The short-period limit of contact binaries

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ABSTRACT

The stability of mass transfer is important in the formation of contact binaries from detached binaries when the primaries of the initially detached binaries fill their Roche lobes. Using Eggleton’s stellar evolution code, we investigate the formation and the short-period limit of contact binaries by considering the effect of the instability of mass transfer. It is found that with decreasing initial primary mass from 0.89M$_\odot$ to 0.63M$_\odot$, the range of the initial mass ratio decreases for detached binaries that experience stable mass transfer and evolve into contact. If the initial primary mass is less than 0.63M$_\odot$, detached binaries would experience dynamically unstable mass transfer when the primaries of detached binaries fill their Roche lobes. These systems would evolve into a common envelope situation and probably then to a complete merger of two components on a quite short timescale. This results in a low mass limit at about 0.63M$_\odot$ for the primary mass of contact binaries, which might be a main reason why the period distribution of contact binaries has a short limit of about 0.22 days. By comparing the theoretical period distribution of contact binaries with the observational data, it is found that the observed contact binaries are above the low mass limit for the primary mass of contact binaries and no observed contact binaries are below this limit. This suggests that the short-period limit of contact binaries can be explained by the instability of the mass transfer that occurs when the primaries of the initially detached binaries fill their Roche lobes.

Key words: instabilities – binaries: close – binaries: eclipsing – stars: evolution–stars: formation
1 INTRODUCTION

Contact binaries are the most common eclipsing binaries in the solar neighborhood (Shapley 1948). The period distribution of contact binaries has a range from 0.22d to more than 100d, but a strong maximum near 0.37d that is very close to a short-period limit at about 0.22d (Rucinski 1992, 1998, 2007; Paczynski et al. 2006). The shortest period sky-field contact binary currently known is GSC 01387-00475 (ASAS 083128+1953.1) which has a period of 0.2178 d (Rucinski 2007, 2008). The existence of this system confirms that the short-period limit of contact binaries at about 0.22d is very sharp and well defined (Rucinski 2008), although a shorter contact binary V34 is in globular cluster 47 Tuc with $P=0.2155$d (Weldrake et al. 2004). It is an interesting puzzle to determine why contact binaries have a very well-defined short-period limit. Moreover, understanding the reason of this limit helps to improve our understanding of the theory of stellar and binary evolution with low mass components.

The short-period limit of contact binaries has been investigated by many authors (Rucinski 1992, 2007, 2008; Stepień, Schmitt & Voges 2001; Stepień 2006; Paczynski et al. 2006). Rucinski (1992) attempted to explain the short-period limit by the full convection limit for low-mass stars that the fully convective configuration leads to a strong limit on the parameters of contact binaries. But he found that the full convection limit is some distance from the reddest observed contact systems and he suggested that the full convection limit is not the main reason of the short-period limit.

A traditional view for the formation of contact binaries is that they are formed from detached binaries of comparable periods. Recently, Stepień (2006) investigated the timescale of detached binaries for reaching a stage of Roche lobe overflow (RLOF), and hence for forming contact binaries. He found that for a detached system with initial mass of the primary of $0.7M_\odot$ and initial period of 2d, the timescale for reaching RLOF is greater than the age of the Universe because the angular momentum loss (AML) timescale increases with decreasing stellar mass. Therefore, he suggested that the short-period limit of 0.22d of contact binaries corresponds to a lower limit of around $1.0 - 1.2M_\odot$ for the total mass of the system and is due to the finite age of the binary population forming contact systems of several Gyr. However, observations show that there are some short-period detached (or semidetached) binaries below the total mass limit, such as OGLE BW3 V38 ($P=0.198$d,
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Maceroni & Montalbán (2004), GSC 2314-0530 ($P=0.192$ d, Dimitrov 2010), NSVS 01031772 ($P=0.37$ d, Lopez-Morales et al. 2006), GU Boo ($P=0.49$ d, Lopez-Morales & Ribas 2005). The existence of these systems suggests that the AML rate is higher than that postulated by Stepień (2006), or such low-mass binaries could have very short periods at birth. Therefore, the short-period limit of contact binaries could not be explained completely by the finite age of the binary population forming contact systems of several Gyr suggested by Stepień (2006). It seems that further investigation is needed in the formation of contact binaries from detached binaries in order to confirm the reason of the short-period limit.

Nelson & Eggleton (2001) constructed a large grid of models ($0.8 M_\odot \leq M_{10} \leq 50 M_\odot$) of case A binary evolution, according to the assumption of conservative evolution. They showed that in case AR (rapid evolution to contact) and AS (slow evolution to contact), the secondary expands in response to the thermal-timescale mass transfer or the nuclear timescale mass transfer from the primary and fills its own Roche lobe before either component has left the main sequence (MS). They suggested that this probably leads to a contact binary. However, in case AD (dynamic RLOF), the radius of the primary increases faster (or decreases more slowly) than the Roche lobe when RLOF begins. Mass transfer is dynamically unstable and quickly accelerates to the dynamic mass transfer. The secondary can not accrete all the proffered material. This probably leads to complete engulfment of the secondary, creating a common envelope binary (Paczyński 1976; Hjellming & Webbink 1987). These systems might coalesce on a quite short timescale (Eggleton 2000; Nelson & Eggleton 2001) and could not form contact binaries. The instability of mass transfer has been studied in the past (Hjellming & Webbink 1987; Ge et al. 2010; Deloye & Taam 2010). Ge et al. (2010) show that the instability of mass transfer may occur promptly upon the primary filling its Roche lobe, if the primary has a surface convection zone of any significant depth. MS stars with $M < 1.25 M_\odot$ have a convective envelope and the mass of convective envelope increases with decreasing mass of stars (Hurley, Pols & Tout 2000). This means that the instability of mass transfer needs to be taken into account in investigating the formation of contact binaries from detached binaries with less massive components.

The purpose of this study is to investigate the period limit of contact binaries. Employing the Eggleton stellar evolution code, we construct a grid of binary models for a Population I metallicity $Z=0.02$. We compare the observational data with the theoretical period distribution of contact binaries, and find that the short-period limit could be explained by the
instability of mass transfer that occurs when the primaries of the initially detached binaries fill their Roche lobes.

2 THE SHORT-PERIOD LIMIT OF CONTACT BINARIES

In the formation of contact binary from detached binary, the primary of detached binary fills its Roche lobe and transfers some of its mass to the secondary. The secondary would expand to fill its Roche lobe and the system come into contact. To determine whether the mass transfer rate reaches the dynamic timescale before the secondary fills its Roche lobe, it is necessary to perform detailed binary evolution calculations. Here we use Eggleton’s stellar evolution code to study the instability of mass transfer in the formation of contact binaries from detached binaries. This code was originally developed by Eggleton (1971, 1972) and Eggleton, Faulkner & Flannery (1973) and has been updated with the latest input physics during the last four decades (e.g. Han, Podsiadlowski & Eggleton 1994; Pols et al. 1995, 1998; Nelson & Eggleton 2001; Eggleton & Kiseleva-Eggleton 2002). The current code includes a model of dynamo-driven mass loss, magnetic braking, and tidal friction to the evolution of stars with cool convective envelopes, and the simplification is considered that only the primary is subject to these nonconservative effects (Eggleton & Kiseleva-Eggleton 2002). Considering these nonconservative effects, we construct a grid of stellar evolutionary models that covers the following ranges of initial primary mass $M_{10}$ and initial mass ratio $(q_0 = M_{20}/M_{10})$:

\[
\begin{align*}
\log M_{10} & = -0.25, -0.2, -0.19, -0.15, -0.1, -0.05, \\
\log(1/q_0) & = 0.25, 0.2, 0.15, 0.1, 0.05, 0.02.
\end{align*}
\]

We present one initial period, log $(P_0/P_{ZAMS})=0.5$, where $P_{ZAMS}$ is the period at which the initially more massive component would just fill its Roche lobe on the zero-age main sequence (Nelson & Eggleton 2001).

In Fig.1, we present four examples (solid lines) of our binary evolution calculations with log$(1/q_0)=0.1$ ($q_0=0.79$) after the primaries fill their Roche lobes. It shows the radius ratio of the primary $(R_1/R_c$, where $R_1$ and $R_c$ are the radius of the primary and the Roche lobe radius of the primary) and the mass transfer rate $(dM/dt)$. Figs 1(a) and (b) represent the evolution of a binary system with an initial mass of the primary of $\log M_{10} = -0.05$ ($M_{10}=0.89M_\odot$). The primary fills its Roche lobe on the MS which results in case A RLOF.
The ratio of $R_1/R_c$ increases slower after this value is greater than 0.0012 as shown in Fig 1(a). Then, the mass transfer is stable and the mass-transfer rate does not increase quickly as shown in Fig 1(b). Nelson & Eggleton (2001) suggested that the mass transfer is determined to be dynamic when the mass-transfer is greater than $10M/t_{KH}$ ($t_{KH}$ is the thermal or Kelvin-Helmholtz timescale), which is shown as dotted line in Fig 1. The mass-transfer rate of this system is not beyond the dotted line before the secondary fills its Roche lobe and this system evolves into contact shown as filled star. Figs 1(c) and (d) show another example for an initial system with log $M_{10} = -0.1$ ($M_{10}=0.79M_\odot$). The binary evolves in a similar way as in the previous example and the main difference between this example and the previous one is the ratio of $R_1/R_c$ roughly constant after the value is greater than 0.0017.

Figs 1(e) and (f) represent the third example for initial system with log $M_{10} = -0.15$ ($M_{10}=0.71M_\odot$). Fig 1(g) and (h) represent the last example for initial system with log $M_{10} = -0.2$ ($M_{10}=0.63M_\odot$). In these two systems, the radius ratio of the primary ($R_1/R_c$) increases quickly after the onset of RLOF. This leads to the mass-transfer rate that increases sharply, and is beyond the dotted line. Hence the mass transfer becomes dynamically unstable. Such
systems might evolve into a common envelope situation and probably coalescence on a quite short timescale (Eggleton 2000, Nelson & Eggleton 2001).

Fig. 2 summarizes the final outcome of binary evolution calculations in the initial mass ratio-primary mass \((q_0, M_{10})\) plane. Crosses show systems that are unstable to dynamical mass transfer and filled stars indicate systems that do not experience the dynamical instability and evolve into contact. It is seen from Fig. 2 that with decreasing initial mass of the primaries from 0.89\(M_\odot\) to 0.63\(M_\odot\), the range of the initial mass ratio decreases for detached binaries that experience stable mass transfer and evolve into contact, and the range of initial mass ratio increases for detached binaries such that the mass transfer is on the dynamical timescale. If the initial primary mass is less than 0.63\(M_\odot\), the initially detached binaries would suffer dynamically unstable mass transfer.

**Figure 2.** Final outcomes of the binary evolution calculations in the initial mass ratio-primary mass \((q_0, M_{10})\) plane. Crosses denote the systems that experience the dynamical instability and filled stars indicate contact binaries are formed without experiencing the dynamical instability as shown in Fig 1.

**Figure 3.** The theoretical distribution of the period and the primary mass of binaries when they evolve into contact (filled stars) and that of binaries that experience the dynamical instability (crosses). Open stars show the position of observed contact binaries, open square and open triangles represent observed semidetached binary and observed detached binaries, respectively.
Table 1. The physical parameters of some binaries with short period.

| Stars                  | Type | \(P\) (d) | \(M_1\) (\(M_\odot\)) | \(M_2\) (\(M_\odot\)) | \(R_1\) (\(R_\odot\)) | \(R_2\) (\(R_\odot\)) | References |
|------------------------|------|------------|-------------------------|-------------------------|--------------------------|--------------------------|------------|
| GSC 01387-00475        | C    | 0.2178     | 0.638                   | 0.392                   | -                        | -                        | (1)        |
| CC Com                 | C    | 0.221      | 0.79                    | 0.41                    | 0.73                     | 0.54                     | (2)        |
| V523 Cas               | C    | 0.2337     | 0.75                    | 0.38                    | 0.74                     | 0.55                     | (3)        |
| BI Vul                 | C    | 0.2518     | 0.86                    | 0.59                    | 0.82                     | 0.7                      | (2)        |
| VZ Psc                 | C    | 0.2612     | 0.79                    | 0.72                    | 0.77                     | 0.74                     | (2)        |
| FS Cra                 | C    | 0.2636     | 0.86                    | 0.65                    | 0.82                     | 0.73                     | (2)        |
| FG Sct                 | C    | 0.2706     | 0.87                    | 0.68                    | 0.83                     | 0.73                     | (2)        |
| XY Leo                 | C    | 0.2841     | 0.82                    | 0.50                    | 0.86                     | 0.69                     | (4)        |
| TZ Boo                 | C    | 0.2976     | 0.72                    | 0.11                    | 0.97                     | 0.43                     | (4)        |
| V829 Her               | C    | 0.3582     | 0.856                   | 0.372                   | 1.058                    | 0.718                    | (5)        |
| F1 Boo                 | C    | 0.39       | 0.82                    | 0.31                    | 1.1                      | 0.71                     | (6)        |
| BH Cas                 | C    | 0.4059     | 0.73                    | 0.35                    | 1.09                     | 0.78                     | (7)        |
| GSC 2314-5530          | SD   | 0.192      | 0.51                    | 0.26                    | 0.55                     | 0.29                     | (8)        |
| OGLE BW3 V38           | D    | 0.198      | 0.44                    | 0.41                    | 0.51                     | 0.44                     | (9)        |
| NSVS 01031772          | D    | 0.37       | 0.54                    | 0.50                    | 0.53                     | 0.51                     | (10)       |
| NSVS 07453183          | D    | 0.37       | 0.73                    | 0.68                    | 0.79                     | 0.72                     | (11)       |
| V405 And               | D    | 0.465      | 0.49                    | 0.21                    | 0.78                     | 0.23                     | (12)       |
| GU Boo                 | D    | 0.49       | 0.61                    | 0.60                    | 0.62                     | 0.62                     | (13)       |
| NSVS 06507557          | D    | 0.51       | 0.65                    | 0.28                    | 0.60                     | 0.44                     | (14)       |
| 2MASS 04463285+1901432  | D    | 0.62       | 0.47                    | 0.19                    | 0.56                     | 0.21                     | (15)       |
| YY Gem                 | D    | 0.81       | 0.60                    | 0.60                    | 0.62                     | 0.62                     | (16)       |

Columns: Stars-name of star; Type-type of binary configuration (C = contact, SD = semidetached, D = detached); \(P\)-orbital period; \(M_1\)-mass of the primary; \(M_2\)-mass of the secondary; \(R_1\)-radius of the primary; \(R_2\)-radius of the secondary.

References in Table 1: (1) Rucinski (2008); (2) Maceroni & vant Veer (1996); (3) Zhang & Zhang (2004); (4) Yakut & Eggleton (2005); (5) Gazeas et al. (2005); (6) Terrell et al. (2006); (7) Zola, Niachars & Dapergolas (2001); (8) Dimitrov & Kjurkchieva (2010); (9) Maceroni & Montalbán (2004); (10) Lopez-Morales et al. (2006); (11) Coughlin & Shaw (2007); (12) Vida et al. (2009); (13) Lopez-Morales & Ribas (2005); (14) Cakirly & Ibanoglu (2010); (15) Hebb et al. (2006); (16) Bopp (1974), Torres & Ribas (2002).

Fig. 3 shows the theoretical distribution of the period and the primary mass of the binaries when they evolve into contact (filled stars) and that of binaries that experience the dynamical instability (crosses). It is seen in Fig. 3 that the theoretical period of binaries that experience the dynamical instability could be as short as 0.165d (log\(P\) = −0.781). The theoretical period of contact binaries has a low limit at about 0.20d (log\(P\) = −0.698), which results from the low mass limit at about 0.63M\(\odot\) for the primary mass of contact binaries (solid line). This suggests that the distribution of the period of contact binaries depends on the formation of contact binaries, and then on the stability of mass transfer when the primaries of detached binaries fill their Roche lobes.

In addition, we collected the physical parameters of some binaries with short period where both components are MS stars from literature (listed in Table 1). These observed systems are also plotted in Fig. 3 with open symbols (open stars = contact binaries, open square = semidetached binary, open triangles = detached binaries). As seen from Fig. 3, the observed contact binaries are above the low mass limit for the primary mass of contact binaries. There are no observed contact binaries below this limit. We also note that one semidetached binary and some detached binaries are below this limit.
We compare the orbital evolution of the initially detached binaries in our model with that in the model based on the AML rate given by Stepień (2006). They are shown in Fig. 4 for the systems with log $M_{10} = -0.25$, log $1/q_0 = 0.25$, and $P_0 = 0.46, 1.0, 2.0\text{d}$. It is seen from Fig. 4 that the initially detached binaries in our model (solid lines) reach RLOF more rapidly than those in model based on Stepień’s AML rate (dotted lines). For example, a system with an initial period $P_0 = 1.0\text{d}$ in the model adopting Stepień’s AML rate spends a much longer time ($\sim 8\text{Gyr}$) to reach RLOF than that in our model ($\sim 0.25\text{Gyr}$). This suggests that the AML rate assumed by Stepień (2006) is much lower than the rate used in this study in Eggleton & Kiseleva-Eggleton (2002).

3 DISCUSSION AND CONCLUSIONS

In this paper, we investigated the short-period limit of contact binaries by using the Eggleton stellar code with considering the effect of the instability of mass transfer that occurs when the primaries of detached binaries fill their Roche lobes.

Stepień (2006) suggested that the short-period limit might be caused by the fact that the initially detached binaries with low-mass components do not have time to reach RLOF even within the age of the Universe since the AML timescale increases with decreasing stellar mass. However, this could not explain the existence of the short-period low-mass binary systems, such as V405 And. This suggests that the AML rate is underestimated by Stepień (2006), or some low-mass binaries could have a very short orbital period at their birth. We found that contact binaries have a low mass limit at about $0.63M_\odot$ for the primary mass due to the instability of the mass transfer when the primaries of the initially detached binaries...
fill their Roche lobes. This suggests that the formation of contact binaries depends on the stability of mass transfer when the primaries of detached binaries fill their Roche lobes.

The distribution of the period of contact binaries depends on the formation of contact binaries, and then on the stability of mass transfer when the primaries of detached binaries fill their Roche lobes. By comparing the theoretical period distribution of contact binaries with the observational data as shown in Fig 3, it is found that the observed contact binaries are above the low mass limit for the primary mass of contact binaries and no observed contact binaries are below this limit. This means that the observed contact binaries might be formed from detached binaries that experience stable mass transfer and the short-period limit of contact binaries can be explained by the instability of the mass transfer that occurs when the primaries of detached binaries fill their Roche lobes. We also note that one semidetached binary (GSC 2314-0530) and some detached binaries are below this limit. These systems would experience unstable mass transfer and coalescence on a quite short timescale. This suggests that GSC 2314-0530 might be still a detached binary as suggested by Norton et al. (2011), but the primary might be very close to its Roche lobe.

Our study showed that contact binaries have a low mass limit at about 0.63M\(_\odot\) for the primary mass due to the instability of the mass transfer. It should be noted that the range of the initial mass ratio is very narrow for systems (\(M_{10} \leq 0.7M_\odot\)) that do not experience dynamically unstable mass transfer. This might be the reason why there is only one contact binary GSC 01387-004750 (Rucinski 2008) where the primary mass is smaller than 0.7M\(_\odot\). Tout et al. (1997) and Hurley, Pols & Tout (2002) suggested that mass transfer to a component proceeds dynamically if the primaries are low-mass MS stars (\(M \leq 0.7M_\odot\)) that are deeply convective. Our result is not much different from the suggestion given by Tout et al. (1997) and Hurley, Pols & Tout (2002).

In this paper we only presented a grid of stellar evolutionary models with one initial period to study the stability of mass transfer in the formation of contact binaries. But many parameters, such as the initial period, the metallicity, the mass loss, etc., are related to the stability of mass transfer, which is also affected by the detailed process of mass transfer. The effects of these parameters need to be taken into account in the future study of the stability of mass transfer and the formation of contact binaries.
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