed rather inconservative. The other extreme in this example is provided by the Scenario Machine of Lipunov et al. (1996) in which case the accreting star hardly gains any mass but most mass is ejected from the binary system (last three columns). The large period after mass transfer indicates that little angular momentum is carried with the lost material. (The change in orbital period can be reconstructed assuming that mass lost from the binary carries 0.71 times the specific angular momentum of the binary system, which is about the specific angular momentum of the accreting star at the onset of the mass transfer.) This model results in a single Thorne-Żytkow object (a giant with a neutron star core) after the second phase of mass transfer.

The two models in the middle of Table 3 (Tutukov & Yungelson and SeBa) both lead to a neutron star binary. In these cases the intermediate stages of the binaries, however, are quite different; the binary in the TY93 model remains rather close, where SeBa results in a much wider intermediate state. So in the TY93 case, more mass is lost carrying, on average, more angular momentum. In SeBa mass leaves the binary system with 3 times the specific angular momentum of the binary; applying this prescription to the model of TY93 we find that ~ 5.3 times the angular momentum of the binary system is lost per unit mass. Note however, that TY93 use a completely different treatment of non-conservative mass transfer. The differences in the treatement of the common envelope in the second phase of mass transfer makes that the final binaries computed with the TY93 and SeBa models are very similar.

Table 3. Various stages (first column) of the evolution of a close binary with massive stars; (A): birth [$t = 0$], (B): start 1st Roche-lobe contact [$t \simeq 14.2$ Myr], (C): before 1st supernova [$t \simeq 16.1$ Myr], (D): after 1st supernova, (E): start 2nd Roche-lobe contact [$t \simeq 19.9$ Myr], (F): before 2nd supernova [$t \simeq 20.8$ Myr], (G): after 2nd supernova (not present in the LPP96 case). Masses (M and m) are in solar units, orbital period (P) in days. The various evolutionary models are: fully conservative (indicated by Conservative), Tutukov & Yungelson (1993, TY93), Portegies Zwart & Verbunt (1996, SeBa, see also `http://ww.sns.ias.edu/~starlab`) and Lipunov, Postnov & Prokhorov (1996, LPP96, see `http://xray.sai.msu.ru/sciwork/scenario.html`).

Stage	Conservative			TY93			SeBa			LPP96		
	M	m	P	M	m	P	M	m	P	M	m	P
A:	13.1	9.8	39.2	13.1	9.8	39.2	13.1	9.8	39.2	13.1	9.8	39.2
B:	13.1	9.8	39.2	13.1	9.8	39.2	12.7	9.8	40.7	12.2	9.6	43.2
C:	3.0	19.9	390	3.3	15.4	20.3	3.7	18.7	204	3.7	10.0	301
D:	1.4	19.9	411	1.4	15.4	30.7	1.3	18.7	259	1.4	10.0	241
E:	1.4	19.9	411	1.4	15.4	24.6	1.3	17.6	263	1.4	9.9	181
F:	1.4	5.1	9.7	1.4	4.2	0.1	1.3	3.4	0.2	4.3	TŻO	
G:	dissociated			1.4	1.4	2.2	1.3	1.3	2.4	4.3	black hole	

5. Why Are the Models so Different

The differences between the calculations presented in Table 3 are rather big but can be brought back to a few assumptions about the mass transfer. These assumptions determine 1) the fraction of mass that is accreted by the companion star during mass transfer, 2) the amount of specific angular momentum which is carried away with the mass that leaves the binary system.

Even bigger differences are expected from introducing new physics in the models, which may lead to unexplored channels for the formation of various types of binaries or to completely new classes of objects. An example is the model in which a neutron star in a common envelope accretes a significant fraction of this envelope. This causes the neutron star to grow in mass until it exceeds the stability limit and collapses into a low-mass black hole (Chevalier & Kirshner 1979). Bethe & Brown (1998) used this new understanding to calculate the number of neutron star binaries in the Galaxy with an analytic model. The computer powered population calculations of Portegies Zwart & Yungelson (1998) gave identical numbers for the models with similar assumptions (see their model H). The agreement between the two completely different techniques indicates that the uncertainties in binary population synthesis are mainly caused by differences in the assumption about the underlying physics and in a lesser extent in the proper choice of various key parameters. By lack of a proper understanding of some of the background physics these parameters are, for now, to be adjusted such that the observed binaries can be explained.

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