Dynamics of jets during the Common Envelope phase

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ABSTRACT

Common envelope (CE) is an important phase in the evolution of many binary systems. Giant star / compact object interaction in binaries plays an important role in high-energy phenomena as well as in the evolution of their environment. Material accreted onto the compact object may form a disk and power a jet. We study analytically and through numerical simulations the interaction between the jet and the CE. We determine the conditions under which accreting material quenches the jet or allows it to propagate successfully, in which case even the envelope may be ejected. Close to the stellar core of the companion the compact object accretes at a larger rate. A jet launched from this region needs a larger accretion-to-ejection efficiency to successfully propagate through the CE compared to a jet launched far from the stellar core, and is strongly deflected by the orbital motion. The energy deposited by the jet may be larger than the binding energy of the envelope. The jet can, thus, play a fundamental role in the CE evolution. We find that the energy dissipation of the jet into the CE may stop accretion onto the disk. We expect the jet to be intermittent, unless the energy deposited is large enough to lead to the unbinding of the outer layers of the CE. Given that the energy and duration of the jet are similar to those of ultra-long GRBs, we suggest this as a new channel to produce these events.

Key words: Accretion, accretion disks – Gamma-ray burst: general – Methods: numerical – Binaries: general – Stars: evolution – Stars: jets

1 INTRODUCTION

Most massive stars are in binary systems (71% of O-type stars according to Sana et al. 2012). The interaction between stars in binaries is responsible for producing a variety of transient phenomena in astrophysics, including, among others, type Ia supernovae (single degenerate: Whelan & Iben 1973; double degenerate: Webbink 1984 and Iben & Tutukov 1984), gamma-ray bursts (e.g., Brown, Lee, & Moreno Méndez 2007; Moreno Méndez et al. 2011; Berger 2014), ultraluminous x-ray sources (e.g. Rappaport, Polskiadowski, & Pfahl 2005; Liu et al. 2013), novae (Crawford & Kraft 1956; Darnley et al. 2012), millisecond pulsars (Wijnands & van der Klis 1998), gravitational waves (Taylor & Weisberg 1982; Abbott et al. 2016), and common envelopes (CE; Ivanova et al. 2013), among others.

The CE phase, in which one of the components of a binary system is engulfed by the stellar envelope of the secondary star, is a brief but crucial phase in the formation of many compact binary systems. This is especially true in binary systems formed by compact objects with an orbital distance smaller than the radius of the progenitors (e.g., Hulse & Taylor 1975; Burgay et al. 2003). The CE phase generally occurs after a phase of unstable mass transfer where the binary system loses angular momentum, or when one of the stars has a fast radius increase due to, e.g., the onset of the red-giant phase, and it fills its Roche lobe (RL; see, e.g., Eggleton 1983).

CE phases are short-lived (∼ a year to a few hundreds of years) when compared to other stellar stages. Thus, observational examples of CEs are scarce. Nonetheless, Tylenda et al. (2011) and Tylenda & Sokol (2006) have suggested that events like those observed in V1309 Sco and V838 Mon, among others, are the result of a CE leading to a merger. Also, MacLeod et al. (2017) discussed a luminous red nova outburst in M31 as the onset of CE.

Analytical studies of CE evolution are limited because its description involves complicated, unsteady physical processes (e.g., mass transfer and accretion disk physics). On the other hand, physical phenomena happening at very different scales (e.g., the size of a giant star ∼ 10^{13} cm and a disk around a compact object ∼ 10^6 cm; Taam & Sandquist...
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limit the use of numerical simulations.

As a consequence, CE evolution is far from being a well understood problem. In particular, what brings a CE phase to an end is not well comprehended. This may be due to the conversion of orbital energy into kinetic energy of the expelled envelope (Ivano-va et al. 2013). It is also not clear how much mass is accreted by the engulfed object. This question is especially relevant to determine whether a neutron star (NS) or a black hole (BH)-NS binary system are produced after a CE episode between two NS progenitors.

The Bondi-Hoyle-Lyttleton (BHL, Bondi & Hoyle 1944; Hoyle & Lyttleton 1939) accretion radius can be a considerable fraction of the stellar radius. The accretion rate estimated by Brown (1995) and Chevalier (1996), when including highly-efficient neutrino cooling, is large enough to favour the formation of BH-NS systems over NS-NS systems. However, when one considers the density gradient expected inside the envelope of a star, angular momentum prevents accretion by a factor of up to a hundred (MacLeod & Ramírez-Ruiz 2015; Lora-Clavijo, Cruz-Osorio, & Moreno Méndez 2015), likely avoiding the formation of a BH.

The BHL rate is much larger than the mass accretion rate obtained from the Eddington limit, which considers spherical accretion of material without external pressure. However, this limit does not directly apply to accretion through a disk (Shakura & Sunyaev 1973). Hypercritical accretion may occur during certain mass transfer stages in binaries with compact objects (Chevalier 1995; Brown & Weingartner 1994; Moreno Méndez et al. 2008; Moreno Méndez 2015). This is especially the case when the mass transfer rate is at least three to four orders of magnitude larger than the Eddington limit for accretion, as it is likely that the energy radiated by the accreted mass will be neutrino dominated.

Numerical simulations are essential to understand the CE. The first CE numerical studies were limited to one- and two-dimensions (e.g., Bodenheimer & Taam 1984; Fryxell & Taam 1988). Three-dimensional (3D) hydrodynamical studies of the CE phase have also been carried out (e.g., Terman, Taam, & Hernquist 1994; Rasio & Livio 1996; Livio & Soker 1988). Sandquist et al. (1998) studied the stages when the envelope is ejected. Also, Bobrick et al. (2017), found that jet appearance and quenching during CE can produce transient objects. Other 3D studies focused on the formation of degenerate stars (Sandquist, Taam, & Burkert 2000), the formation of Wolf-Rayet stars (De Marco et al. 2003), and the interaction of stellar objects within the CE phase, either by employing Eulerian (Ricker & Taam 2008, 2012) or Lagrangian (Passy et al. 2012) meshes.

Velocity gradients (Ruffert 1997, 1999; Armitage & Livio 2000) as well as density gradients (Lora-Clavijo, Cruz-Osorio, & Moreno Méndez 2015) can provide enough angular momentum to form a disk. Studies of jets at different scales (e.g., proto-stellar jets, jets from X-ray binaries, AGN, among others, see e.g., Livio 1999) show that accretion from a disk to a central star is typically associated to the creation of a jet with a velocity of order of the escape velocity and an ejection mass rate of ~10% of the accreting mass rate.

The presence of a jet may change the accretion rate onto the disk surrounding the compact object and, hence, the accretion onto the compact object itself. In addition, jets moving through a medium transfer energy to the surrounding environment, and have thus been suggested as an energy-deposition channel which may allow for the removal of the envelope during a CE phase (Armitage & Livio 2000; Soker 2014). Soker (2004) considered a jet launched by a main-sequence star or a white dwarf inside the envelope of a red giant (RG), while Papish, Soker, & Bukay (2015) considered a jet launched by a neutron star (NS) inside a 16 M⊙ RG. Both of them concluded that the jet feedback can eject the entire envelope and even part of the stellar core.

In this paper, we present detailed three-dimensional simulations of the interaction of a jet within the CE. Previous simulations that the jet can be deflected by the relative motion (orbital) of the compact object (Soker et al. 2013); or, if the jet grazes around the CE, it interacts with the ejected gas and produces hot low-density bubbles Shiber et al. (2017).

The paper is organised as follows. In Section 2 we estimate analytically under which conditions a jet can successfully propagate through the CE. Section 3 presents the numerical method and the results of three dimensional adaptive mesh refinement, hydrodynamic simulations. In Section 4 we discuss the results and in Section 5 we present our conclusions.

2 DYNAMICS OF THE JET PROPAGATING THROUGH THE COMMON ENVELOPE

In this Section, we present a simple analytical description of the interaction between the jet and the stellar envelope.

We consider a compact object moving through the envelope of a RG star. Accretion onto the compact object during the CE phase can lead to the formation of a disk which may drive a jet. Accretion onto the compact object engulfed inside the CE happens at a fraction of the Bondi-Hoyle-Lyttleton (BHL) rate

$$\dot{M}_{\text{BHL}} = \frac{4\pi G^3 M_{\infty}^2 \rho_{\infty}}{(c^2 + v^2)^{3/2}} \approx \frac{4\pi G^2 M_{\infty}^2 c \rho_{\infty}}{v_{\infty}^3},$$

where $M_{\infty}$ is the mass of the compact object, $\rho_{\infty}$ and $c_{\infty}$ are the density and sound speed of the stellar envelope, $v_{\infty}$ is the velocity of the compact object with respect to the velocity of the stellar envelope.

We assume that the orbital motion is supersonic, i.e. $v_{\infty} \gg c_{\infty}$, and place the reference system in co-motion with the compact object. Therefore, in this system of reference the compact object is static and a “wind” moves towards it due to the compact object motion through the envelope of the RG.

The jet dynamics depend on the jet properties at the injection region and on the density stratification ($\rho_{\infty}$; see equation 2) of the CE. If we assume that a fraction of the accreted mass, $\dot{M}_{\text{BHL}}$, ends powering the jet, the jet kinetic luminosity is directly proportional to the density of the material surrounding the compact object (see equation 1).

Following Papish, Soker, & Bukay (2015), we consider a 16 M⊙ red giant model (Taam, Bodenheimer, & Ostriker 1978) with a density profile given by

$$\rho_{\infty} = 0.68 \times \left(\frac{a}{R_{\odot}}\right)^{-2.7} \text{ g cm}^{-3},$$

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velocity, radius and density of the accretion flow are

$$v_r = -\sqrt{v_{\infty}^2 + \frac{2GM_{\odot}}{r}} \frac{\zeta^2 v_{\infty}^2}{r^2},$$

$$r = \frac{\zeta^2 v_{\infty}^2}{GM_{\odot}(1 + \cos \theta) + \zeta v_{\infty}^2 \sin \theta},$$

$$\rho_a = \frac{\rho_{\infty} \zeta^2}{r \sin \theta (2 \zeta - r \sin \theta)},$$

where $\zeta$ is the impact parameter and $\theta$ is the polar angle. We can determine the ram pressure of the material falling vertically onto the compact object (i.e., with $\theta = \pi/2$) by inverting these equations. We get

$$P_a = \rho_a v_r^2 = \rho_{\infty} v_{\infty}^2 \left( \frac{GM_{\odot}}{rv_{\infty}} \right)^2 \frac{1}{\sqrt{1 + \frac{2GM_{\odot}}{r v_{\infty}^2}}}. \quad (6)$$

In the system of reference of the compact object, the CE material streaming sideways acts as a wind moving towards the jet and compact object system with velocity $v_{\infty}$, corresponding to a wind ram pressure:

$$P_w = \rho_{\infty} v_{\infty}^2. \quad (7)$$

Figure 2 shows the ram pressures (equations 4, 6, 7) as a function of the distance $a$ from the centre of the RG star (assuming $\theta_j = 0.1$ radians, $v_j = c/3$, $M_\odot = 1 \ M_\odot$, and $r = 10^{11}$ cm). The shaded area represents the region of the parameter space where the jet successfully overcomes the accreting material ($P > P_a$), within the expected efficiencies (i.e., $\epsilon \lesssim 10^{-3}$). Regions above the $\epsilon \approx 10^{-2}$ line are excluded as there is not enough mass accreted to the disk to power the jet. Observations of astrophysical jets show that typically $M_j \sim 0.1 \ M_\odot$. Thus, we assume $M_j \lesssim 10^{-2} \ M_{\text{BHL}}$. The kinetic luminosity of the wind determines whether the jet trajectory is substantially deflected. The amount of deflection of the jet trajectory also determines the jet energy and momentum deposition into the envelope.

Following the evolutionary track corresponding to $\epsilon = 10^{-2}$ in Figure 2 (with the compact object approaching the stellar core with time), the jet initially propagates unperturbed. When the compact object moves to radii $a \lesssim 10^{11}$ cm, the jet is substantially deflected by the sideways streaming wind. For lower efficiencies (e.g., $\epsilon \lesssim 10^{-4}$), the jet propagates unperturbed until $a \gtrsim 10^{13}$ cm. For radial distances $a \lesssim 2 \times 10^{11}$ cm the jet is quenched. For very low efficiencies ($\epsilon \lesssim 10^{-5}$) the jet is quenched at all radii. It is easy to see from equations 4 and 6 that $P_j/P_w$ increases with jet collimation (i.e., smaller $\theta_j$), larger accretion/ejection efficiencies $\epsilon$, larger distances $a$ and for CE with lower masses $M(a)$. As the ratio $P_j/P_w \propto M(a)$, at a fixed radial distance from the centre of the CE, jets from white dwarfs and neutron stars are much more deflected than jets from BH.

In order to better understand the dynamical evolution of the system, in the next Section we present numerical simulations.

1 Numerical simulations by MacLeod & Ramirez-Ruiz (2015) show that the mass accretion rate $M_a$ can be ten to a hundred times smaller than $M_{\text{BHL}}$. 

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**Figure 1.** Schematic representation of the reference system used in this paper. $xz$ is the orbital plane, $a$ is the orbital separation between the centre of the donor star and the compact object (located at $x = a$, $y = z = 0$). $v_{\infty}$ is the compact object velocity through the common envelope; $r$ is the distance from the compact object to a point $P$. The jet is assumed to move along the $y$-axis with velocity $v_j$ and opening angle $\theta_j$, where $a$ is the distance from the centre of the donor star to the position of the compact object (see Figure 1 for a schematic representation of the geometry of the system).

For this stellar profile, the BHL mass accretion rate (equation 1) for a $5M_\odot$ BH is given by:

$$M_{\text{BHL}} = 5 \times 10^{29} \left( \frac{M_{\odot}}{400 M_\odot} \right)^2 \left( \frac{M(a)}{20 M_\odot} \right)^{-3/2} \left( \frac{a}{R_\odot} \right)^{-1.2} \text{g s}^{-1}$$

where $M(a)$ is the mass enclosed within the radius $a$, and we assume that the compact object moves with keplerian velocity $\sqrt{GM(a)/a}$.

Once the jet is ejected from the compact object/disk system, it has to make its way through the dense CE material which is falling onto the compact object. The jet is “successful” (i.e. it is able to propagate through the CE) if its ram pressure is larger than that of the material accreting onto the compact object. To understand under which conditions this happens, we next estimate the ram pressures of the jet and of the accreting material.

The density of the jet at a distance $r$ from the compact object is given by $\rho_j = M_j/[4\pi(1 - \cos \theta_j)r^2 v_j^3]$, where $v_j$ and $\theta_j$ are the velocity and opening angle of the jet (measured from the polar axis). Assuming $\theta_j \ll \pi/2$, and taking the jet mass ejection rate $M_j = \epsilon M_{\text{BHL}}$ as a fraction $\epsilon$ of the BHL mass accretion rate, the jet ram pressure is then given by

$$P_j = \rho_j v_j^2 = \rho_{\infty} v_{\infty}^2 \left( \frac{GM_{\odot}}{rv_{\infty}^2} \right)^2 \frac{2\epsilon v_j}{\theta_j^2 v_{\infty}}. \quad (4)$$

To estimate the ram pressure of the accreting material, we use the approximate description of Bisnovatyi-Kogan et al. (1979) (see also Edgar 2004 and references therein), which studied the ballistic (i.e., assuming a “cold” fluid) trajectory of the gas falling towards the compact object. The radial
3 NUMERICAL SIMULATIONS OF A JET INSIDE A CE

In this Section, we present the numerical setup and numerical simulations of the interaction between a jet launched from a BH, the material accreting onto the BH, and a wind with a density gradient.

In our simulations we assume that the jets are launched perpendicular to the orbital plane (i.e. parallel to the orbital angular momentum). Considering the supernova kick a compact object may receive when formed, this may not always be the case. However, it is a highly likely scenario for a 5 \(M_\odot\) BH (the larger mass of the BH gives a lower velocity for similar momenta when compared to a NS, if a SN happens at all). Furthermore, binary interactions after the SN happens at all). Furthermore, binary interactions after the BH is formed may align the BH spin with the orbit as all mass transfer will occur with the orbital angular momentum. Nonetheless, the dynamics of strongly misaligned jets may be very different from that of our simulations.

3.1 Simulations setup and input parameters

We study the dynamics of a jet propagating through a common envelope by performing a series of three-dimensional (3D) simulations. The simulations employ the adaptive mesh refinement, Eulerian code \textit{Mezcal} (De Colle et al. 2012a), which solves the hydrodynamics equations using a second order shock-capturing solver. The code has been extensively used to study the dynamics of Newtonian (e.g., De Colle & Raga 2006; De Colle, Raga, & Esquivel 2008) and relativistic (e.g., De Colle et al. 2012b,c) jets.

For the CE density stratification, we consider a 16 \(M_\odot\) red giant star (see equation 2). For the compact object, we consider a BH with a mass \(M_{co} = 5 \ M_\odot\) located at a radial distance \(a = 1.1 \times 10^{13}\ \text{cm}\) from the centre of the RG\(^2\).

Although our simulations refer to a particular compact object mass, we expect results qualitatively similar for other compact object masses. In particular, the results of these simulations can be applied also to the case of a NS engulfed in the envelope of a giant star.

A conical jet with an opening angle \(\theta_j\), a velocity \(v_j = c/3\) and a density \(\rho_j\) is launched from a spherical boundary centred in \((x, y, z) = (0, 0, 1.1 \times 10^{13}\ \text{cm})\) and with a radius \(r_{in} = 10^{13}\ \text{cm}\) (see Figure 1). The jet is injected into the computational box at \(t = t_{lag}\) (either at a time large enough for the BHL accretion to achieve a steady state, or at \(t = 0\)). The jet density is initialised as \(\rho_j = \eta \rho_{in} (x^2 + y^2)/v_j^2\), where \(\eta = P_j/P_w\) is the ratio between the jet and wind ram pressures. We vary \(\eta\) from 0 to 1000, and we consider models with \(\theta_j = 15^\circ\) and \(\theta_j = 30^\circ\).

The wind material is launched from the \(x y\) plane at \(z = 2 \times 10^{12}\ \text{cm}\), with keplerian velocity \(v_{\infty}\). The simulations are performed in the system of reference (SoR) of the compact object. In this SoR, the CE material moves towards the compact object with a velocity \(v_{\infty}\), acting as a wind. The gravitational effects of the compact object are included in the calculation. Given that the total accreting mass in the computational box \((\sim 0.01 \ M_\odot)\) is much smaller than the mass of the compact object, we neglect the self-gravity of the CE.

The numerical domain, centred at the compact object position, spans \(\pm 2 \times 10^{12}\ \text{cm}\) in the equatorial plane \((x z)\) and \(2 \times 10^{12}\ \text{cm}\) along the polar axis \((y\)-axis\). We take reflection boundary conditions across the equatorial plane \((y = 0)\), inflow boundary condition at the \(xy\) plane and outflow boundary conditions in the other boundaries. We employ \((64, 32, 64)\) cells at the coarsest level of refinement, with three or four levels of refinement, corresponding to a maximum resolution of \(\Delta x = \Delta y = \Delta z = 7.8/15.6 \times 10^6\ \text{cm}\) for the high- and low-resolution models (labelled with “HR” and “LR” in Table 1) respectively. The base of the jet and the surrounding region \((r \leq 3 \times 10^{13}\ \text{cm})\) is resolved at the maximum resolution, while the jet cocoon by lower levels of refinement. The total integration time is either 0.2, 1.4, or \(10 \times 10^9\ \text{s}\) (the wind crossing time is \(10^5\ \text{s}\)) depending on the model. The values of \(\eta, v_{\infty}, \theta_j, R_{lag}\), jet opening angle \(\theta_j\), resolution and integration time \(t_{int}\) for all the models are shown in Table 1.

3.2 Accretion on the compact object

To test the implementation of our initial conditions, we simulate the accretion onto a compact object in the case when there is not a jet injected in the computational domain, and including a density gradient in the accreting material.

Figure 3 shows the temporal evolution of the accretion on the compact object (model BHLhr). The shocked material accreting onto the compact object forms an elongated structure (hereafter, the “bulge”) which after approximately \(10^5\ \text{s}\) completely engulfs the BH and has density values of \(2\) The binary stellar evolution channel leading to this system is similar to those proposed in Chevalier (2012) or Postnov & Yungelson (2014).
order $\rho \sim 10^{-5}$ g cm$^{-3}$, this is, $\sim 10$ times larger than the density of the ambient medium at that radius. Due to the drop in the CE density as a function of $z$ (see equation 2), accretion onto the compact object is asymmetric. The excess in the angular momentum results in the formation of a disk-like structure at $t = 2 \times 10^5$ s, with a radius slightly smaller than $5 \times 10^{11}$ cm, and density values close to $10^{-6}$ g cm$^{-3}$. The latter can be clearly seen in the lower panel of Figure 3.

To check for numerical artefacts, we also ran a simulation with the same input and boundary conditions as model BHLhr, but with lower resolution (three levels of refinement, BHLlr), and two simulations with a smaller computational domain (reducing the size of each axis by a half), for both high and low resolutions (models small lr and small hr, respectively).

The temporal evolution of the mass accretion rate $\dot{M}$ at the inner boundary $r_{in}$ is shown in Figure 4. Independently of the resolution or domain size $\dot{M}$ increases until $t \sim 10^5$ s, when the accretion rate achieves a quasi-steady state with $\dot{M} \sim 10^{-5} M_\odot$ s$^{-1}$ at $t \sim 10^5$ s. This accretion rate is much smaller than $\dot{M}_{\text{BHL}}$ ($\dot{M} \approx 0.1 \dot{M}_{\text{BHL}}$, see the grey line in Figure 4) because of the presence of a density gradient in the CE density profile, and thus in the accreting material.

These results are qualitatively consistent with those of MacLeod & Ramirez-Ruiz (2015), and independent of the resolution when using a large domain. In particular, the mass accretion rate estimated from this simulation (see Figure 4) is slightly larger ($\approx 50\%$) with respect to the value determined by MacLeod & Ramirez-Ruiz (2015) (see their Figure 10).

Figure 4 shows that the size of the computational box must be large enough to avoid boundary effects which strongly affect the BHL accretion at late times. In the rest of the simulations we employ four levels of refinement and the large domain size (as in the simulation shown in Figure 3).

### 3.3 Global morphology of a jet propagating in a CE

In order to understand the dynamics of a jet launched from the disk around a compact object within a CE, we ran a series of numerical simulations with different values of $\eta = P_j/P_w$ (see Table 1). As discussed in Section 3.2, a quasi-steady state in the accretion process on the compact object is achieved after $\sim 10^5$ s, when the accreted material has formed a bulge that covers the BH. Thus, to properly model the interaction between the jet and the accreting material, the jet is injected after a time $t = t_{\text{lag}} = 10^5$ s.

Figure 5 shows the temporal evolution of a jet with $\eta = 300$. The jet first drills through the bulge (i.e., the shocked material accreting onto the compact object) before moving through the stellar envelope with a velocity considerably slower than the injected velocity ($v \sim 0.01 v_j$) and reaches $y \sim 10^{12}$ cm at $t \sim 1.1 \times 10^5$ s. Interestingly, the bulge pressure and density gradients push the jet against the wind (i.e. in the compact object orbital direction). As the jet breaks out of the accreting structure (central, bottom panels of Figure 5), it expands and accelerates into the CE.

| Model  | $\eta = P_j/P_w$ | $t_{\text{lag}}$ (s) | $\theta_j$ | Resolution | $t_{\text{int}}$ (10$^5$ s) |
|--------|------------------|----------------------|------------|------------|-----------------------------|
| BHLhr  | 0                | 0                    | 30         | HR         | 10.0                        |
| BHLlr  | 0                | 0                    | 30         | LR         | 10.0                        |
| small hr | 0            | 0                    | 30         | HR         | 10.0                        |
| small hr | 0            | 0                    | 30         | LR         | 10.0                        |
| $\eta_{100}$ | 100        | $10^2$               | 30         | HR         | 1.4                         |
| $\eta_{200}$ | 200        | $10^2$               | 30         | HR         | 1.4                         |
| $\eta_{300}$ | 300        | $10^3$               | 30         | HR         | 1.4                         |
| $\eta_{1000}$ | 1000       | $10^5$               | 30         | HR         | 1.4                         |
| narrow | 300             | $10^5$               | 15         | HR         | 1.4                         |
| nolag | 100             | 0                    | 30         | HR         | 0.2                         |
environment. The stellar material (accelerated and heated by the forward shock), and the jet plasma (decelerated by the reverse shock), expand sideways forming a cocoon which by \( t \sim 1.3 \times 10^5 \) s has covered the bulge completely.

### 3.4 Varying the jet ram pressure

To understand how the pressure of the jet (compared to that from the accreted material) affects the morphology of the jet, we performed numerical simulations of jets injected with different \( \eta \) values.

Figure 6 shows the morphology of three jets with different ram pressures (\( \eta = P_j / P_w = 225, 500, \) and 1000) all at the same time (\( t = 1.1 \times 10^5 \) s) and with the rest of the jet parameters and boundaries identical to those of the \( \eta = 300 \) model (see Section 3.3 and Table 1 for more details). As discussed in Section 2, the jet needs a ram pressure larger than that of the material accreting onto the compact object in order to successfully propagate through the stellar envelope.

From our set of simulations, we find that for the chosen input parameters a jet which is injected with a ram pressure \( P_j \lesssim 225 P_w \) is quenched (as, at this radius, \( P_a \gg P_w \), see figure 2). In this case, the evolution of the system is similar to the case of BHL accretion discussed in Section 3.2. On the other hand, if the ram pressure of the jet is \( P_j \gtrsim 225 P_w \), then the jet is able to propagate through the bulge and stellar envelope. As expected, simulations with larger jet kinetic luminosities (corresponding to larger \( \eta \) values) move through the bulge and stellar envelope faster and deposit a larger amount of energy into the cocoon. Nevertheless, the global morphology of the jet and cocoon is basically independent of \( \eta \) as long as it is able to drill through the bulge.

### 3.5 Jet opening angle and jet launched into an unperturbed medium

Lastly, we study how the jet collimation and launching time affect the morphology of the jet by performing a set of numerical simulations with a narrower jet (\( \theta_j = 15^\circ \), model “narrow”) and a jet launched without waiting for a steady state in the accretion rate to be achieved (\( t_{\text{lag}} = 0 \) s, model “nolag”).

The upper panel of Figure 7 illustrates the case of the narrow jet model. As the injected energy is smaller, the jet needs a larger value of \( \eta \) to be able to successfully drill through the bulge and moves slower through the stellar medium. In this case, as long as the jet has \( \eta \gtrsim 250 \), the evolution and the global morphology (the jet and cocoon densities, and the structure of the bulge) is alike the successful jet models with a larger opening angle presented in Section 3.4.

The bottom panel of Figure 7 shows the evolution of the nolag model in which the jet is launched at \( t_{\text{lag}} = 0 \). This scenario corresponds to the case in which the compact object has an accretion disk and a jet when the CE engulfs the compact object (e.g., Soker 2016; Shiber et al. 2017). A much lower kinetic luminosity is needed for the jet to

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Figure 4. Mass accretion rate onto the compact object for different resolutions and different domain sizes. The grey solid line corresponds to the analytic solution of BHL.

Figure 5. \( xz \), \( xy \), and \( yz \) density map slices showing the evolution of a delayed jet with \( \eta = 300 \) (model \( \eta_{300} \), see Table 1). The axis are in units of \( 10^{12} \) cm. The red, orange, green, cyan, and white isocontour lines correspond to \( 10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5} \) g cm\(^{-3} \), respectively. An animation (fig5eta300.mov) of this figure is available in the online journal.
move successfully into the CE, as it does not have to push sideways the material accreting onto the compact object (i.e. the bulge observed in the other simulations).

The nolag model in Figure 7 shows the morphology of a jet with $\eta = 100$ at $t = 1.8 \times 10^4$ s. Comparing such morphology with any other model from Figure 5 or Figure 6 it is clear that the lack of the bulge drastically modifies the evolution of the jet/cocoon. The jet is less dense ($\sim 10^{-9}$ g cm$^{-3}$) and propagates $\sim$10% faster. The cocoon is also less dense ($\sim 10^{-8}$ g cm$^{-3}$), and quenches the mass accretion rate onto the compact object. Since the jet breaks out of the stellar envelope in a shorter time, it deposits less energy in the envelope with respect to the other jet models. Although the jet ram pressure is much larger than the wind ram pressure, the interaction between the jet and the wind slightly bends the jet in the opposite direction with respect to the compact object orbit.

Figure 7. Same as Figure 5 for the models $\theta_{\text{lag}}$ (bottom panel) and “nolag” (bottom panel) of Table 1. The upper panel corresponds to a delayed jet with an opening angle $\theta_j = 15^\circ$ at $t = 1.3 \times 10^5$ s. The bottom panel shows a jet (at the evolutionary time $t = 1.8 \times 10^4$ s) injected at $t_{\text{lag}} = 0$, i.e. without waiting for the formation of a steady-state accretion structure around the compact object. Animations (fig7narrow.mov, fig7nolag.mov) of this figure are available in the online journal.

4 DISCUSSION

Our analytical results (Section 2) are qualitatively consistent with the results of our numerical simulations (Section 3). If the kinetic luminosity of the jet is larger than the ram pressure of the material accreted on the compact object, the jet propagates successfully through the CE.

Nevertheless, we find that the jet dynamics is considerably more complex than what can be predicted analytically. The jet has to move, first, through the asymmetrical bulge (the material accreting onto the compact object). Due to the large pressure and density gradients in the region behind the BH, the jet is tilted forwards in the direction of motion of the compact object within the CE (the “wind” or upstream). During its propagation, the jet deposits energy into a cocoon, which expands mainly upstream with a velocity of order of a half of the jet velocity. Downstream the cocoon expands at a much lower speed as it collides with the dense bulge structure accreting on the compact object. The most important effect of this interaction is the abrupt decline of the mass accretion rate (by an order of magnitude in $\sim 2 \times 10^4$ s) onto the compact object (see Figure 8) due to the ram pressure of the cocoon (what is referred to as negative jet feedback mechanism by Soker 2016). The drop in the accretion rate due to the expanding cocoon implies that the formation of black holes from neutron stars is unlikely, in the presence of a jet.
The jet is powered by a fraction of the accreted material which is ejected from the inner region of the disk/compact object system. As the mass accretion rate drops due to the cocoon expansion, the jet is shut down within a viscous timescale, $t_{\text{visc}} \approx 1.2/\alpha \Omega (R/H)^2$, (Shakura & Sunyaev 1973):

$$t_{\text{visc}} \approx 10^8 \left( \frac{\alpha}{0.1} \right)^{-1} \left( \frac{R}{10^{10} \text{ cm}} \right)^{3/2} \left( \frac{M_a}{0.01 \, M_\odot} \right)^{-1/2} \text{ s},$$

where $R$ and $H$ are the accretion disk radius and vertical size (assumed to be $H = 0.1 R$), $M_a$ is the mass of the disk, $\alpha$ is the accretion efficiency and $\Omega$ is the keplerian disk angular velocity. Thus, we can expect that the jet has a lifetime of a few days to weeks.

It has been suggested that the energy deposited by the jet can be large enough to unbind a substantial fraction of the CE material. In these cases, the cocoon energy (see equation 11) is large enough to unbind a substantial fraction of the CE material. Furthermore, at smaller orbital separation the jet is strongly deflected by the larger ram pressure of the wind. As the orbital period of the binary system is much smaller than the lifetime and crossing time of the jet (i.e. $P = 4 \times 10^4 a_{11}^4 M_2$ s $\ll t_{\text{visc}}$, $v_{\text{jet}}$), the jet deposits a larger amount of energy ($\sim t_{\text{visc}} E_{\text{jet}}/t_{\text{ho}} \gg E_{\text{jet}}$).

Due to numerical limitations, in our simulations we considered relatively large jet opening angles. In the case of a more collimated jet, the cocoon may be tilted enough to allow accretion on a narrow equatorial region where material may still feed a disk thus allowing for accretion disk, jets and their respective cocoons to coexist in a stable phase.

Although in this paper we have considered only the case of a jet created during the CE, a different scenario would be that of a pre-existing disk/jet formed during the mass - transfer phase. Such a disk would be much larger in size and less dense. The jet will only interact with the outskirts of the CE in this case. On the other hand, it is unclear whether the disk would survive the onset of a CE for long time.

A jet ejected at $a \leq 10^{11}$ cm with a relatively large efficiency ($\epsilon \geq 10^{-2}$) deposits an amount of energy large enough to unbind the outer layers of the star. The jet then propagates freely in the interstellar medium. For such large efficiencies and radial distances the jet may reach luminosities of order $10^{51} - 10^{51}$ erg s$^{-1}$. Thus, taking into account that the jets timescale is $\lesssim$ than the viscous timescale, we speculate that this can be an alternative channel to produce highly relativistic jets as those observed associated to ultra-long GRBs (Levan et al. 2014).

When the jet and the cocoon break out of the CE, an X-ray flash would be expected. The energy deposited by the relativistic jet into the fast-moving expanding envelope (the cocoon) should produce a quasi-thermal emission peaking.
in optical and UV bands, associated to the emission generated from the relativistic jet which may or may not point to the observers line of sight. If it does, then a hard spectrum would be expected. Otherwise, an off-axis jet could produce a radio signal from the interaction with the environment. Furthermore, if the jet is launched close to the stellar core of the companion and enough energy is deposited close to it, the core could be disrupted and a SN-like (type II) signal could be produced.

5 CONCLUSION

In this paper we presented three dimensional, hydrodynamic simulations of the interaction between a jet launched from a compact object and the CE. We showed that jets can play a fundamental role in the CE phase.

We find that, in absence of a jet, the accretion rate onto the compact object is a fraction of the BHL rate. Also, we have established the conditions for a jet to be able to traverse through the bulge and the stellar CE: the accretion-to-ejection efficiency (i.e., the rate of accreting material which is converted into an outgoing jet). Depending on the position of the compact object within the engulfing star, this efficiency has to be larger than $10^{-5}$ to $10^{-3}$ and the jet luminosity must be larger than $\sim 10^{39}$ erg s$^{-1}$.

The jet deposits a substantial amount of energy ($E \sim 10^{50}$ erg) into a hot, dense cocoon, which inhibits mass accretion on the compact object, and it is likely to affect substantially the CE evolution. The timescale for disrupting the outer layers of the CE may be substantially shorter than the viscous timescale for the material in the accretion disk, thus, even if accretion is suppressed, the jet is not immediately quenched. This behaviour may lead to three possible scenarios. 1) The jet may be intermittent, as it may push away the accreting material, but eventually restart as the material fall back on the compact object. 2) It may possibly reach a steady state if the jet is very collimated. 3) It may deposit so much energy into the CE that it unbinds its outer layers (if the accretion to ejection efficiency is $\gtrsim 10^{-3}$). However, the donor star may eventually fill its Roche lobe again and lead to another CE phase.

It has been suggested that, during a CE phase, a binary can substantially decrease its period (and separation) by converting orbital kinetic energy into kinetic energy of the outer layers, i.e., unbinding the envelope. As the energy deposited by the jet in the envelope is comparable to the orbital energy dissipation (van den Heuvel 1976), it should be taken into account in the CE energy-balance and may even terminate the CE phase. Also, the characteristic luminosity, duration and environment of a jet ejected from a compact object orbiting at small distances from the center of the CE imply that this can be a possible channel to explain some of the ultra-long GRBs.

Local simulations (e.g., which study only a portion of the CE) as those presented here do not include the full CE phenomenology, e.g. the disk formation by accretion on the compact object or the survival of a pre-existent accretion disk when the CE phase begins, and the long-term dynamical interaction of the jet with the CE and companion star. Nevertheless, we believe that this study represents a step in understanding the key role that jets, if present, may play in the evolution of common envelopes. Future works will help clarifying the rich phenomenology related to this phenomena.

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