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Star formation history: Modeling of visual binaries

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ABSTRACT

Most stars form in binary or multiple systems. Their evolution is defined by masses of components, orbital separation and eccentricity. In order to understand star formation and evolutionary processes, it is vital to find distributions of physical parameters of binaries.

We have carried out Monte Carlo simulations in which we simulate different pairing scenarios: random pairing, primary-constrained pairing, split-core pairing, and total and primary pairing in order to get distributions of binaries over physical parameters at birth. Next, for comparison with observations, we account for stellar evolution and selection effects. Brightness, radius, temperature, and other parameters of components are assigned or calculated according to approximate relations for stars in different evolutionary stages (main-sequence stars, red giants, white dwarfs, relativistic objects). Evolutionary stage is defined as a function of system age and component masses. We compare our results with the observed IMF, binarity rate, and binary mass-ratio distributions for field visual binaries to find initial distributions and pairing scenarios that produce observed distributions.

1. Introduction

A significant fraction of stars are born in binary and multiple systems. Statistics of their orbital parameters bear traces of formation history and help understanding its physics. Binary-star formation is an essential piece in such fundamental areas as stellar mass function, formation of planetary systems, and binary/stellar population synthesis. Also, the multiplicity frequency and distribution of key orbital parameters would prove to be highly valuable from a theoretical standpoint. The dependency of the multiplicity frequency and their associated orbital parameters on primary mass should contain the imprint of the physical processes at play throughout the lifetime of stellar populations (Tokovinin and Kiyaeva, 2016; Tokovinin, 2014; Raghavan et al., 2010).

Close binaries can render stellar radii, distance and sometimes effective temperature from a combined analysis of light and radial velocity curves and are contributing for the cosmological distance ladder (Paczynski, 1997; Ribas et al., 2005; Bonanos et al., 2006). The chemical evolution of galaxies and the intergalactic medium are studied by close binary systems hosting white dwarfs (Pagel, 1997). Wide binaries can also probe the processes and conditions of star formation as a function of age and metallicity in star-forming regions (White and Ghez, 2001), and as a function of environment during the assembly of the Galaxy (Chanamé and Gould, 2004).

Understanding statistical distributions of visual binaries is one of the difficult problems of present-day astronomy (see, e.g., Abt and Levy, 1976; Duquennoy and Mayor, 1991; Raghavan et al., 2010; Duchêne and Kraus, 2013). In the solar neighborhood, a couple of hundred parsecs of distance, most of the double stars are visual binaries. Thus, we can assume that all stars are conceived in binary systems. Based on this assumption, we modeled visual binaries in the solar neighborhood, considering different forms of initial distributions of parameters and compared our calculations with observations.

Similar studies were carried out by different authors, e.g., Kouwenhoven et al. (2007), Kobulnicky and Fryer (2007), Kouwenhoven et al. (2009), Bate (2012), Hernández-Pérez and Bruzual (2013), see also an extensive review in Bate (2015). However, only in the present study we incorporate different distributions on semi-major axis, eccentricity, mass and mass ratio, as well as the most complete set of pairing scenarios (see below Section 2 for details). It will allow us to make conclusions on the star formation function of wide binaries.

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Parameters of the models and different assumptions are described in Section 2. All distributions of parameters, number of simulated pairs, pairing scenarios, and star formation rate of the models are explicitly discussed. Results of the modeling and its comparison with catalogued binaries are presented in Section 3. Finally, in Section 4 we applied χ^2-criterion to assess viability of scenarios, presented our conclusions and suggested directions for later studies.

2. The model

We have carried out simulations in which various pairing scenarios are used. Then we involve stellar evolution and selection effects. Brightness, radius, temperature and other parameters of components are assigned or calculated according to Hurley et al. (2000) or approximate relations for stars of various evolutionary stages. Evolutionary stage is calculated as a function of system age and component masses. The method is described in Malkov and Zinnecker (2001) and Malkov (2002). Initial distributions and parameters are described below.

2.1. Spatial distribution

In the present study we use a barometric spatial distribution with three different values of the characteristic scale of the galactic disc for different ranges of stellar masses and ignored the radial gradient across the galactic disk, as presented by Eq. (1):

$$z = \left\{ \begin{array}{cc} 50, & \text{for } m > 10, \\ 10^{0.832\log(m)+2.531} & \text{for } 1 \le m \le 10 \\ 340, & \text{for } m < 1 \end{array} \right\} \tag{1}$$

where the vertical scale z is in pc and stellar mass m is in $m_\odot$ (See Gilmore and Reid, 1983; Kroupa, 1992; Reed, 2000; Gould et al., 1996; Bahcall and Soneira, 1980). Then the density of the stars in the direction perpendicular to the galactic disk depends on stellar mass as shown in Fig. 1.

2.2. Number of pairs simulated

The model should be normalised by Galactic disk density of stars. For this, recent Gaia results are used. Data of Bovy (2017) predict about 0.01033 A0V-K4V stars per cubic parsec, and according to that estimation binaries are simulated until the number of objects of corresponding spectral types in a sphere of radius 500 pc attains about 43,300.

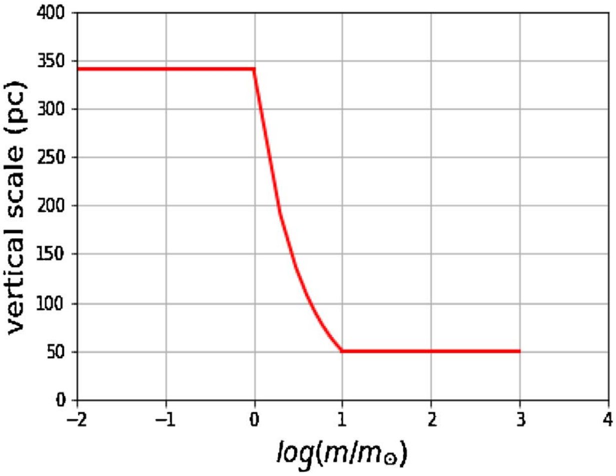

Fig. 1. Vertical scale of the disc vs. logarithm of stellar mass.

2.3. Pairing scenarios

In our simulations, to generate a binary system, it is necessary to accept a pairing scenario (see Kouwenhoven et al. (2009) for discussion of possible scenarios). We have to select two fundamental parameters out of primary mass (m_1), companion mass ($m_2 \le m_1$), total mass ($m_t = m_1 + m_2$), and mass ratio ($q = m_2/m_1$). Two other parameters are then derived. We have adopted three scenarios from Kouwenhoven et al. (2009): *random pairing* (**RP**), *primary constrained pairing* (**PCP**), and *split-core pairing* (**SCP**). We have also considered an additional scenario — *total and primary pairing* (**TPP**).

In **RP**, two masses are drawn randomly and independently from the fundamental mass distribution $N_m(m)$ (see Section 2.4), then the larger one is appointed to be m_1 and the other is m_2. In **PCP**, m_1 is drawn from $N_m(m)$, and q is drawn from mass ratio distribution $N_q(q)$ (see Section 2.5). In **SCP**, m_t and q (where $0 < q \le 1$) are drawn from $N_m(m)$ and from $N_q(q)$, respectively, and then the total mass was split between components with masses $m_1 = m_t(1 + q)^{-1}$ and $m_2 = m_t(1 + q^{-1})^{-1}$. In the scenario **TPP**, m_t and m_1 were drawn from the fundamental mass distribution $N_m(m)$, and individual masses m_1 and m_2 are then derived accordingly. Some of the used scenarios have previously been examined: **RP** was considered by Malkov et al. (1998) for pre-MS and by Malkov and Zinnecker (2001) for MS binaries, while Goodwin (2013) has argued that system mass is the more fundamental physical parameter to use.

It should be noted that in **PCP, SCP**, and **TPP** scenarios companion mass can appear smaller than the lower limit of stellar masses $m_{\min}$, which we set to 0.08 $m_\odot$, (see Section 2.4). In such a case, there are several ways to treat low-mass companions ($m_2 < m_{\min}$). The first one is to accept the low-mass companions, and, consequently, include binaries with substellar mass components into statistics as well. The second one is to reject low-mass companions and consider primary star as a single star. The third one is to redraw one or both randomised parameters (e.g., in **TPP** they are m_t and m_1) until $m_2 \ge m_{\min}$. At last in the fourth way one should re-calculate limits for randomisation of the second parameter, after the first one is drawn (e.g., in **TPP**, when m_t is drawn, m_1 is randomised in the range between $2m_{\min}$ and $m_t - m_{\min}$; and in this case one can be sure that $m_{\min} \ge m_2 \ge m_1$).

One can see that in the third and fourth ways, mass distribution of randomised primary components will differ from the initial $N_m(m)$, as small values of m_1 will be avoided to prevent appearance of “illegal”, too low massuve secondary components ($m_2 < m_{\min}$). It is the case also for the m_t distribution. That is why we have decided to make a treatment according to the first way, and, consequently, accept secondary component with brown dwarf / planet masses (it will be shown later that from observational point of view this is equivalent to the second way, where we deal with single stars).

2.4. Mass distribution

One of the most important clues to the understanding of the origin of stars is provided by initial mass function (IMF), the frequency distribution of stellar masses at birth. The notion of IMF which was introduced by Salpeter (1955) also became a basic function for evolutionary or population synthesis modeling of galaxies.

In the literature, various mass distributions are discussed: besides Salpeter (1955), see Zinnecker (1984), Scalo (1998), Chabrier (2001) and Kroupa (2001a); 2001b). Distribution of stars in solar neighborhood over mass is usually described by power-law, lognormal or piece-linear (in logarithmic scale) function.

In our simulations, as a $N_m(m)$, we use power-law mass functions with masses ranging from 0.08 to 100 $m_\odot$:

$$N_m(m) \sim m^\alpha, \tag{2}$$

where, for Salpeter IMF, $\alpha = -2.35$, and for Kroupa IMF: