FINAL COMMON ENVELOPE EJECTION BY MIGRATION AND JETS
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ABSTRACT

I summarize recent analytical and numerical studies of the common envelope (CE) process and suggest to replace the commonly used $\alpha_{CE}$-prescription for the CE ejection by a prescription based on final migration and jets launched by the companion or the core of the giant stellar primary. In the migration process the core-companion binary systems is surrounded by a highly oblate (flatten) envelope, a thick circumbinary disk, formed by the large angular momentum transferred from the core-companion system to the envelope. I then show that the energy that can be released by an accreting main sequence companion can surpass the mutual gravitational energy of the core and the companion. An efficient channel to leash the accretion energy to expel the CE is through jets operating via a feedback mechanism (JFM).

1. INTRODUCTION

During the common envelope (CE) phase of a binary system the orbital separation between the core of the large star and the smaller secondary star decreases due to gravitational drag and tidal interaction (e.g., Paczynski 1976; van den Heuvel 1976; Iben & Livio 1993; Taam & Sandquist 2000; Podsiadlowski 2001; Webbink 2008; Taam & Ricker 2010; Ricker & Taam 2012; Ivanova et al. 2013). The exact process that determines the core-secondary final orbital separation is one of the major unsolved questions of the CE process. Another related open question is the duration of the final phase of the CE evolution, being days to several weeks (e.g., Rasio & Livio 1996; Livio & Soker 1988), or months (e.g., Sandquist et al. 1998; De Marco et al. 2008, 2009; Passy et al. 2011; Ricker & Taam 2012).

In the commonly used $\alpha_{CE}$-prescription the gravitational energy released by the spiraling-in binary system, $E_G$, is equated to the envelope binding energy (e.g., Webbink 1984; Taurs & Dewi 2001; Ivanova et al. 2013), $E_{bind}$, with an efficiency of $\alpha_{CE}$: $\alpha_{CE} E_G = E_{bind}$. Many researchers include the internal energy of the envelope (e.g., Han et al. 1994; Maxted et al. 2002; Zorotovic et al. 2010; Xu & Li 2010; Davis et al. 2011; Rebassa-Mansergas et al. 2012), or the enthalpy (Ivanova & Chaichenets 2011), in the energy-balance equation.

In the $\alpha_{CE}$-prescription the CE is ejected in a uniform manner and there is no separation between envelope parts. However, numerical simulations have shown the separation of the CE to ejected and bound segments, e.g., Lombardi et al. (2006); Sandquist et al. (1998), as another example, found that only about a quarter of the CE is ejected; the rest of the envelope remains bound to one or both of the interacting stars. They also obtained a differentially rotating thick disk or torus at intermediate stages of the CE evolution. Soker (1992) (see also Soker 2004) analytically obtained a similar thick disk structure. In these cases a rapid merging is expected as well, unless an extra energy source is applied, such as accretion onto the secondary star. Passy et al. (2011) found in their simulations that when the envelope is lifted away from the binary, $\gtrsim 80$ per cent of the envelope remains bound to the binary system. De Marco et al. (2011) suggested that

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envelope material still bound to the binary system at the end of the CE falls back, forms a circumbinary disk, and influences further binary evolution. Ricker & Taam (2012) find that during the rapid inspiral phase (the plunge-in phase; see Ivanova et al. 2013) only $\sim 25\%$ of the energy released by the spiraling-in process goes toward ejection of the envelope. Passy et al. (2012) made a detailed study of the CE evolution and found that not only most of the CE stays bound ($\gtrsim 90\%$), but the final orbital separations in their simulations are much larger than those observed.

The separation of the CE to ejected and bound parts was shown also analytically by Kashi & Soker (2011). They argue that the $\sim 1 - 10\%$ of the ejected envelope that remains bound falls-back and forms a circumbinary disk around the post-CE binary system. The interaction of the circumbinary disk with the binary system further reduces the orbital separation, leading in many cases to a merger at the end of the CE phase or a short time after. A different mechanism for merger at the termination of the CE phase was suggested by Ivanova & Chaichenets (2011).

In a recent paper (Soker 2013) I put another basic assumption of the $\alpha_{\text{CE}}$-prescription into question. The assumption is that most of the core-secondary gravitational energy, that is liberated in the final spiraling-in process, can be used efficiently to unbind the envelope. In that paper I found that when the orbital separation decreases to $\sim 10$ times the final orbital separation predicted by the $\alpha_{\text{CE}}$-prescription, the companion has not enough mass in its vicinity to carry away its angular momentum; see figure 18 in Passy et al. (2012) for a numerical demonstration of this effect. Instead, the binary system interacts gravitationally with a rapidly-rotating flat envelope, as is found in the numerical simulations cited above. This situation resembles that of planet-migration in protoplanetary disks. The envelope convection of the giant star carries energy and angular momentum outward.

Both analytical calculations and numerical simulations show that merger might be a common outcome of the CE evolution. Actually, merger might be too common if no extra energy source to remove the envelope is applied. In this paper I put forward the idea that jets launched by the secondary star act via a feedback mechanism to remove the rest of the envelope. The idea of using jets launched by the secondary star to help removing the CE was proposed in the past, but under specific conditions. In a previous paper (Soker 2004) I discussed the removal of the CE by jets launched by a sufficiently compact secondary star, such that an accretion disk is formed via the Bondi-Hoyle-Lyttleton (BHL) accretion process from the envelope. I showed that such a companion cannot be a main sequence (MS) star, but rather must be a neutron star (NS) or a white dwarf (WD). Chevalier (2012) then explored the possibility that the mass loss prior to an explosion of a core-NS merger process is driven by a CE evolution of a NS (or a BH) in the envelope of a massive star. This explosion process was further developed by Papish et al. (2013). In the present study I concentrate on main sequence (MS) stellar companions, that are the more common types of secondaries in CE systems. The major difference from previous studies, including that of Soker (2004), is that here the main accretion process is not the BHL process, but rather an accretion from a highly distorted oblate envelope residing outside the secondary orbit. Such a process can take place only when the secondary is deep inside the envelope. General properties of the proposed mechanism are discussed in section 2 and some quantitative properties of the flow are studied in section 3. A summary is in section 4.

2. PHASES OF JET ACTIVITY

I examine the conditions for accretion disk formation, and assume that a massive accretion disk launches jets. For the formation of an accretion disk the specific angular momentum of the accreted mass must be
sufficiently large. This in turn requires a highly asymmetric accretion flow. In Table 1 I list the phases when an accretion disk might be formed. These are drawn schematically in Fig. 1.

Table 1: Jet activity phases

| Secondary star activity | Mass source | Role of Jets | Observational signatures | Comments |
|-------------------------|-------------|--------------|--------------------------|----------|
| (a) Outside envelope.  | RLOF        | Shaping the slow giant wind. | Bipolar symbiotic nebulae; Bipolar PNe with a narrow waist. |          |
| Mainly in synchronization. |             |              |                          |          |
| (b) Outer CE. Spinal-in. | Bondi-Hoyle-Lyttleton accretion. | No jets from a main sequence secondary. | Bipolar PNe | Possible jets from NS and WD secondaries. |
| (c) Inner CE. Migrates-in due to circumbinary disk. | Circumbinary thick disk (flatten CE). | Removing and accelerating the CE. | Elliptical PNe. | A feedback process. |
| (d) Post CE. Residual migration. | Circumbinary thick disk or fall-back gas. | Shaping the nebula; Forming hot bubbles in elliptical PNe. | Elliptical PNe+ansae; Mildly bipolar PNe. Diffuse X-ray in elliptical PNe. | Jets might be launched also from the core. |
| (e) Merger (during or after CE ejection). Core launches jets. | Destroyed secondary or fall-back gas. | Shaping the nebula; Forming hot bubbles in elliptical PNe. | Elliptical PNe+ansae; Mildly bipolar PNe. Diffuse X-ray in elliptical PNe. | Jets might be highly collimated. |

The table refers to a late AGB primary star and a main sequence (MS) secondary (companion) star. Many items are relevant to other types of binary systems. Schematic illustrations of the different phases are drawn in Fig. 1. ‘Ansae’ stand for two opposite small bullets, one at each side of an elliptical PN, that generally move faster than the rest of the nebula.

(a) When the secondary is outside and close to the giant envelope a Roche lobe overflow (RLOF) process, or a similar one if the orbit is not synchronized with the giant’s spin, supplies mass with sufficiently high specific angular momentum to form an accretion disk. The companion can be a MS star, a WD, a NS, or a BH. In the case of a WD companion a bipolar symbiotic nebula can be formed. Later on, whether the companion enters or not a CE, a bipolar PN with narrow waist can be formed.

(b) I consider the formation of a CE due to further evolution of the giant and/or angular momentum loss in the wind. As long as the accretion process onto the secondary star during the CE evolution is the Bondi-Hoyle-Lyttleton (BHL) accretion process, the specific angular momentum of the accreted mass is low, and no accretion disk will be formed around a MS star; disks might be formed around WD or NS companions (Soker 2004). However, a WD cannot accrete at a high rate, as the hydrogen is ignited and the outer layers of the accreting WD are inflated to prevent further accretion.

(c) When the companion is deep inside the envelope, a flatten envelope is formed (Ricker & Taam 2012; Passy et al. 2012). The flatten envelope might have two effects on the core-secondary binary system. First, a tidal interaction of the binary system with the flatten envelope residing outside the secondary orbit, which is a thick circumbinary disk, can lead to reduction of the orbital separation (Kashi & Soker 2013), in what is termed here a migration process (Soker 2013).

Second, the mass accreted from the circumbinary disk is likely to have sufficient specific angular momentum to form an accretion disk around the secondary star, even if it is a MS star. If a disk is formed,
Fig. 1.— Schematic drawing (not to scale) of the phases considered here that are summarized in Table 1. The study concentrates on a main sequence (MS) companion interacting with an evolved AGB star. The image on the right side of panel c is a numerical simulation of a jet-inflated bubble in a PN taken from Akashi & Soker (2008). I suggest that a qualitatively similar flow takes place in the final CE evolution: bubbles inflated by jets launched by the companion remove a significant part of the leftover envelope. This is the negative-feedback cycle. Vortices induced by the bubbles channel some envelope mass toward the plane to feed the accretion disk. This is the positive-feedback cycle.

It is likely to launch jets, as shown schematically in panel c of Fig. 1 where a flow pattern from a different numerical setting is presented. The simulation presented is of a wide jet launched inside a spherical nebula,
to mimic the formation of a bipolar PNe (Akashi & Soker 2008). The simulation is of the entire volume, but a cylindrical symmetry is assumed, hence the numerical grid is 2D. Symmetry is assumed around the jet’s axis (vertical axis in the figure), and a mirror symmetry is assumed about the orbital plane (horizontal line in the figure). Only one quarter of the meridional plane is simulated and presented. The simulation is for a different setting than the CE jets studied here in that the companion is outside the envelope. It is presented only to demonstrate the formation of a hot bubble. It is not intended to present the the formation of the accretion disk. A qualitatively similar flow, I suggest, can take place when jets are launched by the secondary star inside the envelope. As discussed in the next section, for example, the orbital motion of the secondary star leads to wide jets.

I emphasize that the formation of an accretion disk in phase c is a new ingredient. In Soker (2004) I only studied the formation of an accretion disk via the BHL accretion process from the envelope, where an accretion disk around a MS star cannot be formed. In phase c the process is more like that in young stellar objects, where a circum-binary disk feeds the stars, and an accretion disk can be formed around a MS star. When the binary system is deep in the envelope, the highly distorted circum-binary oblate envelope contains most of the angular momentum of the system. Due to tidal interaction and friction in the rotating envelope, I suggest that the envelope feeds the binary system with gas possessing sufficiently high specific angular momentum. This claim will have to be studied with 3D numerical simulations. The numerical study of this feeding process from a rotating oblate envelope is more complicated than the 3D numerical studies of the CE phase that have been conducted till now (and much more complicated than the feeding from a geometrically thin accretion disk), but are highly encouraged.

The removal of the envelope with the inflation of hot low-density bubbles operates through a feedback cycle composed of a positive part and a negative part. The positive part is the processes by which the bubbles push material toward the equatorial plane (Akashi & Soker 2008), that can further supply mass to the secondary and amplify the jets power. The negative part is simply the removal of envelope mass, hence reducing the accretion rate.

(d) After the removal of the envelope a residual circumbinary disk might be left. Its life can be prolonged by fall back of nebular gas. Post CE jets (PCEJ) might be launched. Due to the orbital motion they will not be well collimated, and might show signs of precessions. At later times, when the leftover envelope mass on the core is removed and shrinks, the core itself might accrete mass through a disk, and lunch jets. Soker & Livio (1994) considered the launching of jets before and after the CE phase, but not during the CE phase. In the PCE phase they considered mass transfer from the secondary to the core and fall back gas, hence the core launches the jets. Both in the final CE phase and in the post-CE phase mass can be transferred from the leftover envelope residing on the core to the secondary star. This mass transfer is also likely to form an accretion disk. Namely, in the energy balance there is no need to include the envelope mass residing within $\sim 0.5R_\odot$ from the core.

(e) Finally, the secondary can merge with the core (Soker 2013) and forms and accretion disk. In Soker (1996) I proposed this mechanism for brown dwarf and massive planet companions. Here I extend it to low mass MS stars (low mass relative to the envelope mass). As there is no orbital motion any more, the jets might be well collimated.
3. AVAILABLE ENERGY

If the jet feedback mechanism (JFM) is responsible for the removal of a significant part of the envelope, then the energy $E_{\text{jets}}$ released by accreting mass $M_{\text{acc}}$ onto the companion of mass $M_2$ and radius $R_2$ should be comparable or larger than the binding energy of the CE (at least the envelope residing above the final orbital separation). I derive the required accreted mass onto the companion from this condition. Instead of the explicit expression for the CE binding energy, I use the equivalent energy from the $\alpha_{\text{CE}}$-prescription, $E_{\alpha_{\text{CE}}}$. A plausible scaling gives

$$E_{\text{jets}} \simeq \frac{GM_2M_{\text{acc}}}{2R_2} \left( \frac{\alpha_{\text{CE}}}{0.5} \right)^{-1} \left( \frac{M_{\text{acc}}}{0.1M_{\text{core}}} \right) \left( \frac{R_2}{0.2a_{\text{final}}} \right)^{-1} E_{\alpha_{\text{CE}}}. \quad (1)$$

To be consistent with the definition of $E_{\text{jets}}$ I take

$$E_{\alpha_{\text{CE}}} = \frac{GM_{\text{core}}M_2}{2a_{\text{final}}} \alpha_{\text{CE}}, \quad (2)$$

and $a_{\text{final}}$ is the final core-companion orbital separation according to the $\alpha_{\text{CE}}$-prescription. I also assume that at these very high accretion rates most of the liberated accretion energy is channelled to outflow at about the escape speed from the secondary star.

Not all the accretion energy will be channelled to the jets. On the other hand there are two other processes to consider. (1) The spiral-in process already lifted part of the envelope. As well, the migration processes will release energy and will further inflate the envelope. The binding energy of the inflated envelope is lower than its pre-CE value. (2) The very inner envelope mass that is close to the core, within $\sim 0.5R_\odot$, does not need to be removed. It can be accreted onto the secondary star. This segment of the envelope has a high binding energy, which is removed from the energy budget in the JFM for CE removal.

Over all, to equate the energy given by the classical $\alpha_{\text{CE}}$-prescription, $E_{\text{jets}} \simeq E_{\alpha_{\text{CE}}}$, the companion should accrete a mass of

$$M_{\text{acc}} \simeq 0.06 \left( \frac{M_{\text{core}}}{0.6M_\odot} \right) \left( \frac{R_2}{0.5R_\odot} \right) \left( \frac{a_{\text{final}}}{2.5R_\odot} \right)^{-1} \left( \frac{\alpha_{\text{CE}}}{0.5} \right) M_\odot, \quad (3)$$

which is another presentation of equation (1). The parameters $\alpha_{\text{CE}}$ and $a_{\text{final}}$ appear here as $a_{\text{final}}/\alpha_{\text{CE}} = 5R_\odot$, which is compatible in general terms with the findings of [De Marco et al. (2011)]. If the mass in the jets is half the accreted mass, then the scaling in equation (3) requires, for example, that a mass of $0.03M_\odot$ be lost in the jets at a velocity of $\sim 620$ km s$^{-1}$ (similar to the solar wind speed).

Very crudely, the migration phase lasts for $\sim 1$ yr [Kashi & Soker (2010)]. In the present scenario the accretion from the envelope outside the companion orbit starts when the envelope is highly distorted to an oblate shape. The total accretion period is longer than the migration phase, but not by much. If accretion occurs intermittently, then the effective accretion time is somewhat shorter. Overall, the accretion period lasts for several months to more than a year, and the accretion rate onto the companion is $\sim 0.05 - 0.1M_\odot$ yr$^{-1}$ for the above scaling. In one year the star accretes $\sim 0.1$ of its mass, as might have been the case in the Great Eruption of Eta Carinae [Kashi & Soker (2010)]. At these very high accretion rates it has been suggested that the mass ejected in the jets is a large fraction of the accreted mass, up to $\sim 0.5$, e.g., [Kashi & Soker (2010)] in their modelling of the Great Eruption of Eta Carinae. The accretion period is $\sim 100$ times the typical dynamical time of the accretion disk around a MS star (at several stellar radii), and there is no unusual demands on the viscosity in the disk.
The response of a MS star to such a high accretion rate sensitively depends on the energy content of the accreted mass (or its entropy). On the inner boundary of an accretion disk touching the accreting star, the gravitational energy value is twice that of the kinetic energy. Namely, the accreted gas already obeys the virial relation, implying that the accreting star does not need to radiate extra energy or heat much the accreted mass. The accreting star radius will not change much. As well, the accreted mass will be mixed in the convective envelope of low mass MS stars. In the envisioned scenario presented here the jets carry a large fraction of the accreted energy, such that the accreted gas might have a kinetic energy less than half the value of the gravitational energy. For example, this can happen if some fraction of the energy in the boundary layer, where disk-kinetic energy is transferred to thermal energy, is removed by jets. In such a case an accreting MS star might even shrink.

The ratio of the orbital velocity of the secondary to the jet velocity in the final CE phase is

$$v_{\text{orb2}} / v_{\text{jet}} = 0.25 \left( \frac{v_{\text{jet}}}{650 \text{ km s}^{-1}} \right)^{-1} \left( \frac{M_{\text{core}} + M_2}{1.0M_\odot} \right)^{-1/2} \left( \frac{M_{\text{core}}}{0.6M_\odot} \right) \left( \frac{a_{\text{final}}}{2.5R_\odot} \right)^{-1/2}. \quad (4)$$

The ratio $v_{\text{orb2}} / v_{\text{jet}} \sim 0.25$ implies that over an orbit the jets will be launched on a wide angle, even if the jets are narrow at ejection. If the jets have a half opening angle at source of $10^\circ$, for example, with the orbital velocity given in equation (4) the half opening angle over an orbit is $\sim 25^\circ$. (At each moment the jets still have an opening angle of $10^\circ$, but due to the orbital motion at each orbital phase the jets will be bent by $\sim 15^\circ$ to a different direction.) The jets can interact with a large fraction of the CE volume. Because of the orbital motion the jets’ axis is constantly displaced and the jets encounter fresh envelope material. The jets don’t manage to penetrate through the envelope, and hence deposit their energy inside the envelope (Soker 2004; Papish et al. 2013).

The inequality $(v_{\text{jet}} / v_{\text{orb2}})^2 \gtrsim 10$ implies that the shocked jet material will be hotter than the gas temperature of the envelope near and outside the secondary orbit. Hence, low density hot bubbles will be formed. The later evolution of these bubbles must be studied in more details, and with 3D numerical simulations.

4. SUMMARY

I proposed a scenario where the final removal of the common envelope (CE) in cases where a merger of the secondary with the core is avoided is done by jets launched by the secondary star. This process is suggested to replace the classical $\alpha_{\text{CE}}$-prescription for the CE final ejection. Specifically, I suggest a paradigm shift where the one equation used over the last 40 years of $E_{\text{bind}} = E_{\alpha_{\text{CE}}}$, be replaced by

$$E_{\text{bind}} = E_{\text{jets}} + E_{\alpha_{\text{CE}}}, \quad (5)$$

where in many cases, most cases of surviving binary systems, $E_{\text{jets}} > E_{\alpha_{\text{CE}}}$. Here $E_{\text{bind}}$ is the binding energy of the envelope, $E_{\alpha_{\text{CE}}}$ is the energy released by the binary gravitational energy in the $\alpha_{\text{CE}}$-prescription (eq. 2), and $E_{\text{jets}}$ is the energy carried by the jets launched by the companion (eq. 1). One implication of he proposed paradigm shift is that the numerical study of the common envelope evolution can substantially move forward only if jets launched by the secondary star are incorporated into CE simulations.

The different phases when jets might be launched from an accretion disk around a main sequence (MS) star are summarized in Table 1 and Fig. 1. The relevant phase is phase c, when the secondary is in the inner part of the CE and the envelope is highly oblate (flat). The formation of an accretion disk around
the companion and the launching of energetic jets during phase c is the main new ingredient introduced in the present study. In phase c, I suggest, accretion from material residing outside the secondary orbit, a circumbinary thick disk or oblate envelope, ensures sufficiently high specific angular momentum to form an accretion disk. The typical amount of mass required to be accreted onto a MS star to eject the envelope is given by equation (3).

Due to the orbital velocity of the secondary (eq. 4), the opening angle of the jets over an orbit will be large, and the jets will interact with a large volume of the CE along the polar directions. Typical jets velocities of $v_{\text{jet}} \gtrsim 500 \text{ km s}^{-1}$ imply that the shocked jets’ material form hot low density bubbles. These bubbles then remove a large fraction of the envelope mass. After the removal of the CE, leftover circumbinary gas is likely to survive. Its life can be prolong with fall back nebular gas, leading to the formation of post-CE jets (PCEJs). The presence of PCEJs has been deduced from observations of some PNe (e.g., Huggins 2007; Tocknell et al. 2014). The PCEJs can form hot bubbles in the descendant elliptical planetary nebula (PNe) and be observed as diffuse X-ray emission (Akashi et al. 2008). The diffuse X-ray emission observed in some elliptical PNe might hint at the operation of the jet feedback mechanism (JFM) in the final removal of the CE (Freeman et al. 2014).

Let me end by listing the basic ingredients of the proposed scenario for a final CE removal by a JFM.

1. The gravitational energy released by the in-spiraling core-secondary system is essential in inflating the envelope and reducing its binding energy.

2. The angular momentum transferred from the core-secondary system is essential in forming a flatten envelope (highly oblate), which turns into a thick circumbinary disk that feeds the accretion disk around the secondary star.

3. For these two process to operate, the orbital separation must be small, $\sim 5 - 30 R_\odot$ for an AGB star with a MS companion. That is, the JFM starts to operate only when the secondary is deep in the envelope.

4. The orbital separation continues to decrease mainly due to tidal interaction with the thick circumbinary disk (migration).

5. A large fraction of the mass in the accretion disk, $\sim 20 - 40\%$, is launched in two opposite jets. The accreted mass amounts to $\sim 0.1$ times the core mass, and the jets are launched with typical velocities of $\sim 700 \text{ km s}^{-1}$ when the companion is a MS star.

6. Typically, the jets’ material is shocked to temperatures above those of the envelope, and hot bubbles are formed. These bubbles interact with the envelope, much as X-ray deficient bubbles interact with the intrachannel medium of clusters of galaxy (Soker et al. 2013), and remove part of the envelope.

7. The very inner part of the giant envelope need not be expelled, as it can be accreted by the companion as part of the JFM. This reduces the energy required to supply to the ejected envelope.

8. The removal of the envelope is composed of a negative-feedback part where the removal of the envelope reduces accretion rate, and a positive-feedback part where the inflated bubbles push CE gas toward the equatorial plane and resupply material to the circumbinary disk.

9. In many cases the jets will be active well after the ejection of the CE. These jets will further shape the descendant PNe and might form extended X-ray emission in young elliptical PNe.
10. As the jets are not expected to be effective in all cases, in many cases the CE process ends in merger.

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