The Lives and Death-Throes of Massive Stars
Proceedings IAU Symposium No. 329, 2016
J.J. Eldridge, J.C. Bray, L.A.S. McClelland & L. Xiao, eds.

doi:10.1017/S1743921317003398

Common envelope: progress and transients

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Abstract. We review the fundamentals and the recent developments in understanding of common envelope physics. We report specifically on the progress that was made by the consideration of the recombination energy. This energy is found to be responsible for the complete envelope ejection in the case of a prompt binary formation, for the delayed dynamical ejections in the case of a self-regulated spiral-in, and for the steady recombination outflows during the transition between the plunge-in and the self-regulated spiral-in. Due to different ways how the recombination affects the common envelope during fast and slow spiral-ins, the apparent efficiency of the orbital energy use can be different between the two types of spiral-ins by a factor of ten. We also discuss the observational signatures of the common envelope events, their link a new class of astronomical transients, Luminous Red Novae, and to a plausible class of very luminous irregular variables.

Keywords. binaries: close, hydrodynamics, stars: outflows

1. Introduction: the energy sources and the energy sinks

Common-envelope events (CEEs) are fate-defining episodes in the lives of close binary systems. During a common envelope phase, the outer layers of one of the stars expand to engulf the companion, and two stars start to temporarily orbit within their shared envelope. This pivotal binary changeover ends with a luminosity outburst, leaving behind either a significantly shrunk binary, or a single merged star. These episodes are believed to be vital for the formation of a wide range of extremely important astrophysical objects, including X-ray binaries, close double-neutron stars, the potential progenitors of Type Ia supernovae and gamma-ray bursts, and double black holes that could produce gravitational waves (for more details on overall importance of the CEEs, as well as on many aspects of the involved physics, see the review in Ivanova *et al.* 2013).

The outcomes of the CEEs are believed to fall into two main divergent categories – either a close binary formation, or a merger of the two stars into a single star. The boundary between the outcomes is usually found by comparing the available energy source (the energy difference between the orbital energies before and after the CEE, $\Delta E_{\rm orb}$), and the required energy expense (the energy required to displace the envelope to infinity, $E_{\rm bind}$). This is known as the energy formalism (Webbink 1984; Livio & Soker 1988):

$$\alpha \Delta E_{\rm orb} = E_{\rm bind} = \frac{G m m_{\rm env}}{\lambda R} \tag{1.1}$$

Here, α is the efficiency of the use of the orbital energy, and it can be only less than one. m is the mass of the donor star – the star whose expanded envelope has formed the CE, $m_{\rm env}$ is the mass of that envelope, R is the radius of the donor. The parameter λ relates the envelope's binding energy $E_{\rm bind}$ as integrated from the stellar structure with its parameterized form.

This famous equation, while seems to be transparent and straightforward, buries a lot of not yet fully understood physics. For example, there are plenty of uncertainties in how to determine $E_{\rm bind}$. That includes such questions as what is the boundary between the core and the ejected envelope, whether the thermal energy can be converted effectively in the mechanical energy of the envelope, and whether the out-flowing envelope should be evaluated using Bernoulli integral which is inclusive of the P/ρ term in addition to thermal energy (Dewi & Tauris 2000; Deloye & Taam 2010; Ivanova & Chaichenets 2011; Ivanova 2011a). For instance, the uncertainty in the boundary may lead to an order of magnitude uncertainty in the value of $E_{\rm bind}$, and, consequently, same uncertainty in the orbital separations of a post-CEE binary (Ivanova 2011a).

Another deficiency of the classic energy formalism is that, by design, the Equation (1.1) implies that the kinetic energy of the ejected envelope at infinity is zero (or, in other words, is substantially smaller than the two considered energies). However, as has been shown recently for the case of low-mass giants, if the entire envelope has been successfully ejected, that envelope can carry away between 20% and 55% of the released orbital energy, mainly in the form of the kinetic energy, and, to a lesser degree, in the form of the thermal energy (Nandez & Ivanova 2016).

Considering three fundamental energies – gravitational potential energy, thermal energy of the envelope and kinetic energy – CEEs were studied using different three-dimensional (3D) hydrodynamic codes. Universal evolution of a CEE in 3D simulations is to start a plunge-in of the companion, during which the binary orbit shrinks strongly on the timescale comparable to the initial binary orbital period. By the end of the plunge-in, the strength of all frictional interactions between the shrunken binary and the inflated envelope is strongly reduced. The binary settles into a slow spiral-in with a minuscule orbital dissipation rate (Ricker & Taam 2008; De Marco *et al.* 2011; Ricker & Taam 2012; Passy *et al.* 2012; Nandez *et al.* 2015; Ohlmann *et al.* 2016a; Staff *et al.* 2016). Independently the type of employed code, only partial envelope ejections had been obtained. It showed clearly that something essential is missing, and the missing piece is neither the type of the code, nor the resolution, but should be related to physics that has not been yet taken into account.

Indeed, there are other, "non-fundamental", ways in which the energy can be generated or lost during a CEE.

One of the sources of energy is due to accretion on a companion while it swirls inside the common envelope. Energy comes from the release of the potential energy of the accreted material while it reaches the surface of the companion, in the form of heat and radiation. If the companion does not accept all the accreted material, some energy may be released back via jets. Jets inject the kinetic energy back to the common envelope, inflating "bubbles" and helping to remove the common envelope this way (Akashi & Soker 2016; Shiber *et al.* 2017). The total input from this energy source depends on the mass of the companion, on the mass accretion rate, and the time during which the accretion takes place. To find the accretion rate, a common way in the past was to use Bondi-Hoyle-Lyttleton prescription (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Bondi 1952). It has been found however that in 3D simulations the accretion rate onto the companion is significantly smaller than the Bondi-Hoyle-Lyttleton prescription would provide (Ricker & Taam 2012). On the other hand, more recent, albeit simplified, studies of the accretion during a CEE, have found accretion rates that approach the Bondi-Hoyle-Lyttleton prescription (MacLeod & Ramirez-Ruiz 2015a,b). It is not clear if one of the accepted simplifications, or the differences in the considered stellar models in 3D studies and in simplified studies, have led to the striking difference in the accretion rates. The time on which this energy can be generated efficiently can be as small as the initial orbital period, as this dictates the timescale of the plunge-in. After the plunge, a shrunken binary clears out its neighborhood and may avoid continued accretion. Whatever accretion rate would be eventually found to be correct, the case when the accretion source of energy can become comparable to the binding energy of the envelope is likely limited to the case when a companion, while accreting at its Eddington rate, is spiraling-in to a very large donor, $\sim 1000 R_{\odot}$.

The role of the magnetic field has also been contemplated. Magnetic fields were found to strongly shape the outflows from the common envelopes (Nordhaus & Blackman 2006; Nordhaus *et al.* 2007). For little-bound envelopes of AGB stars, these magnetic outflows has been argued to help to unbind the entire envelope, although the complete ejection was not directly obtained in simulations. For low-mass red giants, the presence of the magnetic field was determined to be dynamically irrelevant for a common envelope ejection, despite strong amplification of the magnetic fields (Ohlmann *et al.* 2016b).

In some CEEs, if a non-degenerate companion has initially failed to eject the common envelope, and has to merge with the donor's core, the companion's material can trigger an explosive nucleosynthesis on the outer parts of the core of the evolved donor. This can lead to the explosive ejection of not just the envelope, but also of both the hydrogen and the helium layers (Ivanova 2002; Podsiadlowski *et al.* 2010).

The energies listed above are not guaranteed to be present in all CEEs. However, there is one source of energy which is naturally present in all the cases – the recombination energy. It is important that four phases of a CEE, qualitatively different in the involved dominant physical processes and the timescales, are currently distinguished: (a) loss of corotation, (b) plunge-in (this is the stage which is often mistaken for a CEE as a whole), (c) self-regulating spiral-in (this stage only takes place if the plunge-in did not lead to complete envelope ejection); (d) termination of the self-regulating phase, with either a delayed dynamical ejection, or a nuclear ejection, or with a merger (for qualitative definitions of the phases, see Ivanova 2011b; Ivanova *et al.* 2013, and quantitative definitions can be found in Ivanova & Nandez 2016). Recently, it was shown that during the loss of corotation, a substantial fraction of the initial envelope mass can be lost before the CEE enters the dynamical phase during which the energy formalism is applicable. The mass is lost while the the donor overfills its Roche lobe, but the expanded envelope does not yet go beyond L_2/L_3 points, and the phase can last for thousand of years (Pavlovskii & Ivanova 2015; Pavlovskii *et al.* 2017). The self-regulating phase also could last thousand of years (Meyer & Meyer-Hofmeister 1979; Podsiadlowski 2001). At this timescale the radiative energy loss from the common envelope surface is becoming large enough to affect the overall energy budget (Ivanova 2002). As it has appeared, the recombination energy plays an important, while varying, role during most of stages of a CEE.

2. The role of the recombination energy

As the common envelope expands and its material cools down, the ionized plasma can recombine, releasing binding energy which is usually referred to as recombination energy, $\Delta E_{\rm rec}$. We note that as cooling continues, formation of molecules can take place, also releasing energy, but here we will not consider the energy related to molecule formation. Recombination energy was suggested to be helpful for ejecting outer stellar layers even before the concept of a CEE, to say nothing of the energy formalism (e.g., Lucy 1967; Roxburgh 1967). Binary population synthesis studies have shown that the inclusion of the recombination energy in the energy formalism, as a part of the envelope's internal energy, provides the best fits to the observations of subdwarf B stars (Han *et al.* 1994, 2002). On the other hand, it has been argued that the recombination energy cannot help ejecting the CE, as the most of the recombination energy would leave the envelope immediately in a form of radiation, as opacity in the envelope might be too low to effectively reprocess energy released in photons of specific wavelengths (Soker & Harpaz 2003). We note that this restriction is indeed valid if the optical depth of the layer where the recombination takes place is small (it is close to the photosphere), and the layer itself is very thin, so the released photons can not be used to heat the envelope material.

The amount of the recombination energy that is stored in an envelope of the mass $m_{\rm env}$ prior the start of a CEE, neglecting the ionization of the elements others than hydrogen and helium, can be evaluated as follows:

$$\Delta E_{\rm rec} \approx 2.6\times 10^{46} \times \frac{m_{\rm env}}{M_\odot} {\rm ergs} \times (X f_{HI} + Y f_{HeII} + 1.46 Y f_{HeI}) \tag{2.1}$$

Here X is the hydrogen mass fraction, Y is the helium mass fraction, f_{HI} is the fraction of hydrogen that becomes neutral, f_{HeI} is the fraction of helium that becomes neutral, and f_{HeII} is the fraction of helium that becomes only singly ionized. With a typical value for helium content and assuming complete recombination from initially completely ionized material, the released energy can be as high as $\Delta E_{\rm rec} \approx 3\times 10^{46} \times m_{\rm env}/M_\odot$ erg. Comparing this energy with the binding energy as in the Equation (1.1), one can see that once the radius of the star exceeds $R \gtrsim 127 R_\odot/\lambda$, a star can be said to have positive total energy even before the start of the CEE, i.e. it is unbound. However, first of all, the release of this energy has to be triggered. Second, this energy should not escape in a form of radiation, but be reprocessed by the envelope itself.

2.1. *Recombination during a plunge-in phase*

As was mentioned above, an unavoidable outcome of 3D simulations of a CEE with a hydrodynamic code that did not include the recombination energy in the adopted equation of state is to obtain a plunge-in phase, to eject a part of the envelope, to inflate the remaining bound envelope well above the binary orbit, and to start a slow spiral-in, during which the depletion of the binary orbit is becoming too small to be further treated by a hydrodynamic code (Ricker & Taam 2008; De Marco *et al.* 2011; Ricker & Taam 2012; Passy *et al.* 2012; Nandez *et al.* 2015; Ohlmann *et al.* 2016a; Staff *et al.* 2016). The primary reason for this outcome is the decoupling of the shrunken binary orbit from the remaining inflated envelope, as both gravitational or viscous drags are becoming too small (Ivanova & Nandez 2016). On the other hand, the very first attempt to include the recombination energy in the equation of state have resulted in the complete common envelope ejection (Nandez *et al.* 2015).

This very first study, where the common envelope was completely ejected, have considered the formation of the specific double-white dwarf (DWD) binary WD 1101+364, a well-measured binary system that has $P_{\rm orb} = 0.145$ d, and a mass ratio of $q = M_1/M_2 = 0.87 \pm 0.03$, where $M_1 \simeq 0.31 M_\odot$ and $M_2 \simeq 0.36 M_\odot$ are the masses of the younger and older WDs, respectively (Marsh *et al.* 1995). DWD binaries are the best test-site for CEE as their younger white dwarfs must have been formed during a CEE, and their pre-CEE binary separations are strongly restricted by the well known core-radius relation of low-mass giants, albeit there is a fairly small dependence on the total giant mass (van der Sluys *et al.* 2006). Several simulations performed to form WD 1101+364 using the allowed range of the initial binaries and using the equation of state that did not include the recombination energy, also did not unbind the envelope (Nandez *et al.* 2015). The analysis has shown that the binding energy of the remaining bound envelope could be easily overcome by the release of the recombination energy, if the recombination energy release will be triggered at the right time. This is exactly what the simulations with the recombination energy taken into account have shown (Nandez *et al.* 2015).

The physics of the complete envelope ejection can be understood via introduction of the *recombination radius* – the radius at which the released specific recombination energy is larger than the local specific potential energy (for more detail, see Ivanova & Nandez 2016). Usually hydrogen starts its recombination when all helium is already recombined; in this case this radius is $r_{\rm rec,H} \approx 105 R_\odot \times m_{\rm grav}/M_\odot$. Here $m_{\rm grav}$ is the mass within the recombination radius – this mass includes the companion, the core of the donor, and the mass envelope within $r_{\rm rec,H}$.

During a CEE, at first, the frictional forces dissipate energy from the binary orbit and dump the same energy into the common envelope. This leads to the first dynamical ejection of a fraction of the envelope, and it is the ejection that is present in all the types of 3D simulations, independent of the equation of state or the adopted method.

If a still bound envelope has been dynamically expanded beyond of the envelope's recombination radius, its material is doomed to be ejected to infinity via the recombination outflows on a dynamical timescale, leading to a prompt binary formation (Ivanova & Nandez 2016). If the envelope expansion beyond the recombination radius is slow (only a small fraction of the envelope has been expanded beyond the recombination radius on a dynamical timescale), a transition to a slow spiral-in takes place. In this case, recombination leads to *steady* recombination-powered outflows, the mass lass through these outflows can be slowly accelerating, as $m_{\rm grav}$ decreases during the continuing mass loss (Ivanova & Nandez 2016). We note that it has been proposed, but not yet verified against the 3D outcomes, that in the case when *steady* outflows are established, the envelope's enthalpy rather than the envelope's thermal energy determines the outcome (Ivanova & Chaichenets 2011). During the transition to a slow-spiral-in, the remaining bound envelope can also "fall" back on its parabolic trajectory. Such a fallback triggers another partial envelope ejection that acts on a dynamical time and is presumably powered by the compression ionisation and then recombination of the helium layer (Ivanova & Nandez 2016).

Let us now consider the efficiency of the use of the recombination energy. It has been found that the structure of ionisation zones in an expanded common envelope is drastically different from the same in unperturbed stars. The zones of partial ionisation of helium and hydrogen, i.e. where f_{HI}, f_{HeI} and f_{HeII} are changing from 0 to 1, are very thick in mass each – e.g., they can reach $\sim 0.5 M_\odot$ in a low-mass giant. Hydrogen is still 1% ionized at an optical depth of 100 or more (Ivanova *et al.* 2015; Ivanova & Nandez 2016), although a smaller degree of ionisation can remain in some cases closer to the photosphere. The recombination energy therefore can be well reprocessed. Notably, the recombination energy of helium has absolutely no chance for escape in a form of radiation and all can be used for the envelope expansion (Ivanova *et al.* 2015).

2.2. *Recombination during a self-regulated spiral-in*

During a self-regulated spiral-in, the energy transfer throughout the common envelope, the nuclear energy generation, and the energy losses from envelopes surface are becoming important both for the energy budget and for the thermal structure of the shared envelope. At the same time, the orbital period of the shrunken binary is becoming substantially smaller than the dynamical timescale of the inflated envelope, mandating a 3D hydrodynamic code to switch to a timestep which is extremely small if compared to the timescale on which the envelope evolves. As a result of these complications, no existing 3D hydrodynamic code is capable of following the self-regulated spiral-in (we note that the first step towards treating the convection properly has been made recently by

Ohlmann *et al.* 2017). There is a 3D study that specifically investigated how the plunge-in transits, via a slow spiral-in, into the self-regulated spiral-in (Ivanova & Nandez 2016). However, the simulations had to end by the time when the thermal timescale processes could become important. Instead of 3D, a common approach for studying a self-regulated spiral-in is to use an one-dimensional (1D) stellar code, modifying it to *mimic* CEE conditions, with a number of simplifications which could be different from study to study (the pioneering studies are Taam *et al.* 1978; Meyer & Meyer-Hofmeister 1979, and many thereafter).

In one of the 1D studies, it has been found that during the self-regulated spiral-in, after the envelope has been inflated, a delayed dynamical instability initiating pulsations of growing amplitude takes place (Ivanova 2002; Han *et al.* 2002). These growing pulsations might lead to a delayed dynamical ejection of the envelope, although the ejection itself was not obtained.

Ivanova *et al.* (2015) have explored 1D CEE evolution for a low-mass giant in a systematic way, by introducing a constant "heating" source of the two types – uniform heating throughout the envelope, and a shell-type at the base of the envelope. As a reaction to the artificial "heating", the envelope readjusts by expanding to its new "equilibrium" radius – the radius at which the inflated star radiates away the amount of energy that it receives from both the artificial heating and the shell nuclear burning – and is cooling down. Double ionized helium starts its recombination. This recombination is becoming energetically important and can produce an even higher rate of the energy input than the artificial heating. The recombination zones of once ionized helium and hydrogen propagate inwards in mass. With high heating rates and quick initial envelope expansion, outer layers start moving faster than their local escape velocity. For moderate heating rates, the envelope expands to its "equilibrium" radius but is becoming unstable. Ivanova *et al.* (2015) determined that, due to the expansion of the zones of partial ionisation of hydrogen and helium in mass, the envelope's pressure-weighted Γ_1 becomes less than 4/3, and almost the entire envelope becomes dynamically unstable.

In further studies, using a similar approach for an artificial heating source while using a 1D stellar code that includes hydrodynamic terms, Clayton *et al.* (2017) found that the heated envelopes, if not dynamically ejected at high heating rates, also become unstable and start to experience non-regular pulsations, with the periods between 3 and 20 years. Some pulsations lead to the ejection of a fraction of the envelope, with up to 10% of the envelope mass escaping per ejection episode. These ejections have a nature similar to the shell-triggered ejections found earlier in 3D studies of slow spiral-ins (Ivanova & Nandez 2016).

2.3. *Recombination and the outcomes of CEEs*

Two families of the outcomes are expected.

If a CEE has resulted in a prompt binary formation, the "classical" α that relates the initial donor and the final orbit, as in the Equation (1.1), can be as large as one or even a bit more that one. The revised energy formalism that taken into account the energy that the ejected material carried away and the recombination energy can be found in Nandez & Ivanova (2016). This revision of the energy formalism is based on the fits of 3D simulations of CEEs for the grid of initial binaries with low-mass giant donors and low-mass white dwarfs.

If a CEE has resulted in a self-regulated spiral-in, the "classical" α is only about 0.05-0.25, and the envelope's material is lost in semi-regular recombination-triggered pulsations with an interval between the ejections of 3-20 years (Clayton *et al.* 2017). We note however that this value of α does not yet take into account that some material

https://doi.org/10.1017/S1743921317003398 Published online by Cambridge University Press

has been ejected "dynamically" before the self-regulated spiral-in has started, and more studies are needed.

2.4. *Appearance of the CEEs*

All CEEs, including those that end up as mergers, are accompanied by a dynamical ejection of at least some envelope material. As plasma expands, it cools down and starts recombination. Before the recombination starts, gas expansion is adiabatic. As most of envelope material has initially about the same entropy, the location at which the recombination starts is also similar for the ejected material. Opacities below the place where gas recombines are high, while above they are low, at least until the cooled gas can form dust. This recombination front appears as a "photosphere" that hides beneath it the common envelope, for as long as there is plasma to be recombined. Once all material have recombined, it reveals the common envelope. This model of Wavefront of Cooling and Recombination (WCR) has been proposed by Ivanova *et al.* (2013). It utilizes an analytical model of Popov (1993), proposed for hydrogen envelope cooling in Type II supernovae during the plateau phase.

This WCR model explains naturally curious observational features of the new class of transients, Luminous Red Novae:

• Large "apparent" size and luminosities, plateau phase for the light-curve.

• "Red" color (temperature of the object is about 5000K).

• Fast decline of luminosities (timescale of the decline is a fraction of the plateau time, and it is much smaller than the inferred dynamical timescale of the object)

• Spectroscopic velocities, which are few hundreds of km/s, are larger than the expansion rate of the "effective" radius, which are less than a hundred of km/s

Ivanova *et al.* (2013) have shown that the range of the expected plateau time and luminosities for stellar mergers is consistent with the observed ranges for LRNe, and that the rate at which LRNe are observed can also be provided by the stellar mergers. Some attempts are made to fit the observed light-curves of LRNe. To fit V1309 Sco outburst (Tylenda *et al.* 2011), Ivanova *et al.* (2013) have used Popov's analytical model, for which velocities and the mass of the ejecta were provided by 3D simulations (detail of 3D simulations are in Nandez *et al.* 2014). The light-curve of M31 2015 LRN was fitted with the merger of a binary system in which the primary star is a $3 - 5.5 M_\odot$ sub-giant branch star with radius of $30 - 40 R_\odot$ (MacLeod *et al.* 2017).

If a CEE has entered into self-regulated spiral-in, the common envelope object appears as a luminous pulsation variable (note that an LRN-type outburst is expected to precede this). On the Hertzsprung-Russell diagram, the pulsations swirl around the equilibrium point, the position of which is dictated by the heating rate. Depending on the heating rate, that point can be located at $\log_{10} T_{\rm eff} \approx 3.4 - 3.5$ (while $\log_{10} T_{\rm eff}$ during the pulsation can be changing between 3.2 and 3.7) and at $\log_{10}(L/L_\odot) \approx 4.0 - 4.4$ (while $\log_{10}(L/L_\odot)$ can vary by up to 500 times between the minimum luminosity during the pulsation, and the maximum luminosity). The pulsations are not symmetric with time, and the time that a heated envelope spends at higher than equilibrium luminosity is much smaller than the time it takes for the star to be "re-heated" back to its equilibrium value (for examples of light-curves, see Clayton *et al.* 2017).

However, if a CEE had neither resulted in a clean merger, nor had entered in a self-regulated spiral-in, the observational signatures are less understood. While the first dynamical ejection can provide an LRN-type outburst, further outflows take places when some initially available recombination energy has been processed to unbind the envelope. This may change the observed luminosities, presence of the plateau, and the timescale of the outbursts. No self-consistent 3D modeling of a CEE leading to a binary formation inclusive of radiative energy loss have been done yet, and is the important subject of future studies.

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