The detached-binary channel for the formation of contact binaries

Dengkai Jiang\textsuperscript{1,2,*}, Zhanwen Han\textsuperscript{1,2†}, and Lifang Li\textsuperscript{1,2}

\textsuperscript{1}Yunnan Observatories, Chinese Academy of Sciences, P.O. Box 110, Kunming, Yunnan Province, 650011, China
\textsuperscript{2}Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, P.O. Box 110, Kunming, Yunnan Province, 650011, China

Accepted .... Received ......; in original form ....

ABSTRACT

The detached-binary channel is an important channel for the formation of contact binaries, according to which a detached binary might evolve into contact by evolutionary expansion of the components, or angular momentum loss through the effect of magnetic braking (MB). We have carried out a detailed binary population synthesis (BPS) study of this channel, and obtained the parameter regions for detached binaries to evolve into contact. Combining the observations from the \textit{Kepler} satellite with our results, we found that the ratio of the birth rate of the progenitors of contact binaries to that of contact binaries is greater than about 1.2. This suggests that for the detached-binary channel, the progenitors can be sufficient to produce observed contact binaries. In this channel, we find that the distribution of orbital period for contact binaries has a peak at about 0.25 days and a tail extending to longer periods, and the formation timescale of contact binaries has a large range from \(\sim 1\) Myr to 15 Gyr. These results show that the detached-binary channel could explain satisfactorily the main observational characteristics of contact binaries, in particular the distribution of orbital period shown by the \textit{Kepler} observations and the existence of very young contact binaries.

\textbf{Key words:} stars: activity – binaries: close – stars: formation – stars: evolution

\* E-mail: dengkai@ynao.ac.cn
\† E-mail: zhanwenhan@ynao.ac.cn
1 INTRODUCTION

Contact binaries are interacting binaries in which two components are overflowing their own Roche lobe and share a common envelope. In general, contact binaries show periods from $\sim 0.2$ to $1.5$ d (Geske, Gettel & McKay 2006; Paczynski et al. 2006). They are located near or just above the main sequence (MS) (Bilir et al. 2005) and have the shortest periods possible for binaries consisting of non-degenerate, MS stars (Baliunas & Guinan 1985). Mass transfer and energy transfer between two components of contact binary would make the evolution of the components different from that of single stars (Yakut & Eggleton 2005; Jiang et al. 2009).

Contact binaries form an important class of binaries in several respects. First, they could be used to investigate the merger process of binaries. The recent observation of the remarkable system V1309 Sco gave a direct evidence, for the first time, that contact binaries indeed merge into the single objects (Tylenda et al. 2011). Secondly, contact binaries could be used to study the Galactic structure because they have a high spatial frequency of occurrence, are easy to detect and provide an absolute magnitude calibration (Rucinski 1997). Finally, contact binaries play an important role in stellar evolution as they are possible progenitors for some objects, such as blue stragglers (Eggen 1989; Mateo et al. 1990; Andronov, Pinsonneault & Terndrup 2006; Chen & Han 2008), FK Comae type stars (Webbink 1976a), $\lambda$ Bootis type stars (Andrievsky 1997) and Oe/Be stars (Eggleton 2010; de Mink et al. 2013; Jiang et al. 2013a). Understanding the formation and evolution of contact binaries can help to improve our understanding of the formation of these objects.

The detached-binary channel is an important channel for the formation of contact binaries (Rucinski 1986), according to which a detached binary might evolve into Roche lobe overflow (RLOF), and subsequently into contact, by evolutionary expansion of the components (Webbink 1976b), or by angular momentum loss through the effect of MB (Vilhu 1982). From previous observations, evidence was found that chromospherically active binaries, which are one class of detached binaries, lose angular momentum and evolve towards shorter orbital periods (Demircan 1999; Karatas et al. 2004; Eker et al. 2006). These binaries might be primary candidates for the progenitors of contact binaries (Eker et al. 2006). In addition, the presence of contact binaries in intermediate age and old open clusters implies that they have evolved into contact from detached progenitors (Baliunas & Guinan 1985; Rucinski 1998, 2000; de Marchi et al. 2007; Liu et al. 2011). Therefore, the detached-binary
The formation of contact binaries is considered and investigated as the main formation channel of contact binaries (Rucinski 1986; Li et al. 2007).

However, based on the All-sky Automated Survey (ASAS) data, Paczynski et al. (2006) found that the number of detached binaries with periods $P < 1\,\mathrm{d}$, which are believed to be the progenitors of contact binaries, is insufficient to produce the number of observed contact binaries. Therefore, they suggested that some contact binaries might be formed in triple systems, where the inner binaries with longer orbital period decrease the orbital period by Kozai cycles and tidal friction, and evolve into contact binaries (Eggleton 2001). In addition, Bilir et al. (2005) found a small group of very young (< 0.5 Gyr) contact binaries. They suggested that the very young age of this group does not leave enough time for detached binaries to evolve into contact, and these contact binaries might be formed at the beginning of the main sequence or during the pre-main-sequence contraction phase by a fission process (Roxburgh 1966). van Eyken et al. (2011) found that two contact binaries are candidate members of 25 Ori or Orion OB1a association, and they suggested that the 7 – 10 Myr age of the 25 Ori region is too short for the formation of contact binaries from detached binaries. Therefore, the formation of contact binaries seems to be still an open question.

The detached-binary channel of contact binaries has been investigated by many authors, e.g. Huang (1966), Mestel (1968), van’t Veer (1979), Vilhu (1982), Maceroni & van’t Veer (1991), Stepien (1995, 2011), Demircan (1999), Tukov, Drymonova and Svechnikov (2004), Bilir et al. (2005) and Eker et al. (2006). Vilhu (1982) calculated the period evolution of detached binaries with a total mass $2\,M_\odot$ that evolve into contact by considering the angular momentum loss. He suggested that contact binaries could be produced from detached binaries in old ($\sim 5 \times 10^9\,\mathrm{yr}$) and in intermediate age ($\sim 5 \times 10^8\,\mathrm{yr}$) clusters, but in very young clusters only if the initial period is sufficiently short. Therefore, the formation of contact binaries from detached binaries depends on the initial distribution of parameters of detached binaries (Vilhu 1982; Eker, Demircan & Bilir 2008). Moreover, the rate of angular momentum loss through the effect of MB is another important but rather poorly known factor (Vilhu 1982). The evolution of orbital period determines which detached binary can evolve into contact, and is very different for different models of MB (Vilhu 1982; Bradstreet & Guinan 1994; Stepien 1995). Therefore, further investigation is needed of the detached-binary channel for the formation of contact binaries.

The purpose of this paper is to investigate the formation of contact binary from detached binary by using binary population synthesis. The outline of this paper is as follows. In Section
2. we describe the BPS method. The results are shown in Section 3. Finally, we give the discussion and conclusions in Section 4.

2 BINARY POPULATION SYNTHESIS

In the detached-binary channel, the primary of detached binary would first fill its Roche lobe and transfer some of its mass to the secondary. If the secondary also fills its Roche lobe in response to thermal time-scale or nuclear time-scale mass transfer, these binaries would evolve into contact when both components are still MS stars. To determine whether the binaries evolve into contact, we use Hurley’s rapid binary evolution code (Hurley, Pols & Tout 2000; Hurley, Tout & Pols 2002), and perform seven sets of simulations (see Table 1) in the BPS study. In each simulation, we follow the evolution of $10^6$ sample binaries ($Z = 0.02$) from the star formation to the formation of contact binaries. If both components of a binary are MS stars and fill their Roche lobes, we assume this results in a contact binary, and the properties of the contact binary at the moment of their formation are obtained. In addition, in order to understand the detached-binary channel better, it is more instructive to compare the theoretical distribution of orbital periods and temperatures with that of the observed binaries. Prša et al. (2011) compiled a Eclipsing Binary Catalogue based on the observation of the Kepler space mission. This catalogue is updated by Slawson et al. (2011) and Matijevič et al. (2012), and an online version is maintained at http://keplerEBs.villanova.edu and on Mikulski Archive for Space Telescopes (MAST), http://archive.stsci.edu/kepler. We will compare our results with the observed binaries in this catalogue.

2.1 Monte Carlo simulation parameters

In the BPS study, the Monte Carlo simulations require the following physical input: the initial mass function (IMF) of the primaries, the initial mass-ratio distribution, the distribution of initial orbital separations, the eccentricity distribution of binary orbit, and the star formation rate (SFR) (e.g. Han et al. 2002, 2003; Liu 2009; Wang, Li & Han 2010):

(i) We use a simple approximation to the IMF of Miller & Scalo (1979) and the initial mass of the primary ($M_{10}$) is generated using a formula of Eggleton, Tout & Fitchett (1989),

$$M_{10} = \frac{0.19X}{(1 - X)^{0.75} + 0.032(1 - X)^{0.25}},$$

(1)
where \( X \) is a random number uniformly distributed between 0 and 1. The study of IMF by Kroupa, Tout & Gilmore (1993) supports this IMF.

(ii) We take a constant mass-ratio \((q_0)\) distribution \((\text{set 1, 3-7})\),

\[
n(q_0) = 1, \quad 0 \leq q_0 \leq 1
\]  

(2)

where \( q_0 = M_{20}/M_{10} \), and \( q_0, M_{20} \) are the initial mass ratio and the initial mass of the secondary (Mazeh et al. 1992; Goldberg & Mazeh 1994). In order to study the influence of the mass ratio distribution, we also take an alternative mass-ratio distribution where both components are chosen randomly and independently from the same IMF \((\text{set 2})\).

(iii) We assume that all stars are members of binary systems and that the distribution of separations is constant in \( \log a \) for wide binaries, where \( a \) is the orbital separation and falls of smoothly at small separation

\[
an(a) = \begin{cases} 
\alpha_{\text{sep}} \left( \frac{a}{a_0} \right)^m, & a \leq a_0, \\
\alpha_{\text{sep}}, & a_0 < a < a_1,
\end{cases}
\]  

(3)

where \( \alpha_{\text{sep}} \approx 0.070, a_0 = 10 \, R_\odot, a_1 = 5.75 \times 10^6 \, R_\odot = 0.13 \, \text{pc} \), and \( m \approx 1.2 \). This distribution implies that the numbers of wide binary systems per logarithmic interval are equal, and that about 50% of stellar systems have orbital periods less than 100 yr (Han, Podsiadlowski & Eggleton 1995, HPE95). To investigate the effect of initial distribution of orbital separation, we also take a well-determined period distribution of solar-type MS binaries (Duquennoy & Mayor 1991; Raghavan et al. 2010, DM91,R10), and the orbital period \((P_0)\) is generated using a formula of Eggleton (2006),

\[
P_0 = 5.0 \times 10^4 \left( \frac{X}{1 - X} \right)^{3.3},
\]  

(4)

where \( X \) is a second, independent, random number uniformly distributed between 0 and 1. This distribution is a good fit to the Duquennoy-Mayor distribution (Eggleton 2006).

(iv) A circular orbit is assumed for all binaries.

(v) We assume either a single starburst or a constant SFR over the 15Gyr. For the case of a single starburst, we assume a burst producing \( 10^6 \) binaries to investigate the formation of contact binaries in a star cluster. In the case of a constant SFR, we assume \( \text{SFR} = 5 \, M_\odot \, \text{yr}^{-1} \) in a similar way to the study of supernova rate (Wang, Li & Han 2010).
3.2 The magnetic braking

The rate of angular momentum loss (AML) by magnetic braking (MB) is a very important parameter for the orbital evolution of detached binaries, and therefore for the formation of contact binaries from detached binaries. In simulation set 1, we adopt the AML rate by MB used by Hurley, Tout & Pols (2002, HTP02), which is expressed as

$$\frac{dJ_{\text{MB}}}{dt} = -5.83 \times 10^{-16} q_{\text{conv}} (R\Omega_{\text{spin}})^3 M_\odot R_\odot^2 \text{yr}^{-2},$$

where $q_{\text{conv}}$, $R$ and $\Omega_{\text{spin}}$ are the mass fraction of the surface convective envelope ($M_{\text{env}}/M$), the radius of the component in solar units, and the spin frequency of the component in units of year$^{-1}$.

In order to investigate the effect of the magnetic braking, we also take other descriptions of the AML by MB. In set 4, we adopt the description of AML by MB from Stepień (1995, 2011, S95,S11):

$$\frac{dJ_{\text{MB}}}{dt} = -4.9 \times 10^{41} (R_1^2 M_1 + R_2^2 M_2)/P,$$

where $M_{1,2}$ and $R_{1,2}$ are the masses and radii for the primary and the secondary in solar units, $P$ is the period of binary in days, $J_{\text{MB}}$ is in cgs units and time is in years. This description of MB was derived and calibrated from observations of spin-down of single stars (Stepień 1995), and we assume that the binary systems are in synchronous rotation. In addition, the expression for the AML by MB from Sills, Pinsonneault & Terndrup (2000, SPT00) is used in set 5:

$$\frac{dJ_{\text{MB}}}{dt} = \begin{cases} -K \omega^3 \left( \frac{R}{R_\odot} \right)^{0.5} \left( \frac{M}{M_\odot} \right)^{-0.5}, & \omega \leq \omega_{\text{crit}}, \\ -K \omega_{\text{crit}}^2 \omega \left( \frac{R}{R_\odot} \right)^{0.5} \left( \frac{M}{M_\odot} \right)^{-0.5}, & \omega > \omega_{\text{crit}}, \end{cases}$$

where $K = 2.7 \times 10^{47}$ g cm$^2$ s$^{-1}$ (Andronov, Pinsonneault & Sills 2003), $\omega$ is the angular velocity of synchronized binary, and $M$, $R$ and $\omega_{\text{crit}}$ are the mass of component, the radius of
component and the critical angular velocity at which the angular momentum loss rate reaches a saturated state (Krishnamurthi et al. 1997). This description of the AML by MB adopt a modified Kawaler (1988) AML rate with $N = 1.5$ wind law (Sills, Pinsonneault & Terndrup 2000).

The effect of MB is expected to be reduced when the convective envelope becomes too small (Podsiadlowski, Rappaport & Pfahl 2002), and this is not considered in Equations (6) and (7). Therefore, we add an ad hoc factor $\exp(-0.02/q_{\text{conv}} + 1)$ if $q_{\text{conv}} < 0.02$ in these equations following the suggestion of Podsiadlowski, Rappaport & Pfahl (2002). On the other hand, to investigate the effect of the dependence of MB on $q_{\text{conv}}$, in set 3 we retain the functional dependence of the braking on stellar radius and spin frequency given by Equation (5), but use the ad hoc factor $\exp(-0.02/q_{\text{conv}} + 1)$ instead of $q_{\text{conv}}$ in set 3. For the exponential form in sets 3-5 and 7, the effect of MB is a decrease for stars with mass greater than $\sim 1.0 M_\odot$ (corresponding to $q_{\text{conv}} < 0.02$), while the effect of MB does not depend on $q_{\text{conv}}$ for star with mass smaller than this mass. For the linear form in sets 1 and 2, the effect of MB decreases with decreasing $q_{\text{conv}}$, when the mass of star increases from 0.35 to 1.25 $M_\odot$.

3 RESULTS

3.1 The orbital evolution for the formation of contact binaries

The orbital evolution of detached binaries is very important for the formation of contact binaries in the detached-binary channel. In Fig. 1 we present the evolution of orbital periods of the typical examples in the simulations with different MB models. We do not show the orbital evolution of binary systems in the simulation sets 2 and 7, which are the same as that in the simulation sets 1 and 3. For systems with $M_{10} = 1.5 M_\odot$ and $q = 1.0$ (Fig. 1a), the orbital periods are almost constant. This is because there is no MB effect for the components with mass larger than 1.25 $M_\odot$ that do not have a convective envelope (Hurley, Pols & Tout 2000). Binary systems with very short period ($P_0 = 0.5, 1.0$ d) can evolve into contact by evolutionary expansion of the components while both components are still MS stars. For systems with period $P_0 = 2.0, 3.0$ d, the components do not fill their Roche lobes, and do not evolve into contact before they leave MS.

For systems with the mass of components less than 1.25 $M_\odot$, such as systems with $M_{10} = 1.0, 0.8 M_\odot$ (Figs 1b, c and d), the orbital periods of systems with MB effect (solid, dashed,
dotted and dash-dot curves for set 1, 3, 4 and 5) decrease more quickly than that with no MB effect (dash-dot-dot curves for set 6). This results in the formation of contact binaries for some systems with long period ($P_0 \sim 3\,\text{d}$). However, the results are different for systems with different MB Models. For example, binary systems with $M_{10} = 1.0\,M_\odot$, $q_0 = 1$ and $P_0 = 2.0, 3.0\,\text{d}$ can evolve into contact in set 3, 4 and 5, but not in set 1 as shown in Fig. 1(b). In addition, even in the same MB model, the evolution of the orbital period for systems with $M_{10} = 0.8$ (Fig. 1c) are different from that for systems with $M_{10} = 1.0$ (Fig. 1b). We show the evolution of binary systems in Fig. 1(d) that have different mass ratio ($q_0 = 0.5$) from those in Fig. 1(c). It is obvious that the mass ratio also affects the orbital evolution, and therefore the formation of contact binaries due to the dependence of the magnetic braking on stellar mass.

3.2 Initial parameters for the progenitors of contact binaries

In Fig. 2, we present the initial distribution of detached binaries that produce contact binaries in the $P_0 - M_{10}$ plane. Fig. 2(a) represents the initial parameters of the progenitors of
The formation of contact binaries

Figure 2. The initial distribution of detached binaries from the simulation sets 1-6 in the $P_0 - M_{10}$ plane that produce contact binaries, where $P_0$ is the initial orbital period and $M_{10}$ is the initial mass of the primary.

contact binaries in the simulation with the MB model of Hurley, Tout & Pols (2002) (set 1). For systems with $M_{10} < 0.7 M_\odot$, the primary is deeply convective, and these systems experience unstable mass transfer (Hurley, Tout & Pols 2002). Therefore, they can not form stable contact binaries (Jiang et al. 2012). It should be noted that this mass limit for deeply convective stars is not a sharp limit but a gradual transition (Politano 1996), and therefore this limit for the formation of contact binaries is also not as sharp as assumed, but depends on the mass ratio (Jiang et al. 2012). The lower limit of the initial orbital period (left boundary) for the formation of contact is about $0.22 - 0.5$ d, which is set by the condition of initial
orbital period that neither of the components fills the Roche lobe at birth. The upper limit of
the initial orbital period (right boundary) depends on the initial mass of the primaries,
and is caused by the constraints that detached binaries have to evolve into contact in 15Gyr
and that both components are still MS stars. The upper limit of the initial orbital period
decreases from 1.8 d at $M_{10} \sim 0.7 \, M_\odot$, to $\sim 1.0$ d at $M_{10} \sim 1.3 \, M_\odot$ due to the decreasing
fraction of the convective envelope, which leads to a weaker MB. The simulation with a
mass-ratio distribution with uncorrelated binary components (set 2) has a similar region to
set 1 as shown in Fig. 2(b), although the number is smaller. This is because more binary
systems have very small mass ratios, and the secondaries merge into the primaries following
the onset of RLOF due to dynamical mass transfer (Hurley, Tout & Pols 2002).

Fig. 2(c) shows the distribution of the formation of contact binaries for the simulation
(set 3) with different expression of the mass fraction of the convective envelope in the MB
model from set 1. The main difference between this set and the previous one (set 1) is that
for systems with the mass of the primaries less than $\sim 1.3 \, M_\odot$, the upper limit of the initial
orbital period is about $3 - 3.5$ d, and is much longer than that in set 1. We also note that
the upper limit of the initial orbital period in the simulations with the MB model of Stepien
(1995, 2011) (set 4) and the MB model of Sills, Pinsonneault & Terndrup (2000) (set 5) are
similar to that in set 3, and are much longer than that in set 1 as shown in Figs 2(d) and
(e). The maximum value of the upper limit of the initial orbital period is about 3.7 d in set
(4), and 4.2 d in set (5). This suggests that the expression for the dependence of MB on $q_{\text{conv}}$
has a great influence on the formation of contact binary. We do not show the distribution
of the formation of contact binaries in set 7 that is similar to the distribution in set 3.

Fig. 2(f) shows the distribution of the formation of contact binaries for the simulation
with no MB (set 6). It is shown that for systems with $M_{10} > 1.3 \, M_\odot$, the distribution is
similar to that in other sets. However, for systems with $M_{10} < 1.3 \, M_\odot$, the upper limit of
initial orbital period is about $0.6 - 1$ d, which is significantly shorter than that in other sets.
Therefore, only detached binaries with very short orbital period could evolve into contact if
systems have low mass primaries. This suggests that the effect of MB is important for the
formation of contact binaries with low mass components.
Figure 3. The distribution of the progenitors of contact binaries in the $P_0 - T_0$ plane that produce contact binaries, where $P_0$ is the initial orbital period and $T_0$ is the zero-age main-sequence effective temperature of the primary. Solid curves mark the region for detached binaries that evolve into contact.

Figure 4. The distribution of the observed detached eclipsing binaries in the Eclipsing Binary Catalogue [Prša et al. 2011; Slawson et al. 2011; Matijević et al. 2012]. Solid curves show the parameter region for detached binaries that evolve into contact in set 1 as shown in Fig. 3, and dashed, dotted, dash-dot and dash-dot-dot curves show the parameter regions in simulation sets 3 – 6.

3.3 Progenitors of contact binaries: comparison with observations

In order to understand the detached-binary channel better, we compare our theoretical distribution of progenitors of contact binaries with that of the observed detached binaries in the Eclipsing Binary Catalogue given by [Prša et al. 2011], Slawson et al. (2011) and Matijević et al. (2012). Fig. 3 shows the theoretical distribution of initial orbital period ($P_0$)–initial temperature ($T_0$) for detached binaries in set 1 that evolve into contact, where $T_0$ is taken as the zero-age main-sequence effective temperature of the primary. Solid curves mark the parameter region for detached binaries that evolve into contact. In Fig. 4 we plot the distribution of observed detached binaries in the Eclipsing Binary Catalogue [Prša et al. 2011; Slawson et al. 2011; Matijević et al. 2012], where $T_{\text{KIC}}$ is the Kepler Input Catalog.
effective temperature. The curves show the regions for detached binaries that evolve into contact in different simulations sets.

It is apparent that many observed detached binaries are located in the formation region of contact binaries as shown in Fig. 4. For the simulation with no MB (set 6), the number of detached binaries in the formation region of contact binaries is 75. In the simulations (set 1, 3, 4 and 5) considering the effect of MB, the numbers are 179, 312, 292 and 331, respectively. These detached binaries might be the progenitors of contact binaries, and their number seems to be comparable to the number of observed contact binaries, which is 469 in the Eclipsing Binary Catalogue (Prša et al. 2011; Slawson et al. 2011; Matijević et al. 2012). In addition, detached binaries located outside of the formation region of contact binaries can not result in stable contact binaries.

To estimate whether the progenitors of contact binaries are sufficient to produce the number of observed contact binaries, we roughly derive the actual ratio of the number of observed progenitors of contact binaries to that of observed contact binaries by taking into account observational selection effects. The detection probability of contact binaries should be independent of orbital period in first order approximation, because the size of the Roche lobe is proportional to the orbital separation. Then, for contact binaries at a given orbital period $P$, the observed number $N_{\text{obs,con}}(P)$ can be expressed as

$$N_{\text{obs,con}}(P) = b \times N_{0,\text{con}}(P),$$

where $b$ is a (constant) detection probability for contact binaries, and $N_{0,\text{con}}(P)$ is the actual number of contact binaries with orbital period $P$. Maceroni & Rucinski (1999) suggested that the probability of discovering an eclipsing system scales as the inverse square of its orbital separation, $\propto a^{-2} \propto P^{-4/3}$. Therefore, for detached progenitor binaries at a given orbital period $P$, the observed number $N_{\text{obs,pro}}(P)$ can be obtained by

$$N_{\text{obs,pro}}(P) = c \times P^{-\frac{4}{3}} \times N_{0,\text{pro}}(P),$$

where $c$ is a constant, and $N_{0,\text{pro}}(P)$ is the actual number of detached progenitor binaries with orbital period $P$. We assume that $N_{\text{obs}}(P) = 1$ for each binary in the Eclipsing Binary Catalogue. Then, for the contact binary population and their progenitor population of detached binaries, their actual numbers can be expressed as

$$N_{\text{con}} = \sum N_{0,\text{con}}(P_i) = \sum \frac{1}{b} \quad i = 1, n_{\text{con}},$$

and
The formation of contact binaries

\[ N_{\text{pro}} = \sum N_{0,\text{pro}}(P_j) = \sum \frac{1}{c \times P_j^{\frac{4}{3}}} \quad j = 1, n_{\text{pro}}, \]  

where \( n_{\text{con}} \) and \( n_{\text{pro}} \) are the observed numbers of contact binaries and the progenitors of contact binaries in the Eclipsing Binary Catalogue.

We can obtain a lower limit of the actual ratio of the number of progenitors of contact binaries to that of contact binaries without the values of \( b \) and \( c \). The range of inclinations for which a contact binary can be detected is larger than that for a detached binary with same orbital period and stellar masses, if the orientations of the orbital planes are assumed to be randomly distributed for contact binaries and detached binaries. This is because both components of contact binaries overfill their Roche lobes, while both components of detached binaries are inside their Roche lobes. Therefore, the detection probability for a contact binary should be larger than that of a detached binary at any orbital period, in other words: \( b > c \times P^{-4/3} \) for any value of \( P \). Then, we obtain

\[ N_{\text{con}} = \sum \frac{1}{b} < \sum \frac{1}{c \times P_i^{\frac{4}{3}}} \quad i = 1, n_{\text{con}}. \]  

Finally, we can get a lower limit of the ratio \( N_{\text{pro}} / N_{\text{con}} \), and for simulation set 3, this ratio is larger than about 2.5.

To compare the birth rates of the progenitor population with that of the contact binary population, the relative lifetimes in the detached and contact phases also need to be considered. For the detached binaries that evolve into contact in the simulation set 3, the mean lifetime of detached phase is about 2.1 Gyr. Jiang et al. (2013b) show that the lifetime of contact phase is about 4%-10% of the main sequence lifetime of the primaries. We adopt the middle value 7%, and get the lifetimes of contact phase for every contact binaries in simulation set 3. The mean lifetime of contact phase is about 1.04 Gyr for these contact binaries. Therefore, the ratio of the lifetime of detached phase to that of contact phase is \( \approx 2 \). Combining the lower limit to the ratio \( N_{\text{pro}} / N_{\text{con}} \), the ratio of the birth rate of the progenitors of contact binaries to that of contact binaries is estimated roughly to be greater than about 1.2.

3.4 The distribution of orbital periods of contact binaries

Fig. 5 shows the distribution of orbital period of contact binaries at the moment of the formation for simulation sets 1 – 7. The distribution of contact binaries has a peak around 0.25 d and a long tail extending beyond 1 d. This peak comes from contact binaries mainly
formed by the effect of MB, although the formation of these contact binaries might be also affected by evolutionary expansion of the components. The number of contact binaries in this peak strongly depends on the models of MB, the dependence of MB on $q_{\text{conv}}$, the initial mass-ratio distribution and the initial orbital period distribution. In Fig. 6 we compare the distribution of the orbital period in simulation set 3 with that of observed contact binaries in the Eclipsing Binary Catalogue (Prša et al. 2011; Slawson et al. 2011; Matijević et al. 2012). The distribution of observed contact binaries also show a peak and a tail extending to longer periods. This is similar to the theoretical distribution in the detached-binary channel. However, it should be noted that the distribution of observed contact binaries has a translation to longer period, and its peak is located at $P \sim 0.35 \, \text{d}$.
3.5 The distribution of contact binaries in $P - T$ diagram

We compare the distribution of theoretical contact binaries with that of the observed contact binaries in orbital period-temperature plane. Fig. 7 shows the theoretical distribution of contact binaries at the moment of their formation, and the temperature of contact binaries ($T$) is obtained according to $T^4 = (R_1^2 T_1^4 + R_2^2 T_2^4)/(R_1^2 + R_2^2)$, where $R_1, R_2, T_1$ and $T_2$ are the radii and the effective temperatures of the primary and the secondary at the moment of the formation of contact binaries. Solid curves mark the region of the distribution of contact binaries at the moment of their formation. For clarity, we only show the distribution for the simulation of set 3, as the other simulations give similar results. In Fig. 8, we present the distribution of observed contact binaries in the Eclipsing Binary Catalogue given by Prša et al. (2011), Slawson et al. (2011) and Matijević et al. (2012). Solid curves are the region of the theoretical distribution of contact binaries given by Fig. 7. It is obvious that the distribution of the theoretical contact binaries is in agreement with the observations,
although the observed contact binaries in the highest-density region have longer orbital period, higher temperature than the theoretical contact binaries. This difference will be discussed in Section 4.

It is noted that there is no observed contact binaries with $T_{\text{KIC}} < 4000$ K in Fig. 8, although there are some detached binaries with $T_{\text{KIC}} < 4000$ K shown in Fig. 4 and about 59 candidates of detached binaries with two M dwarfs found by Becker et al. (2011). These detached binaries with very low mass would experience unstable mass transfer and could not form stable contact binaries (Jiang et al. 2012). In Fig. 8, some observed systems are far away from the theoretical region, in the upper-left corner ($P < 0.2$ d and $T_{\text{KIC}} > 6000$ K) and the lower-right corner ($P > 0.5$ d and $T_{\text{KIC}} < 5000$ K), and they might not be contact binaries. For the systems in the upper-left corner, the high temperature is hard to reconcile with the binaries with $P < 0.2$ d that should have M-dwarf components. They might be the class of ellipsoidal variable that exhibit sinusoidal variations (Prša et al. 2011). In the lower-right corner, the evolutionary effects can not produce such low temperature systems from systems with $T_{\text{KIC}} > 6000$ K, or produce such long period systems from systems with $P < 0.4$ d (Rubenstein 2001). These systems in the lower-right corner might have aliased periods (Rucinski 1998).

### 3.6 The birth rate of contact binaries

Fig. 9 displays the evolution of the birth rates of contact binaries for a single starburst of $10^6$ in each simulation sets. In this figure, we see that the birth rate of contact binaries is in the range from $1.7 \times 10^{-8}$ yr$^{-1}$ to $1.7 \times 10^{-5}$ yr$^{-1}$, and the formation timescale of contact binaries has a large range from $\sim 1$ Myr to 15 Gyr. The birth rates are $0.1 - 1.7 \times 10^{-5}$ yr$^{-1}$.
at 1 – 30 Myr. For age older than about 30 Myr, the birth rate decreases with increasing age. Fig. 10 shows birth rates of contact binary for a constant SFR. The simulations in set 3-5 give a birth rate of $2.5 - 3.1 \times 10^{-2}$ yr$^{-1}$ for a population older than 10 Gyr. However, the birth rates are lower in the simulations with different expression for the dependence of MB on $q_{\text{conv}}$ (set 1), different initial mass-ratio distribution (set 2), different initial period distribution (set 7) or no MB (set 6).

In order to investigate the characteristics of young contact binaries and old contact
binaries, we show the $P - T$ distribution of contact binaries at various ages of their formation for a single starburst in Fig. 11. It shows that the region of contact binaries decreases significantly with increasing age. The young contact binaries at an age of 0–2 Gyr can occur in the region of temperature from 4000 to 9000 K, while old contact binaries at 10–15 Gyr have a temperature lower than 6000 K. Moreover, the upper limit of orbital period decreases from > 1 d at 0–2 Gyr to 0.65 d at 10–15 Gyr.

4 DISCUSSION AND CONCLUSION

In this paper, we investigated the detached-binary channel for the formation of contact binaries by carrying out a detailed binary population synthesis study. We obtained the parameter region for detached binaries that evolve into contact and the distribution of contact binaries at the moment of their formation.

The formation of contact binaries in the detached-binary channel depends on many uncertain input parameters. The main uncertainty lies in the evolution of orbital period affected by MB. We found that the dependence of MB on $q_{\text{conv}}$ have a significant influence on the evolution of orbital period of detached binaries, and therefore on the binary parameter space that produces contact binaries, the prominent peak in the distribution of orbital periods and the birth rate of contact binaries. In addition, we varied the initial mass-ratio distribution to investigate the dependence of the formation of contact binaries on this model parameter. The mass-ratio distribution for uncorrelated component masses (set 2) is more likely to have a very low mass secondary, as compared to the constant initial mass-ratio distribution (set 1). This leads to dynamically unstable mass transfer in most cases (Han et al. 2003). As a result, the birth rate of contact binaries is greatly reduced as shown in Fig. 9 and Fig. 10. The initial orbital period distribution is another important parameter, and it affects very much the distribution of orbital period of contact binaries and the birth rate of contact binaries. This is because fewer detached binaries located in the region of the formation of contact binary in set 7 lead to fewer contact binaries formed.

Paczynski et al. (2006) considered detached binaries with $P < 1$ d might be the progenitors of contact binaries, and found that the number of these observed detached binaries appear to be insufficient to produce the number of observed contact binaries based on ASAS data. By considering the effect of MB, we found that for detached binaries that evolve into contact, the upper limit of the initial orbital period could reach about 3–4.2 d. Our results
agree with the suggestion given by Vilhu (1982) that the typical progenitors of contact binaries are detached binaries with periods initially shorter than 4 d. Combining the Eclipsing Binary Catalogue (Prša et al. 2011; Slawson et al. 2011; Matijević et al. 2012), we found that the ratio of the birth rate of the progenitors of contact binaries to that of contact binaries is greater than about 1.2. Therefore, for the detached-binary channel, the progenitors can be sufficient to produce observed contact binaries.

Slawson et al. (2011) found that the period distribution of contact binaries in the Eclipsing Binary Catalogue has a prominent peak and a broader component. We found that the period distribution of contact binaries formed in the detached-binary channel has a peak and a long tail extending beyond 1 d, which is very similar to that of the observed contact binaries as shown in Fig. 6. Contact binaries in the peak are mainly formed by the effect of MB, and this prominent peak results from the decrease of AML rate with increasing orbital period and the short-period limit produced by unstable mass transfer. For the tail beyond 0.5 d, almost all contact binaries are produced by evolutionary expansion of the components. Therefore, the detached-binary channel can explain the shape of the period distribution of the observed contact binaries with a peak and a long tail.

We found a translation of observed contact binaries to longer period relative to the theoretical contact binaries in the distribution of orbital period, and a difference in $P - T$ diagram that the observed contact binaries in the highest-density region have longer orbital period, higher temperature than the theoretical contact binaries. A partial explanation might be that low-mass stars have larger radii than assumed in the models. Observations show that the sub-solar-mass components of detached binaries have significantly larger radii than single-star models (Torres, Andersen and Giménez 2010). Another reason might be that we compute the theoretical distribution of contact binaries at the moment of their formation. The components just fill their Roche lobes and are not in good thermal contact. The period of contact binaries is expected to increase when two components reach good thermal contact (Li, Han & Zhang 2004a,b, 2005). More importantly, in the subsequent evolution of contact binaries, the mass ratio becomes smaller and the mass of the primaries (the massive components) increase during the cyclic evolution of thermal relaxation oscillation (Robertson & Eggleton 1977; Li, Han & Zhang 2004b). This leads to an increase of orbital period from 0.29 to 0.37 d when the mass ratio decreases from 0.6 to 0.22 as shown by Rahnen (1981). In addition, as the primary mass increases, the temperature of contact binaries would increase. Hence, the observed contact binaries in the highest-density region
in $P - T$ diagram have longer orbital period, higher temperature than our model contact binaries.

In the detached-binary channel, the formation timescale of contact binaries has a large range from $\sim 1$ Myr to 15 Gyr for a single starburst. Therefore, the detached-binary channel can explain the formation of contact binaries in intermediate-age or old cluster as suggested by Rucinski (1998). Furthermore, this channel can explain the existence of very young contact binaries, such as a population of ($< 0.5$ Gyr) contact binaries in Moving Group (kinematically coherent group of stars that share a common origin) (Bilir et al. 2005), and two contact binaries as candidate members 25 Ori or Orion OB1a association with age of $7 - 10$ Myr (van Eyken et al. 2011), which are believed too young to be formed by detached binaries. In addition, it is found that the birth rate of contact binaries decreases with increasing age for age older than about 30 Myr. The main reason is that binaries with massive components have short MS lifetime. With the increase of time, the range of the primary mass decreases for detached binaries with two MS components that might evolve into contact. Moreover, the decrease of primary mass range results in the decrease of the upper limit of temperature and the upper limit of orbital period as shown in Fig. 11. Therefore, at the moment of the formation of contact binaries, young contact binaries could have larger range of period and temperature than old contact binaries.

In our study, we did not consider the evolution of contact phase, which has been investigated and discussed by many authors, e.g. Webbink (1976a,b), Kähler (2002a,b, 2004), Li, Han & Zhang (2004a,b, 2005) and Yakut & Eggleton (2005). The evolution of contact binaries should be considered in the further BPS study of the detached-binary channel. In addition, the effect of the third body might be also important and should be considered because it could make more binaries with longer period evolve into the formation region of contact binaries in the detached-binary channel.

ACKNOWLEDGEMENTS

It is a pleasure to thank an anonymous referee for his/her many suggestions and comments which considerably improved the paper. We thank Dr. Andrej Prša for his great help. This work was supported by the Chinese Natural Science Foundation (11073049, 11033008, 11103073 and 11373063) and the Western Light Youth Project.
REFERENCES

Andrievsky S. M., 1997, A&A, 321, 838
Andronov N., Pinsonneault M., Sills A., 2003, ApJ, 582, 358
Andronov N., Pinsonneault M. H., Terndrup D. M., 2006, ApJ, 646, 1160
Baliunas S. L., Guinan E. F., 1985, ApJ, 294, 207
Becker A. C., Bochanski J. J., Hawley S. L., Ivezic Z., Kowalski A. F., Sesar B., West A. A., 2011, ApJ, 731, 17
Bilir S., Karataş Y., Demircan O., Eker Z., 2005, MNRAS, 357, 497
Bradstreet D. H., Guinan E. F., 1994, ASPC, 56, 228
Chen X., Han Z., 2008, MNRAS, 384, 1263
de Marchi F. et al., 2007, A&A, 471, 515
de Mink S. E., Langer N., Izzard R. G., Sana H., de Koter A., 2013, ApJ, 764, 166
Demircan O., 1999, Tr. J. Phys., 23, 425
Duquennoy A., Mayor M., 1999, A&A, 248, 485 (DM91)
Eggen O. J., Iben I. Jr., 1989, AJ, 97, 431
Eggleton P. P., 2006, Evolutionary Processes in Binary and Multiple Systems. Cambridge Univ. Press, Cambridge
Eggleton P. P., 2010, New Astron. Rev., 54, 45
Eggleton P. P., Fitechett M. J., Tout C. A., 1989, ApJ, 347, 998
Eggleton P. P., Kiseleva-Eggleton L., 2001, ApJ, 562, 1012
Eker Z., Demircan O., Bilir S., Karataş Y., 2006, MNRAS, 373, 1483
Eker Z., Demircan O., Bilir S., 2008, MNRAS, 386, 1756
Geske M. T., Gettel S. J., McKay T. A., 2006, AJ, 131, 633
Goldberg D., Mazeh T., 1994, A&A, 282, 801
Han Z., Podsiadlowski Ph., Eggleton P. P., 1995, MNRAS, 272, 800 (HPE95)
Han Z., Podsiadlowski Ph., Maxted P. F. L., Marsh T. R., Ivanova N., 2002, MNRAS, 336, 449
Han Z., Podsiadlowski Ph., Maxted P. F. L., Marsh T. R., 2003, MNRAS, 341, 669
Huang S. S., 1966, ARA&A, 4, 35
Hurley J. R., Pols O. R., Tout C. A., 2000, MNRAS, 315, 543
Hurley J. R., Tout C. A., Pols O. R., 2002, MNRAS, 329, 897 (HTP02)
Jiang D., Han Z., Jiang T., Li L., 2009, MNRAS, 396, 2176
Jiang D., Han Z., Ge H., Yang L., Li L., 2012, MNRAS, 421, 2769
Jiang D., Han Z., Yang L., Li L., 2013a, MNRAS, 428, 1218
Jiang D., Han Z., Yang L., Li L., 2013b, IAUS, 290, 229
Kähler H., 2002a, A&A, 395, 899
Kähler H., 2002b, A&A, 395, 907
Kähler H., 2004, A&A, 414, 317
Karataş Y., Bilir S., Eker Z., Demircan O., 2004, MNRAS, 349, 1069
Kawaler S. D., 1988, ApJ, 333, 236
Krishnamurthi A., Pinsonneault M. H., Barnes S., Sofia S., 1997, ApJ, 480, 303
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
Li L., Han Z., Zhang F., 2004a, MNRAS, 351, 137
Li L., Han Z., Zhang F., 2004b, MNRAS, 355, 1383
Li L., Han Z., Zhang F., 2005, MNRAS, 360, 272
Li L., Zhang F., Han Z., Jiang D., 2007, ApJ, 662, 596
Liu J., 2009, MNRAS, 400, 1850
Liu L., Qian S., Zhu L., He J., Liao W., Li L., Zhao E., Wang J., 2011, MNRAS, 415, 3006
Maceroni C., Rucinski S. M., 1999, AJ, 118, 1819
Maceroni C., van’t Veer F., 1991, A&A, 246, 91
Mateo M., Harris H., Nemec J., Olszewski E., 1990, AJ, 100, 469
Matijević G., Prša A., Orosz J. A., Welsh W. F., Bloemen S., Barclay T., 2012, AJ, 143, 123
Mazeh T., Goldberg D., Duquennoy A., Mayor M., 1992, ApJ, 401, 265
Mestel L., 1968, MNRAS, 138, 359
Miller G. E., Scalo J. M., 1979, ApJS, 41, 513
Paczyński B., Szczęśniak D. M., Pilecki B., Pojmanski G., 2006, MNRAS, 368, 1311
Podsiadlowski Ph., Rappaport S., Pfahl E. D., 2002, ApJ, 565, 1107
Politano M., 1996, ApJ, 465, 338
Prša A. et al., 2011, AJ, 141, 83
Raghavan D. et al., 2010, ApJS, 190, 1 (R10)
Rahnen T., 1981, A&A102, 81
Robertson J. A., Eggleton P. P., 1977, MNRAS, 179, 359
Roxburgh I. W., 1966, ApJ, 143, 111
Rubenstein E. P., 2001, AJ, 121, 3219
Rucinski S. M., 1986, in Cottrell P. L., Hearndshaw J. B., eds, Proc. IAUSymp. 118, Instrumentation and Research Programmes for Small Telescopes. Reidel, Dordrecht, p. 159
Rucinski S. M., 1997, AJ, 113, 407
Rucinski S. M., 1998, AJ, 116, 2998
Rucinski S. M., 2000, AJ, 120, 319
Sills A., Pinsonneault M. H., Terndrup D. M., 2000, ApJ, 534, 335 (SPT00)
Slawson R. W. et al., 2011, AJ, 142, 160
Stępień K., 1995, MNRAS, 274, 1019 (S95)
Stępień K., 2011, Acta Astron., 61, 139 (S11)
Torres G., Andersen J., Giménez A., 2010, A&ARv, 18, 67
Tutukov A. V., Dremova G. N., Svechnikov M. A., 2004, Astron. Repor., 48, 219
Tylenda R. et al., 2011, A&A, 528, 114
van Eyken J. C. et al., 2011, AJ, 142, 60
van’t Veer F., 1979, A&A, 80, 287
Vilhu O., 1982, A&A, 109, 17
Wang B., Li X., Han Z., 2010, MNRAS, 401, 2729
Webbink R. F., 1976a, ApJ, 209, 829
Webbink R. F., 1976b, ApJS, 32, 583
Yakut K., Eggleton P. P., 2005, ApJ, 629, 1055

This paper has been typeset from a \TeX/ \LaTeX file prepared by the author.