CLOSE STELLAR BINARY SYSTEMS BY GRAZING ENVELOPE EVOLUTION

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ABSTRACT

I suggest a spiral-in process in which a stellar companion grazes the envelope of a giant star while both the orbital separation and the giant radius shrink simultaneously, forming a close binary system. The binary system might be viewed as evolving in a constant state of "just entering a common envelope (CE) phase." In cases where this process takes place, it can be an alternative to CE evolution where the secondary star is immersed in the giant's envelope. Grazing envelope evolution (GEE) is made possible only if the companion manages to accrete mass at a high rate and launches jets that remove the outskirts of the giant envelope, hence preventing the formation of a CE. The high accretion rate is made possible by the accretion disk launching jets which efficiently carry the excess angular momentum and energy from the accreted mass. The orbital decay itself is caused by the gravitational interaction of the secondary star with the envelope inward of its orbit, i.e., dynamical friction (gravitational tide). Mass loss through the second Lagrangian point can carry additional angular momentum and envelope mass. The GEE lasts for tens to hundreds of years. The high accretion rate, with peaks lasting from months to years, might lead to a bright object referred to as the intermediate luminosity optical transient (Red Novae; Red Transients). A bipolar nebula and/or equatorial ring are formed around the binary remnant.

Key words: binaries: close – stars: AGB and post-AGB – stars: winds, outflows

1. INTRODUCTION

It is commonly accepted that close binary systems where at least one of the stars is a stellar remnant, mainly a white dwarf (WD) or a neutron star (NS), have evolved through a common envelope (CE) phase (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). There are some major open questions regarding CE evolution. One of these questions is the duration of the final CE phase, lasting months (e.g., Sandquist et al. 1998; De Marco et al. 2003, 2009; Passy et al. 2012a; Ricker & Taam 2012) or maybe only days to several weeks (e.g., Rasio & Livio 1996; Livio & Soker 1988). Another open question involves the process that determines the final core-secondary orbital separation.

The most common practice for calculating the final orbital separation of the CE phase is to equate the gravitational energy released by the spiraling-in binary system, E_G, to the envelope binding energy, E_{bind}, with an efficiency of α_{CE}: $\alpha_{CE} E_G = E_{bind}$ (e.g., Webbink 1984; Tauris & Dewi 2001; Ivanova et al. 2013; see Nelemans & Tout 2005 for an alternative). Many researchers add the envelope internal energy in the energy balance equation of this α_{CE} prescription (e.g., Han et al. 1994; Zorotovic et al. 2010; Xu & Li 2010; Davis et al. 2012; Rebassa-Mansergas et al. 2012; Ivanova & Chaichenets 2011). Numerical studies of the CE process have made progress over the years (e.g., Sandquist et al. 1998; Lombardi et al. 2006; De Marco et al. 2011; Passy et al. 2012a; Ricker & Taam 2012), e.g., the $\alpha_{CE} = 0.25$ found in the study of Ricker & Taam (2012) agrees with the value derived from observations of close binary systems as presented by Nordhaus & Spiegel (2013). Still, better numerical resolutions and additional computer resources for longer runs are required to show that the CE process can indeed lead to the observed systems.

In light of some of the difficulties in the α_{CE} prescription (e.g., Soker 2013), it has been suggested that in many cases jets launched by the more compact companion can facilitate envelope ejection, and that the final spiraling-in process occurs through migration, i.e., the interaction of the binary system with a circumbinary thick disk or a flattened envelope (Soker 2004; Kashi & Soker 2011; Soker 2013, 2014). CE ejection by jets launched from an NS companion have been studied by Armitage & Livio (2000), Chevalier (2012), and Papish et al. (2013) but not as a general CE ejection process. The present approach considers that the launching of jets by the companion is a generic CE ejection process (although not in all CE cases).

Here, I raise the following question. Can it be that jets launched by the secondary star will prevent the formation of a CE phase altogether as the secondary star spirals in toward the core of the giant star? The necessary ingredients for such a grazing envelope evolution (GEE) are discussed in Section 2. I suggest a new type of spiraling-in process where the more compact companion grazes the envelope of a giant star and ejects the outer envelope layers as it circles the giant and spirals in. At the heart of this process are jets, or disk winds, that are launched by the secondary star. Energy considerations are discussed in Section 3, two specific examples are discussed in Section 4, and a short summary is provided in Section 5.

2. INGREDIENTS OF THE GRAZING ENVELOPE EVOLUTION (GEE)

There are two basic mechanisms that lead to the formation a CE phase for a giant and a more compact secondary star. (1) The giant transfers mass to the secondary at a rate which the secondary cannot accommodate. The secondary then inflates a large envelope that merges with the giant envelope. (2) The giant expands and/or the companion spirals in and the giant engulfs the secondary star. This mechanism is efficient when the secondary is far from bringing the giant envelope into synchronization with the orbital motion.

To have a GEE, both these processes must be of small to moderate size, as discussed below. It is important to keep in

mind that the GEE is different from a regular mass transfer in binary systems because in the GEE the system evolves in a constant state of "just entering a CE phase." Namely, parts of the giant envelope overflow the Roche lobe in a large volume around the first Lagrangian point L_1, but jets (or disk wind) launched by the secondary star prevent the formation of a CE. Another point of the GEE is that if it was not for the jets that are lunched by the secondary star, the system would have enter a CE phase. Namely, if a system is not to enter a CE phase through the CE theory, then it would also not enter GEE. The Red Rectangle is such an example and is discussed in Section 4.

2.1. High Accretion Rate

To prevent a CE phase during most, or all, of the evolution, the companion must be able to accrete at a very high rate, $\gtrsim 10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$, without inflating a large envelope. This implies that energy must be removed efficiently from the accreted gas. For an accreting NS, neutrino cooling allows for a mass accretion rate of $\gtrsim 10^{-3}\,M_\odot\,\mathrm{yr}^{-1}$ (Chevalier 2012). For a WD it seems that such a high accretion rate is not possible, as nuclear burning will commence and inflate an envelope.

To prevent the large expansion of main-sequence (MS) stars, the internal energy per unit mass of the accreted mass must be lower than half the magnitude of the specific gravitational energy on the stellar surface $e_{\mathrm{acc}} < 0.5 G M_1/R_1 \equiv e_G$. The inner boundary of an accretion disk that touches the accreting star meets this condition as the specific kinetic energy is $e_{\mathrm{kin}} = 0.5 e_G$. If there is a boundary layer where the disk gas sharply spins down to the stellar rotation, then energy removal from the boundary layer can lead to $e_{\mathrm{acc}} < 0.5 e_G$, and more importantly, can lower the entropy and further prevent much envelope expansion (e.g., Hjellming & Taam 1991).

The way to remove the excess energy is through jets (or a collimated wind) from an accretion disk, as has been suggested for the 1837-1856 Great Eruption of η Carinae (Kashi & Soker 2010). In the process, most of the energy in the disk is transferred to magnetic fields which through violent reconnection eject mass. Namely, the released gravitational accretion energy is channeled to magnetic fields and outflows much more than to thermal energy and radiation (S. Shiber et al. 2015, in preparation). Such an accretion disk not only launches jets, but the asymmetrical structure allows the system to accrete at the Eddington luminosity limit or even somewhat higher. In that model, the average accretion rate by the secondary in η Car over the 20 yr of the Great Eruption was $\sim$0.2–0.3 $M_\odot\,\mathrm{yr}^{-1}$; the accretion rate during periastron passages was much higher. A bipolar nebula (the Homunculus) was formed from this activity.

An MS companion accreting from a giant envelope as it spirals in will not form an accretion disk (Soker 2014; MacLeod & Ramirez-Ruiz 2015). To ensure the presence of an accretion disk, the accretion must be via RLOF while the secondary is outside the envelope before the CE phase, or at the termination of the CE when accretion is contributed by a circumbinary disk (Soker 2014). In GEE, accretion occurs via RLOF. Even if the secondary tries to "dive" into the envelope, the jets will eject the envelope above and below the secondary star, practically preventing a static envelope from being formed outside the secondary orbit. Another fraction of the envelope is ejected

through L_2 (Livio et al. 1979), and a fraction of the envelope is accreted onto the secondary star.

2.2. Preventing Engulfing

New results show that the giant envelope will not expand much because of the rapid mass loss (Woods & Ivanova 2011; Passy et al. 2012b), which is not a route to CE formation. The CE phase can be initiated via rapid spiraling-in evolution. To prevent rapid spiraling in from occurring, in addition to launching jets, the companion must bring the envelope close to synchronization with the orbital motion, i.e., almost corotation. Otherwise, tidal interaction will be strong and bring the secondary deep into the envelope in a relatively short time. Some departure from synchronization is required to allow a spiraling-in process (but not too rapid) due to gravitational drag (tidal forces). This will be the case because mass with specific angular momentum larger than the average in the envelope is lost through mass removal from the envelope.

Tidal interaction becomes strong when the primary radius becomes $R_1 \gtrsim 0.25 a_0$, where a_0 is the orbital separation (Soker 1996). By the time the binary system has spiraled-in to $a \gtrsim R_1$, the primary envelope must achieve (almost) corotation. The moment of inertia of the giant envelope is taken to be $I_1 \simeq \eta M_{\mathrm{env}} R_1^2$, where M_{env} is the convective envelope mass and R_1 is the giant radius. For asymptotic giant branch (AGB) stars and red supergiants $\eta \simeq 0.2$–0.24. We will consider cases where $M_2 \ll M_1$ initially. The above condition to reach synchronization at $a \simeq R_1 \simeq 0.25 a_0$ provides a constraint of

$$M_2 \gtrsim 0.15 \left(\frac{\eta}{0.22} \right) M_{\mathrm{env}}. \tag{1}$$

The system might temporarily evolve through a Darwin unstable phase during which spiraling in is faster. The mass accretion rate during this phase might also be higher, as well as mass loss through L_2. After accretion and removal of some envelope mass, the system regains Darwin stability when $I_B > 3 I_1$. Here I_B and I_1 are the moments of inertia of the binary system and the envelope of the primary star, respectively. The system will become Darwin stable approximately when the secondary to envelope mass becomes $M_2/M_{\mathrm{env}} \gtrsim 0.7(a/R_1)^{-2}$ (for $\eta \simeq 0.22$). Evolution then slows down.

2.3. Evolution Time

Evolution time is very difficult to calculate as it is determined by the mass transfer rate and tidal interaction. These are only known crudely for these systems. None the less, we can crudely take the GEE timescale to be determined by the tidal and Kelvin–Helmholtz (thermal) timescales, $\tau_{\mathrm{T-ev}}$ and $\tau_{\mathrm{KH-env}}$, respectively. When the envelope mass is low, we crudely have (Soker 2008)

$$\tau_{\mathrm{KH-env}} \simeq 50 \left(\frac{M_c}{0.6\,M_\odot} \right) \left(\frac{M_{\mathrm{env}}}{0.5\,M_\odot} \right) \left(\frac{L}{5000\,L_\odot} \right)^{-1}$$
$$\times \left(\frac{R_1}{200\,R_\odot} \right)^{-1}\,\mathrm{yr}, \tag{2}$$

where M_c is the core mass and L_1 is the primary (giant) stellar luminosity.

For the tidal spiral-in timescale I borrow from Equation (6) of Soker (1996), based on Zahn (1977) and Verbunt & Phinney

(1995), assuming that the secondary is somewhat outside the primary $a > R_1$:

$$\tau_{T-ev} \simeq 20 \left(\frac{a}{1.2R_1}\right)^8 \left(\frac{L}{5000 L_\odot}\right)^{-1/3} \left(\frac{R}{200 R_\odot}\right)^{2/3}$$
$$\times \left(\frac{M_{env}}{0.5M_1}\right)^{-1} \left(\frac{M_{env}}{0.5 M_\odot}\right)^{1/3} \left(\frac{M_2}{0.2M_1}\right)^{-1}$$
$$\times \left(\frac{\Omega_{orb} - \omega_1}{0.1\Omega_{orb}}\right)^{-1} \text{yr}, \tag{3}$$

where ω_1 is the rotational angular velocity and Ω_{orb} is the orbital angular velocity.

To continue the spiraling-in process, a strong interaction must take place between the envelope and the secondary star. The two processes, tidal interaction and the adjustment of the giant envelope to mass loss, must have sufficient time to operate. The slower process determines the spiraling-in time. Overall, I crudely estimate the timescale of the GEE phase starting at ~1 AU to be

$$\tau_{GEE} \sim 30\text{--}300 \text{ yr} \simeq \max(\tau_{KH-env}, \tau_{T-ev}). \tag{4}$$

The corresponding average mass accretion rate by the secondary star is $\dot{M}_2 \sim 10^{-4}\text{--}10^{-2} M_\odot \text{ yr}^{-1}$. I note that the accretion rate onto the companion estimated by Ricker & Taam (2012) in their CE numerical simulation is $\sim 0.01 M_\odot \text{ yr}^{-1}$. Therefore, the accretion rate required by the GEE is not as extreme as what the first impression might be.

3. ENERGY CONSIDERATION

Let us compare the accretion energy with that of the α_{CE} prescription, $E_{\alpha_{CE}}$ (see also Soker 2014). The gravitational energy released by an accreting MS star is

$$E_{jets} \simeq \frac{G M_2 M_{acc}}{2R_2}, \tag{5}$$

where M_2 and R_2 are the secondary stellar mass and radius, respectively, and M_{acc} is the accreted mass. The gravitational energy released by the binary system is

$$E_{\alpha_{CE}} = \frac{G M_{core} M_2}{2a_{final}} \alpha_{CE}, \tag{6}$$

where M_{core} is the mass of the core of the giant star (now the remnant), and a_{final} is the final core-companion orbital separation. To liberate energy as in the α_{CE} prescription, the mass accreted onto the secondary star should be

$$M_{acc-\alpha} \simeq 0.06 \left(\frac{M_{core}}{0.6 M_\odot}\right) \left(\frac{R_2}{1 R_\odot}\right) \left(\frac{a_{final}}{5 R_\odot}\right)^{-1} \left(\frac{\alpha_{CE}}{0.5}\right) M_\odot. \tag{7}$$

Namely, jets launched by a secondary star that accretes ~10% of its mass can play a significant, and even the major, role in removing the giant envelope. Moreover, the jets can eject large parts of the envelope at very high velocities, i.e., far above the escape speed from AGB stars. By accreting an extra mass of $\Delta M_{acc} = M_{acc} - M_{acc-\alpha}$ onto an MS star, and assuming that this extra energy is channeled into the kinetic energy of the envelope, the typical outflow velocity of the jet-ejected envelope of mass M_{en-ej} is

$$v_{en-ej} \simeq 100 \left(\frac{\Delta M_{acc}}{0.05 M_{en-ej}}\right)^{1/2} \text{km s}^{-1}. \tag{8}$$

4. SPECIFIC EXAMPLES

In general, the constraints on the parameters for GEE to take place are estimated as follows. To bring the envelope to near synchronization with the orbital motion, we require $M_2 \gtrsim 0.15 M_{env}$ (Equation (1)). In addition, the system should achieve a close contact. Hence, the companion should not bring the envelope into synchronization at too large an orbital separation. This crudely sets a limit of $M_2 \lesssim 0.5 M_{env}$. The initial orbital separation is similar to that required for the system to enter a CE phase. Most important, the companion must be a MS star (or a brown dwarf) but not a WD. These constraints leave a large parameter space for GEE. However, there is another important constraint, which is that the secondary must launch two strong jets in a continuous manner. If some instabilities stop jet injection for too long of a period (about an orbital period), the system will enter a CE phase because without jets the secondary will not be able to remove the envelop gas that overflows its orbit. Determining the process of high-rate mass accretion and jet launching is left for futures studies. I move on to discuss two examples.

The bipolar PN NGC 2346 as a possible GEE descendant. A possible case where GEE could have taken place, at least part of the time, is the PN NGC 2346. This is a bipolar PN (e.g., Corradi & Schwarz 1995) with a central binary star, V651 Monocerotis, that has an orbital period 15.99 day (Mendez & Niemela 1981). Iben & Livio (1993), based on a study by Iben & Tutukov (1993), suggested the following evolutionary scenario. The primary, of mass $M1 = 0.4 \pm 0.05 M_\odot$, is a degenerate helium core, while the secondary star, of mass $M_2 = 1.8 \pm 0.3 M_\odot$, is a MS star. The orbital semi-major axis is $34.9 R_\odot$. Iben & Livio (1993) suggested that the primary overflowed its Roche lobe while on the late red giant branch (a late case B), and the system entered a CE phase. The initial orbital semimajor axis was ~1 AU. During the CE phase, the binary system spirals in to its final separation. In Soker (1998), I proposed that in NGC 2346 and similar planetary nebulae (PNe), the binary system avoid the CE phase for a large fraction of the interaction time. This is required for the secondary to launch jets that shape the bipolar nebula. However, the binary system still needs to spiral-in. The GEE can comprise these two properties.

In short, I argue that the central binary system of NGC 2346, which is the longest of all post-CE central binary systems of PNe, went through GEE, at least for a substantial part of the evolution time.

The Red Rectangle: launching jets but avoiding GEE. The Red Rectangle is a bipolar nebula around a post-AGB star in a binary system. The binary system, HD 44179, has an orbital period of 318 days, and the secondary star is thought to be a MS star of mass ~$0.94 M_\odot$ (Waelkens et al. 1996; Witt et al. 2009). The companion launches two jets (e.g., Witt et al. 2009) that shape the nebula. The mass transfer rate from the primary post-AGB star to the secondary is $\sim 2\text{--}5 \times 10^{-5} M_\odot \text{ yr}^{-1}$ (Witt et al. 2009). This binary system does not enter GEE as much as it does not enter a CE phase. The reason for this is that the secondary is massive enough to bring the AGB envelope to synchronization, and the secondary is actually more massive than the primary. Mass transfer and mass loss act to increase the orbital separation.

With this in mind, it is possible, but not necessary, that the system went through a GEE phase in the past. In that scenario, when the AGB star was more massive the orbital separation decreased and the AGB radius increased to about the same value. Strong interaction started between the two stars. If this

was the case, then to avoid a CE phase with a much smaller final orbital separation than observed, jets launched by the secondary star would have been required to eject a large envelope mass. When the envelope mass decreased enough and the primary mass decreased below the secondary mass, then jets removed the envelope outskirts such that further mass loss and mass transfer increased the orbital separation and spiraling-in ceased. The present nebula was formed during this stable phase. Mass lost in the GEE phase is at very large distances and may already be dispersed in the inter-stellar medium (ISM).

5. SUMMARY

In this preliminary study, I explored a spiraling-in process by which a stellar companion grazes the envelope of a giant star and the system does not enter a CE phase. This is termed GEE. Jets launched by the secondary star are at the heart of the GEE, and distinguish this from a regular mass transfer evolution. The secondary star accretes mass via an RLOF mass transfer such that an accretion disk is formed around it. Jets carry energy from the disk, and most likely lead to the accretion of low-entropy gas. The accretion through a disk therefore allows a MS secondary star to accommodate the accreted mass at a rate of $\sim 10^{-4}$–0.01 $M_\odot$ yr^{-1} without inflating a large envelope (Section 2.1).

In the GEE, the binary system might be viewed as evolving in a constant state of "just entering a CE phase." The jets (or disk-wind) launched by the accretion disk remove the envelope from above and below the equatorial plane in the secondary vicinity, preventing the formation of a CE phase. Without the efficient envelope removal by jets, the system would have entered a CE phase. Namely, systems that enter the GEE are the same systems that would have enter a CE phase if it was not for the efficient envelope removal by jets. The drag force is also similar. In the CE phase, the spiraling in is caused mainly by gravitational drag (Ricker & Taam 2008, 2012). The same holds for the GEE where the gravitational drag occurs with the envelope mass residing inward of the secondary orbit (and hence might be viewed as a tidal force). We can summarize this schematically as follows: (just entering a CE phase)+(efficient jets)→GEE.

Another ingredient that is necessary to slow down the formation of a CE phase is that the secondary star must manage to spin-up the envelope of the giant to almost corotation, and hence substantially prolong the tidal spiral-in timescale to tens of years and longer (Section 2.2). The overall GEE duration time ranges from tens to hundreds of years (Section 2.3).

While MS stars can go through the GEE, WDs cannot accrete at a high enough rate and launch jets. The reason for this is that at a high accretion rate, nuclear burning on the surface of the WD inflates an envelope. Therefore, if jets indeed aid in removing the envelope, then WDs are more likely to merge with AGB cores than are MS stars. The merger of a WD with the core of an AGB star might eventually lead to a type Ia supernovae according to the core-degenerate scenario (Kashi & Soker 2011).

The accretion of mass onto a MS star over tens of years, with some bright peaks lasting months to few years of higher than average accretion rates, can lead to a transient object termed the intermediate luminosity optical transient (Red Novae; Red Transients). The binary interaction and the ejection of the envelope mass by jets (Section 3) lead to a bipolar nebula and/or an equatorial ring around the binary remnant.

What is the relation of the GEE to the CE evolution? It seems that there is a bi-stable evolutionary situation at hand. If the companion enters the envelope and the accretion flow is more like a Bondi–Hoyle–Lyttleton accretion from a medium where an accretion disk does not form around a MS star, then it will spiral in faster than the ejection of the envelope. The binary system experiences a CE evolution. If an accretion disk that launches jets is formed before the secondary enters the envelope, on the other hand, and the system is more or less synchronized such that tidal spiraling-in timescale is long, then the system evolves through the GEE. If for some reason one of the conditions ceases to exist, e.g., the primary suffers instabilities and rapidly expands to engulf the secondary star or the secondary suffers instabilities that prevent jets from being lunched, then the binary system jumps from the GEE to the CE phase. The question of when efficient jets, namely, efficient in removing the envelope, are formed, is a question to be determined in future studies involving heavy three-dimensional numerical simulations. Only then will we be able to construct the binary system parameter space for the GEE.

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