MERGER BY MIGRATION AT THE FINAL PHASE OF COMMON ENVELOPE EVOLUTION
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ABSTRACT

I find the common envelope (CE) energy formalism, the CE $\alpha$-prescription, to be inadequate to predict the final orbital separation of the CE evolution in massive envelopes. I find that when the orbital separation decreases to $\sim 10$ times the final orbital separation predicted by the CE $\alpha$-prescription, the companion has not enough mass in its vicinity to carry away its angular momentum. The core-secondary binary system must get rid of its angular momentum by interacting with mass further out. The binary system interacts gravitationally with a rapidly-rotating flat envelope, in a situation that resembles planet-migration in protoplanetary disks. The envelope convection of the giant carries energy and angular momentum outward. The basic assumption of the CE $\alpha$-prescription, that the binary system’s gravitational energy goes to unbind the envelope, breaks down. Based on that, I claim that merger is a common outcome of the CE evolution of AGB and red super-giants stars with an envelope to secondary mass ratio of $M_{\text{env}}/M_2 \gtrsim 5$. I discuss some other puzzling observations that might be explained by the migration and merger processes.

1. INTRODUCTION

The common envelope (CE) process is in the heart of the formation of many close binary systems (e.g., Iben & Livio 1993; Taam & Sandquist 2000; Podsiadlowski 2001; Webbink 2008; Taam & Ricker 2010). During the CE phase the orbital separation decreases due to gravitational drag and tidal interaction (e.g., Iben & Livio 1993; Ricker & Taam 2012). The transfer of orbital energy and angular momentum to the envelope, as well as other possible energy sources, lead to the ejection of the envelope. One of the major unsolved questions of the 36 years old (Paczynski 1976; van den Heuvel 1976) CE process is the final orbital separation.

In the commonly used energy formalism of the CE the gravitational energy released by the spiraling-in binary system $E_G$, is equated to the envelope binding energy (e.g., Webbink 1984; Tauris & Dewi 2001), $E_{\text{bind}}$, with an efficiency $\alpha$: $\alpha E_G = E_{\text{bind}}$. This is termed the CE $\alpha$-prescription. It is now a common practice to include the internal energy of the envelope in calculating the binding energy (e.g. Han et al. 1994; Maxted et al. 2002; Zorotovic et al. 2016; Xu & Li 2016; Davis et al. 2011), and some authors argue for observational support for that (e.g., Rebassa-Mansergas et al. 2001). Ivanova & Chaichenets (2011) suggest that the enthalpy rather than the internal energy should be included in calculating the binding energy.

The basic assumption of the CE $\alpha$-prescription is that the binding energy is channelled to eject the envelope in a uniform manner (for a thorough discussion of this prescription and other aspects of the CE evolution see Ivanova et al. 2012). Namely, there is no separation between envelope parts. This assumption was put into question by Kashi & Soker (2011) in cases where the final CE phase is a rapid process. While some studies do suggest rapid final evolution, (e.g., Rasio & Livio 1996; Livio & Soker 1988), on the order of days to few weeks, others argue for a final phase that lasts for months (e.g., Sandquist et al. 1998; De Marco et al. 2003, 2009; Passy et al. 2011; Ricker & Taam 2012). In any case, Kashi & Soker (2011) studied the rapid deposition of energy in the very inner regions of a massive envelope of an asymptotic giant branch (AGB) star, and found that a substantial fraction of the ejected mass does not reach the escape velocity. Kashi & Soker (2011) used a self-similar solution and followed the blast wave propagation from the center of the AGB outwards. They showed that $\sim 1 – 10$ per cent of the ejected envelope remains bound to the remnant binary system. They further argued that the bound gas falls-back and forms a circumbinary disc around the post-CE binary system.

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The interaction of the circumbinary disc with the binary system will reduce the orbital separation much more than expected in the CE $\alpha$-prescription. The smaller orbital separation favors a merger at the end of the CE phase or a short time after, while the core is still hot. A different mechanism for merger at the termination of the CE phase was suggested by Ivanova & Chaichenets (2011).

A support to the separation of the envelope to ejected and bound segments comes from numerical simulations as well, e.g., Lombardi et al. (2006). Sandquist et al. (1998) showed that some of the mass of the envelope can remain bound to one or both of the interacting stars. They simulated a 5 $M_\odot$ AGB interacting with a 0.6 $M_\odot$ companion, and found that the companion unbinds $\sim 1.55$ $M_\odot$ ($\simeq 23$ per cent) of the AGB envelope. They also obtained a differentially rotating thick disk or torus at intermediate stages of the CE evolution. Soker (1992) (see also Soker 2004) had analytically obtained a similar thick disk structure. In these cases a rapid merging is expected as well. Passy et al. (2011) present more extreme results in their simulations. They find that when the envelope is lifted away from the binary $\gtrsim 80$ per cent of the envelope remains bound to the binary. In their simulations rotation of the AGB was not included, so the material that remains bound is probably overestimated. They conclude that in some cases parts of the AGB envelope remain bound or marginally bound to the remnant post-AGB core. De Marco et al. (2011) suggest that envelope material which is still bound to the binary system at the end of the CE will fall back onto the system and will form a circumbinary disk. They suggest that such a disk might have some dynamical effects on the binary period.

Ricker & Taam (2012) performed 3D numerical simulation of a low mass binary composed of a 1.05$M_\odot$ red giant and a 0.6$M_\odot$ companion. Although the AGB envelope mass is much lower than the masses considered here, some results are relevant. Ricker & Taam (2012) find that during the rapid inspiral phase (the plunge-in phase; see Ivanova et al. 2012) only a fraction of $\sim 25\%$ of the energy released by the spiraling-in process goes toward ejection of the envelope. The mass loss rate at the end of their simulation is $\sim 2M_\odot$ yr$^{-1}$. As mentioned, Passy et al. (2011) find that most of the envelope stays bound at the end of their simulations (on the comparison between the simulations of Passy et al. 2011 and Ricker & Taam 2012 see Ivanova et al. 2012). These results might imply that for a white dwarf (WD) companion of mass $\sim 0.6M_\odot$ inside an AGB star of mass $> 4M_\odot$, the envelope can stay bound for few years after the orbital separation has shrunk to several solar radii. At the end of the simulation the envelope is concentrated around the equatorial plane of the binary system. This result of a rapidly rotating disk-like envelope structure is one of the motivations for the present paper.

In the present paper I put into question some basic assumptions of the CE $\alpha$-prescription. I do not dispute that the CE helps in ejecting the envelope. However, most of the gravitational energy is released near the final expected separation. There, I argue in section 2 some assumptions of the CE $\alpha$-prescription break down. Despite that, the CE $\alpha$-prescription might give a crude estimate of the final separation in cases that don’t end up in merger. The final migration to merger is discussed in section 3, and a phenomenological toy model is proposed in section 4. Summary and implications for some puzzling observations are discussed in section 5.

2. INTERACTION DEEP IN THE COMMON ENVELOPE

The density profile of AGB stellar envelopes can be approximated by $\rho(r) \propto r^{-\beta}$ where $\beta \simeq 2 - 2.4$. For the purpose of this paper it is adequate to take for the envelope density

$$\rho(r) = \rho_0 \left( \frac{r}{r_0} \right)^{-2.2} = \frac{0.8 \ M_{\text{env}}}{4\pi \ R_\ast^2} \left( \frac{r}{R_\ast} \right)^{-2.2},$$

where $\rho_0$ is the density at a reference radius $r_0$, $M_{\text{env}}$ is the envelope mass, and $R_\ast$ is the stellar radius. The envelope mass inside radius $r$ is given by

$$M_{\text{er}}(r) = M_{\text{env}} \left( \frac{r}{R_\ast} \right)^{0.8} = 0.33 \left( \frac{r}{10R_\odot} \right)^{0.8} \left( \frac{M_{\text{env}}}{5M_\odot} \right) \left( \frac{R_\ast}{300R_\odot} \right)^{-0.8} M_\odot. \tag{2}$$

The binding energy of the envelope is given by the expression

$$E_{\text{bind}} = 0.5 \int_{r_m}^{R_\ast} \frac{G[M_{\text{core}} + M_{\text{er}}(r)]}{r} \frac{4\pi r^2 \rho(r) dr}{4\pi r^2 \rho(r) dr}, \tag{3}$$
where the factor 0.5 comes from the usage of the virial theorem and \( M_{\text{core}} \) is the core mass. Because the integration diverges at low radii for the simple model used here, the binding energy is calculated for the envelope residing above radius \( r_m \sim 1R_\odot \). Performing the integration then gives the binding energy

\[
E_{\text{bind}}(r_m) = \frac{GM_{\text{env}}M_{\text{core}}}{R_\ast} \frac{2}{3} \left( \frac{M_2}{M_{\text{env}}} \right)^{0.2} \left( 3 - \frac{R_a}{r_m} \right)^{-0.6} \equiv \frac{GM_{\text{env}}M_{\text{core}}}{R_\ast} \Gamma,
\]

where the second equality defines \( \Gamma \). For a typical values of \( M_{\text{env}} \simeq 5M_\odot, M_{\text{core}} \simeq 0.7M_\odot, R_\ast \simeq 300R_\odot \) and \( r_m \simeq 1R_\odot \), we find \( \Gamma \simeq 9 \).

According to the CE \( \alpha \)-prescription the final orbital separation would be determined by the equality \( 0.5\alpha GM_{\text{core}}M_2/a_\alpha = E_{\text{bind}} \), where \( M_2 \) is the secondary mass and \( a_\alpha \) the final separation according to the \( \alpha \) prescription. This gives

\[
a_\alpha = 0.01\alpha \frac{M_2}{0.2M_{\text{env}}} \left( \frac{\Gamma}{10} \right)^{-1}.
\]

Substituting \( a_\alpha \) in equation (2) gives the envelope mass inner to that radius

\[
\frac{M_{\text{env}}(a_\alpha)}{M_2} = 0.13\alpha^{0.8} \frac{M_2}{0.2M_{\text{env}}} \left( \frac{\Gamma}{10} \right)^{-0.8}.
\]

For this scaling we find that \( M_{\text{env}}(2a_\alpha) = 0.22M_2 \) and \( M_{\text{env}}(3a_\alpha) = 0.3M_2 \), and that \( M_{\text{env}}(r) = M_2 \) at \( r = 13a_\alpha \). This result implies the following for CE inside evolved red giant stars (AGB, RGB, etc.). As the orbital separation shrinks to \( \sim 10a_\alpha \), the companion has not enough mass in its vicinity to carry away its angular momentum. Hence, the interaction with the gas in the vicinity of the companion cannot cause much further spiralling-in, and no gravitational energy is liberated to unbind the envelope. At this point the so called plunge-in phase, where the spiraling is dynamical and rapid (see Ivanova et al. 2012), must end. The core-secondary binary system must get rid of its angular momentum by interacting with mass residing at \( r > a_\alpha \), where \( a \) is the orbital separation at the given moment. In other words, local interaction with the envelope gas at a typical distance of the Bondi-Hoyle-Lyttleton accretion radius and tidal interaction with the mass residing at \( r < a \), cannot cause further spiralling-in. The binary system interacts gravitationally with a rapidly-rotating flat envelope (Ricker & Taam 2012), where flat envelope refers to a highly oblate envelope structure. This situation becomes more like the planet-migration process in protoplanetary disks rather than the hydrodynamical interaction of a secondary star in the classical prescription of a CE. At this stage the flat envelope dissipates the energy deposited by the spiralling-in binary system, and creates heat that can be transferred outward by convection. The basic assumption of the CE \( \alpha \)-prescription, that the binary systems gravitational energy goes to unbind the envelope, breaks down.

This discussion raises questions about the entire CE \( \alpha \)-prescription. Problems for the CE \( \alpha \)-prescription in explaining observations were noted before, e.g., Nelemans & Tout (2005), Nelemans & Tout (2005) find the CE\( -\gamma \) prescription to better fit observations. In the CE\( -\gamma \) prescription (Nelemans et al. 2000) the angular momentum released by the spiralling-in binary system is assumed to be carried away by mass loss. The CE\( -\gamma \) prescription also seems to break-down at \( a \sim 10a_\alpha \), for the same reason the CE\( -\alpha \) does: there is not enough mass in the vicinity of the secondary and inward to transfer the angular momentum to. In any case, the CE\( -\gamma \) prescription has other severe problems (Ivanova et al. 2012).

### 3. Migration-Induced Merger

The conclusion from the above discussion is that when the orbital separation inside RGB and AGB stars decreases to a radius where \( M(a) \sim M_2 \), which occurs at \( a \gg a_\alpha \), the spiraling-in process substantially slows down. Here as before, \( a \) is the binary separation and \( a_\alpha \) is the final separation predicted by the CE \( \alpha \)-prescription. Although numerical simulations do not always find rapid envelope rotation or a very flattened envelope (e.g., Passy et al. 2011), I assume here that after the slowing down of the spiraling-in process, such a state will be achieved. The binary system transfers angular momentum to the rapidly-rotating circumbinary flat envelope, and
consequently the average radius of the envelope expands, and the binary separation decreases and the eccentricity increases (e.g., Artymowicz et al. 1991). I assume that the structure of the flattened envelope crudely resembles the structure of the disk studied in Artymowicz et al. (1991). In the calculations of Artymowicz et al. (1991) the disk extends from the nearest stable circumbinary orbit of \( \sim 2.5a \) up to \( 6a \). I assume that the binary orbit is circular (\( e_0 = 0 \)). Scaling the results of Artymowicz et al. (1991) by values appropriate for the present study gives the rate of change of the semi-major axis

\[
\frac{\dot{a}}{a} \approx -4.5 \times 10^{-5} \left( \frac{q_d}{0.1} \right) \Omega_b,
\]

where

\[
\Omega_b = \sqrt{\frac{G(M_{\text{core}} + M_2)}{a^3}} = 2.7 \left( \frac{a}{1R_\odot} \right)^{-3/2} \left( \frac{M_{\text{core}} + M_2}{1.4M_\odot} \right)^{1/2} \text{yr}^{-1}
\]

is the binary orbital angular velocity, and

\[
q_d = \frac{M_{\text{er}}(6a)}{M_{\text{core}} + M_2}.
\]

Here \( M_{\text{er}}(6a) \) is the envelope mass inner to \( r = 6a \). The spiraling-in timescale at \( a = 1R_\odot \) with this scaling is

\[
\tau_{\text{in}} \equiv \frac{a}{\dot{a}} \approx 1 \left( \frac{q_d}{0.1} \right)^{-1} \left( \frac{a}{1R_\odot} \right)^{3/2} \left( \frac{M_{\text{core}} + M_2}{1.4M_\odot} \right)^{-1/2} \text{yr}
\]

The Keplerian (orbital) time decreases with decreasing separation, but then so does the mass in the flattened envelope. The time scale of a year is long enough to allow the convective envelope to transport the heat outward. Therefore, instead of expelling the entire envelope, the spiraling-in process increases the luminosity. The wind mass loss rate might increase substantially, but a large portion of the envelope will stay bound in systems where the initial envelope mass is \( M_{\text{env}} \gtrsim \text{several} \times M_2 \). The binary system will merge.

Equation (7), although crude for our case, none the less seems to be adequate for the present goals. In a very recent paper Shi et al. (2012) performed 3D magnetohydrodynamic (MHD) simulations of a circumbinary disk surrounding an equal mass binary system. Similar to earlier studies, they find that strong torques by the binary clear a gap of radius \( \sim 2a \). The binary system gains angular momentum by accretion from the disk, and loses it by the gravitational torque. Over all the orbital separation decreases. We note that the accretion rate onto the two stars in the present study is expected to be very low, or practically zero, due to the high pressure around the core of the AGB star. To the contrary, mass is expected to flow outward. Although the torque found by Shi et al. (2012) is much larger than the one used in the \( \alpha_{\text{d}}-\text{viscosity} \) models (not to be confused with the CE--\( \alpha \)), because of the opposite effect of accretion they find the spiraling-in rate to be only a factor of \( \sim 3 \) higher than found here. The numerical coefficient in equation (7) according to Shi et al. (2012) is \( -8 \times 10^{-5} \). The difference is of no significance for the goal of the present paper.

For type II migration, where the planet is relatively massive and a gap is opened in the disk, the migration rate is limited by viscous transport in the disk. The rate given by Alibert et al. (2005), for example (their eq. 19), gives a similar value to that in equation (7) here when the \( \alpha_{\text{d}}-\text{viscosity} \) coefficient is taken to be \( \alpha_{\text{d}} \approx 0.01-0.1 \). The same holds for the type II migration expression derived by Nelson et al. (2000), for example.

Over all, I conclude that the timescale for the final spiralling-in process for systems with \( M_{\text{env}} \gtrsim \text{several} \times M_2 \) is practically the viscous time scale in the flattened envelope. The major contribution to the viscosity is convection. This implies that on the same time scale that the binary system spirals in, the convection transport the released gravitational energy out. Instead of being used to expel the entire envelope, the released binary gravitational energy is radiated away. The increase in luminosity will substantially expand the envelope and increase mass loss from the surface. However, mass will stay in the vicinity of the binary system, and might lead to a merger (also Kashi & Soker 2011). A different process, based on the reexpansion of gas above the core and inner to the secondary orbit, that might lead to merger was discussed by Ivanova (2011), as well as other papers dealing with post-CE merger, though, do use the energy formalism for the CE ejection (the CE \( \alpha \)-prescription). Here the fundamental assumptions of the CE \( \alpha \)-prescription are criticized.
4. A PHENOMENOLOGICAL SCENARIO

The termination of the CE phase with a core-secondary binary system interacting with material further out is likely to be more violent than the migration of a planet (and more complicated). Here I demonstrate a simple phenomenological approach as a demonstration of a plausible alternative to the CE α-prescription at the phase when the mass inward to the secondary is less than the mass of the secondary. At this preliminary stage this should be considered more as a toy model rather than an established process.

I assume that bound mass is falling toward the binary system. No real disk is formed, but rather when the bound gas gets to a distance of \( \eta a \), where \( \eta \approx 1 \), from the binary system it acquires energy and escapes. For simplicity consider the case where the core and secondary mass are about equal, \( M_{\text{core}} \approx M_2 \). If the secondary mass is much below that of the core, the interaction will not be violent, and migration, more like planet migration, takes place. Consider that the core-secondary system interacts with bound gas of mass \( M_b \), part of which fell to the center, at a typical distance \( a \) from the center of mass. Each binary component is at a distance of \( a/2 \) from the center of mass. As the core and secondary come closer to each other, so does the surrounding bound gas. The binary system ejects the gas. Namely, the gas that is ejected carries a specific energy of \( dE_b \approx G(M_{\text{core}} + M_2)/(\eta a) \). The change in orbital separation is given by energy conservation

\[
d \left( \frac{G M_{\text{core}} M_2}{a} \right) \approx \frac{G(M_{\text{core}} + M_2)}{\eta a} dM_b,
\]

where \( M_b \) is the ejected mass from the binary vicinity (hence increases with time). Integration of the left hand side from the orbital separation \( a_b \) at the time the circumbinary interaction phase starts to a final orbital separation \( a_f \), and the right hand side from zero to \( M_b \), yields, for \( M_{\text{core}} = M_2 \),

\[
a_f \approx a_b e^{-4M_b/\eta M_t} = a_b (0.018)^{M_b/\eta M_t},
\]

where \( M_t = M_{\text{core}} + M_2 \).

In this toy model the final orbital separation is very sensitive to the circumbinary bound mass present when the migration starts. I emphasize again that this toy model applies only when the secondary mass is not much smaller than the primary mass. For \( a_b = 10R_\odot \) and \( \eta = 1 \), for example, the final orbital separation in this toy model is \( a_f = 3.7R_\odot \), \( 1.4R_\odot \), \( 0.5R_\odot \), and \( 0.2R_\odot \), for \( M_b/M_t = 0.25, 0.5, 0.75, \) and \( 1 \), respectively. The last two orbital separations might lead to a rapid merger.

5. DISCUSSION AND SUMMARY

In the previous sections I questioned the basic assumption of the common envelope (CE) energy formalism (the CE α-prescription), and found it to be inadequate to predict the final orbital separation of the CE evolution in massive envelopes. The CE α-prescription might help as long as the envelope mass inward to the location of the secondary is larger than the secondary mass. This does not occur in the inner region when a massive envelope is involved, as evident from equation (10). Based on that, I claim that merger is a common outcome of the CE evolution of AGB and red super-giants stars with an envelope to secondary mass ratio of \( M_{\text{env}}/M_2 \gtrsim 5 \). Many binary systems do survive of course. Here \( M_{\text{env}} \) is the envelope mass at the beginning of the CE phase.

Mergers at the termination of the CE phase were discussed before (e.g., Ivanova & Podsiałowski 2003; Ivanova 2011), as well as the slowing down of the spiraling-in process when the separation is small (see discussion in Ivanova & Podsiałowski 2003). However, these authors and many others do use the CE energy formalism. In the energy formalism of the CE the binary gravitational energy that is released is equated to the envelope binding energy. Most of the binary gravitational energy is released very deep in the envelope. It was found here that where most of the gravitational energy is supposed to be released, there is not enough local envelope mass to absorb the energy released by the binary system (for AGB stars with \( M_{\text{env}}/M_2 \gtrsim 5 \)). The energy must be absorbed by material residing further out in the flattened envelope, a process that proceeds on a viscous time scale, as with migration of planets inside disks. Viscosity is supplied by the convective envelope. The convective
speed in AGB stars is close to the sound speed, and the same convective motion can transport the energy out. A large fraction of the released energy will go to increase the luminosity and inflate the envelope, rather than to expel the inner parts of the envelope.

Merger at the termination of the CE phase might explain some puzzling observations. I list here several of these, each of which deserve much deeper study. I do not list all possible outcomes of CE mergers, e.g., the formation of high-field Magnetic WDs (Tout et al. 2008; García-Berro et al. 2012) and NS-BH mergers (e.g., Dominik et al. 2012), but rather limit myself to those scenarios that are theoretically less developed.

The Core-Degenerate (CD) scenario for Type Ia supernovae. Sparks & Stecher (1974) developed a merger scenario of a WD with an AGB core, in which the result is a type II SN. In a later study Livio & Riess (2003) found that the merger of a WD with an AGB core can lead to a SN Ia that occurs at the end of the CE phase or shortly after. Hydrogen lines will appear, and hence they attribute such a scenario to a rare type of SNe Ia. Kashi & Soker (2011) and Ilkov & Soker (2012) argue for a long time delay between the CE merger and the SN Ia explosion due to a long spin-down process, and termed it the core-degenerate (CD) scenario for SN Ia. They argue that this scenario might account for most SNe Ia. An important conclusion of Livio & Riess (2003) and Kashi & Soker (2011) is that for merger to occur the AGB star should be massive. As explained in Soker (2011), the CD scenario has some key differences from the double-degenerate scenario for SNe Ia, and hence should be referred to as a separate scenario.

R Coronae Borealis stars with a massive expanding shell. The two leading models for the formation of R Coronae Borealis stars are a final-helium-shell flash of a post-AGB star and two WDs merger. In a recent paper Clayton et al. (2011) find R Coronae Borealis to have signatures that are expected from both a WD merger and from a final-helium-shell flash (see also Kameswara Rao & Lambert 2011). The relatively high inferred mass of R Coronae Borealis and its high fluorine abundance support the merger model, while the massive, $\sim 2M_\odot$, expanding shell supports the final-helium-shell flash model. I raise here the possibility that R Coronae Borealis and similar R CrB stars are formed from the merger of a WD with the core of an AGB star.

The bright edge of the planetary nebula luminosity function (PNLF). The bright edge of the PNLF in old and young stellar populations is the same (for a recent paper see Ciardullo 2012). Two scenarios were suggested to account for the puzzling finding that old stellar populations have as bright planetary nebulae (PNs) as young stellar populations do. One is that the bright part of the PNLF in old populations comes from blue-stragglers (Ciardullo 2012), namely, merger of main sequence stars. The other one is that the brightest PNs in old populations are systems in transition from a symbiotic nebula phase to the PN phase (Soker 2006). Here I raise the following scenario to account for bright PNs in old stellar population. In a system of two low mass stars, the more massive lost its envelope to its companion while on the red giant branch (RGB). A helium WD of $\sim 0.2 - 0.3M_\odot$ is formed. Later, when the secondary becomes an AGB star, the WD remnant of the primary star merges with the AGB core before the hydrogen-rich envelope is lost. The now more massive core can ionize the nebula to form a bright PN. This speculative scenario deserves more detailed study.

The formation of single sdB stars. Extreme horizontal branch star (EHB; also termed sdB or sdO stars) are horizontal branch stars that have lost most of their envelope at the end of the RGB phase. Many sdB stars have a close stellar companion that went through CE phase. This explains the envelope ejection (e.g., Han et al. 2003). However, many others might be formed through a CE phase with a substellar companion (Soker 1998). Although some substellar companions might survive the CE phase, there are recent indications that many of the substellar companions merge with the RGB core (Geier et al. 2011).

Ultraluminous core collapse SNe. There are hints that some ultraluminous core collapse SNe experience an extreme mass loss episode $\sim 1 - 100$ yr before explosion (e.g., Chomiuk et al. 2011; see discussion in Chevalier 2012). I speculate that this coincidence can be caused by a companion that spirals-in inside the envelope and collides with the core. The CE process causes the extreme mass loss rate, while the collision with the core expedites the evolution toward explosion. The companion can be a few solar masses main sequence star, or a neutron star. A similar idea was put forward simultaneously by Chevalier (2012). This speculative scenario will be studied in a future paper.
Complicated planetary nebula structures. The CE merger can lead to a PN with very complicated structures. The PN NGC 5189, for example, has a very complicated structure (Sabin et al. 2012), and future studies should examine whether CE merger can indeed explain such a structure.

Missing long-orbital period post-CE binaries. The migration process at the termination of the CE phase reduces the orbital separation even if a merger does not occur. This might explain the finding that all post CE binary systems in the homogeneous SDSS sample have orbital separation well below expectation of the CE α-prescription (Rebassa-Mansergas et al. 2012).

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