# Jets in common envelope evolution

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**ABSTRACT**

**Key words:** binaries: close – accretion, accretion discs – stars: kinematics and dynamics – stars: winds, outflows – stars: jets – hydrodynamics – methods: numerical

## 1 INTRODUCTION

Relevant references:

- Blackman & Lucchini (2014)
- Soker (2004)
- Nordhaus & Blackman (2006)

## 2 MOTIVATION

- Such jets may provide an important source of energy to eject the circumbinary envelope and affect its morphology. They could also help to explain bi-polar PPNe.

## 3 OUTLINE

Results of Paper I show that:

- In the presence of an extremely efficient 'pressure valve' at the location of the secondary, accretion can be sustained at extremely high rates of $\sim 0.2$–$2\,M_\odot\,\mathrm{yr}^{-1}$ over tens of days. For a MS star this corresponds to $10^2$–$10^3$ times the Eddington rate, while for a WD this corresponds to $10^4$–$10^5$ times the Eddington rate $\dot{M}_\mathrm{Edd}$.
- While the pressure valve employed in Model B of Paper I was too efficient to be realistic because the gas is optically thick and thus radiation would not freely stream out, a jet provides an alternative, more plausible pressure release mechanism.
- If the pressure valve is much less efficient or absent altogether, there is a build-up of material, forming a quasi-steady envelope around the secondary that contains some $\sim 10^{-4}$–$10^{-3}\,M_\odot$ of material. This envelope mass increases as the softening radius is reduced, so these values can be interpreted as a lower limit for a WD.
- There is enough specific angular momentum in the flow around the secondary to lead to a rotationally supported disc at unresolved radii if the secondary is a WD, independently of the presence or absence of a pressure valve, but not if the secondary is a MS star.
- A jet involves a highly anisotropic mechanical feedback onto the flow, which can result in accretion rates that exceed $\dot{M}_\mathrm{Edd}$ by up to two orders of magnitude (REF).

Other considerations:

- For realistic accretion, the flow would probably be closer to that of Model A of Paper I where subgrid accretion was not included because realistic accretion rates are likely of order $10^{-1}$–$10^2\dot{M}_\mathrm{Edd}$, which is much smaller than the rates seen in Model B, especially if the secondary is a WD.
- The time of onset of the jet is likely important. Broadly, the jet may turn on (i) before plunge-in, during the Roche-lobe (of the primary) overflow accretion phase, (ii) during plunge-in, before the envelope around the secondary builds up, (iii) after plunge-in, as the envelope around the secondary builds up, or (iv) after the envelope around the secondary has become quasi-steady.
- Once the jet turns on, the build-up of material around the secondary would probably be reduced by the jet feedback. We would expect this to lead to a slower build up of the envelope around the secondary and a smaller quasi-steady envelope mass around the secondary. The jet could be initialized out to the softening radius $r_\mathrm{soft}$ and would, if strong enough, push outward at the poles, likely leading to a torus-shaped morphology.
- If the feedback affects the "accretion" of material onto the envelope around the secondary, does it affect the actual accretion onto the star (modeled using a subgrid prescription)? Assuming that the jet does not direcly disrupt the subgrid disc, we can imagine two extreme possibilities: (a) the subgrid disc is quasi-steady, perhaps self-regulating, and approximately independent of the flow at large (resolvable) radius; (b) if the subgrid disc still has very low mass when the jet turns on, and the jet feedback onto the flow at larger radius is strong enough to cut off the replenishment of the subgrid disc, then the accretion and jet could be arrested and turn off. This would remove the feeback, leading to replenishment of the disc until the jet turned on again, and this would presumably lead to a duty cycle of accretion/jet activity. Scenario (a) might occur for case (iv) while scenario (b) could conceivably happen for case (iii). In general, the subgrid disc parameter values can plausibly be affected by the flow at large radius, for example a more concentrated envelope around the accretor would likely be associated with a more massive subgrid disc and a larger accretion rate.
- The subgrid disk accretion/jet model is assumed to be independent, or depend only parametrically, on the flow at large radius. This is more plausible if the disc is located at small radius, far away from the large-scale flow, as is the case if the secondary is a WD. If the secondary is a MS star, then the accretion onto the star would be directly affected by the resolved flow, but the surface of the star (and other physics like magnetic fields) are neglected in the simulation,

so it is actually not desirable to resolve the star. In other words, to model missing physics we need to implement a subgrid model of accretion/jets. But to do this, the star/disk must be at unresolved scales, i.e. at ∼WD scales (or smaller). A separate reason for assuming the secondary to be a WD rather than a MS star is because, as mentioned above and in Paper I, the specific angular momentum in the flow is not large enough to expect a rotationally supported disc to form around a MS star. While this does not preclude jet formation, it renders it less likely.

- The simplest strategy is to leave the flow within the accretion region $r < r_{\rm sink}$ as it is, that is, as solved by AstroBEAR, even though we know that it will be unrealistic because of missing physics and resolution. However, another possibility is to try to obtain a solution that smoothly matches the flow at some boundary ($r = r_{\rm sink}$ or $r = r_{\rm soft}$ probably) onto an inner solution that mimics what would be expected for the subgrid model (the disc and its immediate surroundings). This would make the region inside the boundary more realistic. This matters insofar as this region can affect the region outside the boundary. How feasible this would be and whether it would make a big difference to the results is not clear.

## 4 METHODS

### 4.1 Setup

We need to code up a subgrid disk accretion model that depends parametrically on the local conditions. Alternatively (or at least to begin with) we can take these parameters as constants. All of the parameter values for the accretion and outflow subgrid models must be estimated from the literature.

Plan of execution:

- We begin the simulation from a snapshot at $t = t_{\rm snap}$ of Model A of Paper I and initiate the outflow immediately, at $t = t_{\rm snap}$.
- The following parameters could be varied between the runs:
  - Accretion rate (different value of $\dot{M}$ in the range 0.1–100$\dot{M}_{\rm Edd}$ for a WD).
  - The collimation angle $\theta_{\rm out}$.
  - Density of outflow via $f_{\rm m}$.
  - Temperature of the outflow $T$.
  - Angular momentum of the outflow via $f_{\rm a}$.

### 4.2 Modelling the accretion

The Krumholz et al. (2004) model, while physically motivated from the Bondi-Hoyle-Lyttleton accretion (Edgar 2004), is not appropriate in the CE context, because (i) there is a large gradient in density and other quantities (the curvature due to the finite radius of the RG is also ignored) and (ii) the local ambient conditions are not constant because the secondary is moving on a changing non-circular orbit at times through gas that has already been “processed” during its interaction with the particles. The Bondi-Hoyle-Lyttleton probably overesimates the accretion rate by several orders of magnitude (Ricker & Taam 2008; MacLeod et al. 2017; Paper I). Moreover, the Krumholz et al. (2004) model has limitations even in the simple Bondi accretion case, and only leads to a stable solution when the ratio of specific heats $\gamma$ is close to unity. This stems from the fact that the ambient density, sound speed, and bulk speed are estimated by averaging over a small region $r < r_{\rm sink}$ around the particle. This generally results in values that are too large, which tends to lead to accretion rates that are too low. In addition, the parameter that determines the extent of this accretion region, the accretion radius $r_{\rm sink}$, is chosen rather arbitrarily, as is the spline softening radius, inside which the gravity of the particle is smoothed. Use of the Krumholz et al. (2004) model was justified in Paper I because we wanted to explore the extreme case of very high accretion rates, and we could do the same thing here to explore this limiting case, but now with jet feedback.

What would be more realistic is to take the secondary to be a WD, and to assume that a disc has formed around it far inside the softening radius (so in a region of the flow that is not reliably modelled by AstroBEAR). We estimated in Paper I by assuming conservation of specific angular momentum that for Model A of that paper without subgrid accretion, a rotationally supported disk could form within ∼ 0.05–0.08 of the secondary. Then we would replace the Krumholz et al. (2004) model with a subgrid model that is suitable for an accretion disc. Without specifying which disc model to use at this point, such models would fall into one of two broad categories. The accretion rate (and other parameters of the accretion model) could be made to be constant (e.g. $\dot{M}_{\rm Edd}$), which would be reasonable if it could be argued that the disc/outflow processes are independent of the flow at $r > r_{\rm soft}$, say, and that they reach a steady state. To conserve mass, accreted material would still be removed from the grid, so accretion would affect the flow even though the flow cannot affect the accretion.

Alternatively, the accretion properties could be made to depend (in some simple way motivated by accretion disc models) on the local properties of the gas. For example, the accretion rate onto the particle could depend on the mass of gas contained within $r_{\rm sink}$. But unlike with the Krumholz et al. (2004) model, the accretion is assumed to be mediated by a disc.

### 4.3 Modelling the outflow

See Federrath et al. (2014) and Table 1.

## 5 RESULTS

### 5.1 Order of magnitude estimates

Let us try to determine how important the feedback would be using order of magnitude estimates. For the feedback to be important, the energy density in the jet must be comparable to or greater than the gravitational potential energy density. For the jet to be able to push its way through the gas outside the star at $r = r_{\rm soft}$, we require

$$\rho_{\rm jet} v_{\rm jet}^2 \gtrsim \frac{GM_2\rho(r_{\rm soft})}{r_{\rm soft}}. \tag{1}$$

Now,

$$\begin{aligned} v_{\rm jet} &= v_{\rm K}(r_{\rm surf}) \simeq Q\sqrt{\frac{GM_2}{r_{\rm surf}}} \\ &= 8.7\times10^3\,{\rm km\,s^{-1}}\left(\frac{Q}{2}\right)\left(\frac{M_2}{M_\odot}\right)^{1/2}\left(\frac{r_{\rm surf}}{0.01\,R_\odot}\right)^{-1/2}. \end{aligned} \tag{2}$$

where $1 \leqslant Q \leqslant 5$ and a best guess is $Q = 2$ (Blackman & Lucchini 2014, and references therein) so that the condition becomes

$$Q^2\frac{\rho_{\rm jet}}{r_{\rm surf}} \gtrsim \frac{\rho(r_{\rm soft})}{r_{\rm soft}}, \tag{3}$$

or

$$\rho_{\rm jet} \gtrsim \frac{1}{Q^2}\frac{r_{\rm surf}}{r_{\rm soft}}\rho(r_{\rm soft}). \tag{4}$$

Now at the end of the simulation for Model A from Paper I at $t = 40\,{\rm d}$, we had $\rho(r_{\rm soft}) \approx 10^{-3}\,{\rm g\,cm^{-3}}$, and $r_{\rm soft} = 1.2\,R_\odot$. The

**Table 1.** Outflow and accretion parameters. (1) refers to Federrath et al. (2014). The symbol $\Delta x$ refers to the size of the smallest resolution element.

| Description | Symbol | Canon. val. in (1) | AstroBEAR var. name | Suggested | AstroBEAR default |
|---|---|---|---|---|---|
| **Outflow** | | | | | |
| Outflow opening angle | $\theta_{\rm out}$ | 30° | collimation | 10°–30° | 30° |
| Fraction of accreted mass that goes into outflow | $f_{\rm m}$ | 0.3 | efficiency | 0.1–0.3 | 0.1 |
| Exponent in outflow smoothing function | $p$ | 1 | p | 1–3 | 1 |
| Fraction of accreted spin AM that goes into outflow | $f_{\rm a}$ | 0.9 | jefficiency | 0.5–1 | 0.5 |
| Radius of outflow initialization region | $r_{\rm out}$ | $16\Delta x$ | radius | $16$–$32\Delta x$ | $16\Delta x$ |
| Radius at which outflow is assumed to be launched | $r_{\rm surf}$ | — | rsurface | $0.01\,R_\odot$ | $1\,R_\odot$ |
| Launch speed, as a fraction of $v_{\rm K}(r_{\rm surf})$ | $Q$ | — | vfact | 2 (REF) | 0.1 |
| Spin axis | — | Same as particle | spin_axes | $z$-axis or s.a.p. | s.a.p. |
| Temperature of outflow | $T_{\rm jet}$ | — | T | | $10^4$ code units |
| **Accretion** | | | | | |
| Radius of accretion region | $r_{\rm sink}$ | $2.4\Delta x$ | r_acc | $4\Delta x$ | $4\Delta x$ |

radius at which the jet is launched can be estimated as the WD radius, about $0.01\,R_\odot$. Then we require

$$\rho_{\rm jet} \gtrsim 2{\times}10^{-6}\,{\rm g\,cm^{-3}} \left(\frac{Q}{2}\right)^{-2} \left(\frac{r_{\rm soft}}{1.2\,R_\odot}\right)^{-1} \left(\frac{r_{\rm surf}}{0.01\,R_\odot}\right) \left(\frac{\rho(r_{\rm soft})}{10^{-3}\,{\rm g\,cm^{-3}}}\right) \quad (5)$$

We can turn this into a corresponding condition on the accretion rate. We have

$$\dot{M}_{\rm jet} = f_{\rm m}\dot{M} = 2\pi r_{\rm surf}^2 v_{\rm jet}\rho_{\rm jet}, \quad (6)$$

where we have assumed maximum collimation (effectively $\theta_{\rm out} = 0$), the width of the jet to be equal to the diameter of the sink region, and the factor of 2 accounts for the bipolarity of the jet. Rearranging we have

$$\rho_{\rm jet} = \frac{f_{\rm m}\dot{M}}{2\pi r_{\rm surf}^2 v_{\rm jet}}. \quad (7)$$

After setting $v_{\rm jet} = Q\sqrt{GM_2/r_{\rm surf}}$, condition (4) becomes

$$\frac{f_{\rm m}\dot{M}}{2\pi r_{\rm surf}^2}\frac{1}{Q}\sqrt{\frac{r_{\rm surf}}{GM_2}} \gtrsim \frac{1}{Q^2}\frac{r_{\rm surf}}{r_{\rm soft}}\rho(r_{\rm soft}), \quad (8)$$

which, after simplifying and solving for $\dot{M}$ becomes

$$\dot{M} \gtrsim \frac{2\pi}{Qf_{\rm m}}\frac{r_{\rm surf}^3}{r_{\rm soft}}\sqrt{\frac{GM_2}{r_{\rm surf}}}\rho(r_{\rm soft}). \quad (9)$$

Putting in reasonable values we obtain

$$\dot{M} \gtrsim 2.9\times10^{-4}\,M_\odot\,{\rm yr^{-1}} \times \left(\frac{Q}{2}\right)^{-1} \left(\frac{f_{\rm m}}{0.3}\right)^{-1} \left(\frac{r_{\rm surf}}{0.01\,R_\odot}\right)^{5/2} \left(\frac{r_{\rm soft}}{1.2\,R_\odot}\right)^{-1} \left(\frac{M_2}{M_\odot}\right)^{1/2} \left(\frac{\rho(r_{\rm soft})}{10^{-3}\,{\rm g\,cm^{-3}}}\right) \quad (10)$$

Meanwhile, the Eddington accretion rate is given by (Paper I)

$$\dot{M}_{\rm Edd} = 2.1\times10^{-5}\,M_\odot\,{\rm yr^{-1}}\,\widetilde{\lambda}\left(\frac{r_{\rm surf}}{0.01\,R_\odot}\right), \quad (11)$$

where $\widetilde{\lambda}$ is a parameter of order unity. Thus, we find

$$\frac{\dot{M}}{\dot{M}_{\rm Edd}} \gtrsim 14\widetilde{\lambda}^{-1} \times \left(\frac{Q}{2}\right)^{-1} \left(\frac{f_{\rm m}}{0.3}\right)^{-1} \left(\frac{r_{\rm surf}}{0.01\,R_\odot}\right)^{3/2} \left(\frac{r_{\rm soft}}{1.2\,R_\odot}\right)^{-1} \left(\frac{M_2}{M_\odot}\right)^{1/2} \left(\frac{\rho(r_{\rm soft})}{10^{-3}\,{\rm g\,cm^{-3}}}\right) \quad (12)$$

This result suggests that for the outflow to be able to have a strong effect on the surrounding gas, we require hypercritical accretion with rates an order of magnitude greater than the Eddington rate.

An alternative approach is to estimate the rate at which envelope mass can be removed by the jet. To this end we equate the jet power with the rate of change of the binding energy The former is given by the ram pressure multiplied by the jet cross-sectional area multiplied by the jet speed, multiplied by two to take into account the bipolar morphology of the jet. We obtain

$$2\pi r_{\rm surf}^2\rho_{\rm jet}v_{\rm jet}^3 = \frac{GM_2}{2r}\dot{m}(r), \quad (13)$$

where the factor of $1/2$ on the RHS was estimated assuming that the gas is virialized. Solving for the rate of mass evacuation $\dot{m}$ at radius $r$ we obtain

$$\dot{m}(r) = \frac{4\pi r_{\rm surf}^2\rho_{\rm jet}v_{\rm jet}^3 r}{GM_2}. \quad (14)$$

Now $v_{\rm jet}$ and $\rho_{\rm jet}$ are given by equations (2) and (7), respectively. Substituting those expressions into the above result for $\dot{m}(r)$ we obtain

$$\dot{m}(r) = \frac{4\pi r_{\rm surf}^2 r v_{\rm jet}^3}{GM_2}\frac{f_{\rm m}\dot{M}}{2\pi r_{\rm surf}^2 v_{\rm jet}} = \frac{2f_{\rm m}\dot{M}v_{\rm jet}^2 r}{GM_2} = 2Q^2 f_{\rm m}\frac{r}{r_{\rm surf}}\dot{M}. \quad (15)$$

Thus, for $r = r_{\rm soft}$, we obtain

$$\dot{m}(r_{\rm soft}) = 2.9\times10^2\left(\frac{Q}{2}\right)^2\left(\frac{f_{\rm m}}{0.3}\right)\left(\frac{r_{\rm soft}}{1.2\,R_\odot}\right)\left(\frac{r_{\rm surf}}{0.01\,R_\odot}\right)^{-1}\dot{M}. \quad (16)$$

If $\dot{M} = f_{\rm Edd}\dot{M}_{\rm Edd}$, given by equation (11) (with $f_{\rm Edd}$ a parameter), then we obtain

$$\dot{m}(r_{\rm soft}) = 6.0\times10^{-3}\,M_\odot\,{\rm yr^{-1}}\,f_{\rm Edd}\widetilde{\lambda}\left(\frac{Q}{2}\right)^2\left(\frac{f_{\rm m}}{0.3}\right)\left(\frac{r_{\rm soft}}{1.2\,R_\odot}\right), \quad (17)$$

with the dependence on $r_{\rm surf}$ cancelling out. From the top panel of Fig. 5 of Paper I we see that the envelope of material around the secondary contains about $5\times10^{-3}\,M_\odot$ between $r = 1\,R_\odot$ and $r = 2\,R_\odot$. From equation (17) we estimate that it would take $\sim 1$ yr to eject this mass if accretion occurs at the Edington rate, $\sim 10^{-1}$ yr if accretion happens at $\dot{M} = 10\dot{M}_{\rm Edd}$, and $\sim 10^{-2}$ yr if $\dot{M} = 10^2\dot{M}_{\rm Edd}$.

### 5.2 Description of runs

In Table 2 we provide a list of potential runs. Each run begins from a frame of Model A of Paper I. For all runs, the outflow launch speed is set to twice the Keplerian speed at the radius $r_{\rm surf} = 0.01\,R_\odot$, which corresponds to the WD surface. The accretion zone (where mass is removed from the grid) has a radius $r_{\rm sink} = 4\Delta x$, while the zone within which the outflow is initiated has a radius $r_{\rm out} = r_{\rm soft}$, corresponding to $\approx 17\Delta x$, which meets the suggestion of Federrath et al. (2014) that $r_{\rm out} > 16\Delta x$ for numerical convergence. The exponent $p$ is set to 1.

Simulations are labeled by the frame at which the outflow is initiated, followed by the accretion rate in units of the Eddington value for a WD ($2.1\times10^{-5}\,M_\odot\,{\rm yr}^{-1}$), followed by $f_{\rm m}$ (e.g. "03" refers to the value 0.3), and finally the value of the collimation angle $\theta_{\rm out}$ in degrees. If the latter two values are omitted and replaced by "X" this means that the simulation has accretion but *no outflow*. These no outflow simulations as well as the original simulation which lacked subgrid accretion act as controls to isolate the separate effects of the outflow and accretion.

In the runs listed, we vary the onset time of the accretion (and outflow where applicable) $t_{\rm on}$, the accretion rate $\dot{M}$, the efficiency at which accreted mass is transferred to the outflow $f_{\rm m}$, and the collimation angle $\theta_{\rm out}$. It may also be interesting to vary quantities like $r_{\rm out}$, $r_{\rm sink}$, $f_{\rm a}$ and $p$ to explore to what extent they might affect the results.

We note that if the mass in the accretion region becomes negative, then this means that solutions are not self-consistent, so the simulation should be stopped.

The simulation of Model A took roughly 1/4 of the presently remaining computational resources and evolved to $t = 40$ d. A way to save would be to perform each run for a shorter duration ($<5$ d). Other possibilities are to reduce the base (ambient) resolution and/or the extent of the region of maximum refinement, but then comparison with Model A becomes less reliable.

## 6 DISCUSSION

### 6.1 Jet speed

In reality, the jet speed $v_{\rm jet}$ at $r = r_{\rm soft}$ is probably overestimated because it assumes that there is no material impeding the jet in between $r_{\rm surf}$ and $r_{\rm soft}$. Let us assume that the jet pushes on material in a momentum conserving 'snowplow' phase (c.f. Blackman & Lucchini 2014). For simplicity, let us assume that the jet is collimated in a pencil beam of cross-sectional area $A$. Then from momentum conservation we can write

$$\begin{aligned}\dot{M}_{\rm jet}(r_{\rm surf})v_{\rm jet}(r_{\rm surf}) &= \rho_{\rm jet}(r_{\rm surf})Av_{\rm jet}^2(r_{\rm surf})\\ &= \dot{M}(r_{\rm soft})v_{\rm jet}(r_{\rm soft})\\ &= [\rho_{\rm jet}(r_{\rm surf})+\rho_{\rm jet}(r_{\rm soft})]Av_{\rm jet}^2(r_{\rm soft}),\end{aligned} \tag{18}$$

where we have assumed for simplicity that the material swept up by the jet between $r = r_{\rm surf}$ and $r = r_{\rm soft}$ has average density $\rho(r_{\rm soft})$. Solving for the jet velocity at $r = r_{\rm soft}$ gives

$$v_{\rm jet}(r_{\rm soft}) = \sqrt{\frac{\rho_{\rm jet}(r_{\rm surf})}{\rho_{\rm jet}(r_{\rm surf})+\rho(r_{\rm soft})}}v_{\rm jet}(r_{\rm surf}). \tag{19}$$

Let us assume for simplicity that the naked jet density is much smaller than the gas density at $r = r_{\rm soft}$, so that

$$\begin{aligned}v_{\rm jet}(r_{\rm soft}) &\simeq \sqrt{\frac{\rho_{\rm jet}(r_{\rm surf})}{\rho(r_{\rm soft})}}v_{\rm jet}(r_{\rm surf})\\ &= \left[\frac{f_{\rm m}\dot{M}v_{\rm jet}(r_{\rm surf})}{2\pi r_{\rm surf}^2\rho(r_{\rm soft})}\right]^{1/2} = \left[\frac{f_{\rm m}\dot{M}Q(GM_2)^{1/2}}{2\pi r_{\rm surf}^{5/2}\rho(r_{\rm soft})}\right]^{1/2}\\ &= 62\,{\rm km\,s^{-1}}\,f_{\rm Edd}^{1/2}\left(\frac{Q}{2}\right)^{1/2}\left(\frac{f_{\rm m}}{0.1}\right)^{1/2}\\ &\quad\times\left(\frac{M_2}{M_\odot}\right)^{1/4}\left(\frac{r_{\rm surf}}{0.01\,R_\odot}\right)^{-5/4}\left(\frac{\rho(r_{\rm soft})}{10^{-3}\,{\rm g\,cm^{-3}}}\right)^{-1/2}.\end{aligned} \tag{20}$$

This can be compared with the naked jet velocity given by equation (2),

$$\begin{aligned}\frac{v_{\rm jet}(r_{\rm soft})}{v_{\rm jet}(r_{\rm surf})} &\simeq \sqrt{\frac{\rho_{\rm jet}(r_{\rm surf})}{\rho(r_{\rm soft})}}\\ &= 7\times10^{-3}\,f_{\rm Edd}^{1/2}\left(\frac{Q}{2}\right)^{-1/2}\left(\frac{f_{\rm m}}{0.1}\right)^{1/2}\\ &\quad\times\left(\frac{M_2}{M_\odot}\right)^{-1/4}\left(\frac{r_{\rm surf}}{0.01\,R_\odot}\right)^{-3/4}\left(\frac{\rho(r_{\rm soft})}{10^{-3}\,{\rm g\,cm^{-3}}}\right)^{-1/2}.\end{aligned} \tag{21}$$

This expression with numerical value $\sim 7\times10^{-3}$ would appear in the results of Section 5.1 multiplying $v_{\rm jet}$ wherever it appears (or wherever $Q$ appears since $v_{\rm jet}\propto Q$ and $Q$ only originates from $v_{\rm jet}$). This would increase the critical $\dot{M}$ in equation (12) by the reciprocal of this factor, or $1.4\times10^2$, and would decrease the rate of mass ejection of equation (17) by the square of this factor, or $5\times10^{-5}$. The situation is not quite as dire if one assumes $f_{\rm Edd} = 10$, $f_{\rm m} = 0.3$, but this result would suggest that the only way that such a jet could have an important dynamical influence on the envelope is if $\rho(r_{\rm soft})$ is much smaller, so before a quasi-steady envelope has had a chance to build up around the secondary. It makes sense then to focus on simulating the jet at the early stages of CEE, so regimes (i), (ii) and possibly (iii), while for (iv) (and most of (iii)) the jet is likely to be quenched before it can propagate past $r = r_{\rm soft}$.

### 6.2 Accretion rate during early stages of CEE

By the above arguments, it becomes crucial to simulate accretion and jet feedback in the early stages, regimes (i) (before plunge-in) and (ii) (during plunge-in). These early times are favourable for jet propagation because the material surrounding the secondary is low density. However, if the material is too low density it would not be able to support a high enough accretion rate, so there must be a time during the CEE where both the accretion rate and density optimally combine to produce a jet that clears out surrounding material. To estimate this time, we need to estimate $\dot{M}$ and $\rho(r_{\rm soft})$ at different times. The latter can be estimated from the simulation, while the former can be estimated using accretion theory. In the very early stages (regime (i)) accretion could be approximated by Roche Lobe overflow, for which analytical estimates for $\dot{M}$ are known (REF). However, our simulation does not realistically capture this regime, since the secondary is initialized just outside the RG surface. If we could argue that soon after the simulation starts and then during plunge-in, the secondary can accrete at say $\dot{M} = \dot{M}_{\rm Edd}$, while the density of material around the secondary is still very low, then we

**Table 2.** Runs are designated according to frame number, mass accretion rate in units of the Eddington rate for a 0.01 $R_\odot$ WD, outflow efficiency $f_m$ and collimation angle $\theta_{out}$. Runs without an outflow are labeled by an “X.” Variables are the time that accretion begins $t_{on}$, corresponding frame of Model A from which the simulation is restarted, regime (see Section 3, smallest resolution element $\Delta x$ (from Model A), softening radius $r_{soft}$ (from Model A), accretion radius $r_{sink}$ (= $4\Delta x$), mass accretion rate $\dot{M}$, radius at which the outflow is assumed to be launched $r_{surf}$, radius up to which the outflow is *set* (i.e initialized at every time step) $r_{out}$, fraction of accreted mass that goes into the outflow $f_m$, fraction of accreted angular momentum that goes into the outflow $f_a$, and collimation angle $\theta_{out}$. For all runs, $Q = 2$ (so that the outflow is launched with twice the Keplerian speed at $r_{surf}$) and the parameter $p = 1$.

| Run | $t_{on}$ [d] | frame on | regime | $\Delta x$ [$R_\odot$] | $r_{soft}$ [$R_\odot$] | $r_{sink}$ [$R_\odot$] | $\dot{M}$ [$M_\odot\,yr^{-1}$] | $r_{surf}$ [$R_\odot$] | $r_{out}$ [$R_\odot$] | $f_m$ | $f_a$ | $\theta_{out}$ [°] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f0-1E-X | 0 | 0 | (i) | 0.140 | 2.4 | 0.56 | $2.1\times10^{-5}$ | — | — | — | — | — |
| f0-1E-03-10 | 0 | 0 | (i) | 0.140 | 2.4 | 0.56 | $2.1\times10^{-5}$ | 0.01 | 2.4 | 0.1 | 1 | 30° |
| f0-1E-03-10 | 0 | 0 | (i) | 0.140 | 2.4 | 0.56 | $2.1\times10^{-5}$ | 0.01 | 2.4 | 0.3 | 1 | 30° |
| f46-10E-X | 10.64 | 46 | (ii) | 0.140 | 2.4 | 0.56 | $2.1\times10^{-4}$ | — | — | — | — | — |
| f46-1E-03-10 | 10.64 | 46 | (ii) | 0.140 | 2.4 | 0.56 | $2.1\times10^{-5}$ | 0.01 | 2.4 | 0.1 | 1 | 30° |
| f46-1E-03-30 | 10.64 | 46 | (ii) | 0.140 | 2.4 | 0.56 | $2.1\times10^{-5}$ | 0.01 | 2.4 | 0.1 | 1 | 6° |
| f46-1E-01-10 | 10.64 | 46 | (ii) | 0.140 | 2.4 | 0.56 | $2.1\times10^{-5}$ | 0.01 | 2.4 | 0.3 | 1 | 30° |
| f46-10E-03-10 | 10.64 | 46 | (ii) | 0.140 | 2.4 | 0.56 | $2.1\times10^{-4}$ | 0.01 | 2.4 | 0.1 | 1 | 30° |
| f78-10E-X | 18.06 | 78 | (iii) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-4}$ | — | — | — | — | — |
| f78-1E-03-10 | 18.06 | 78 | (iii) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-5}$ | 0.01 | 1.2 | 0.1 | 1 | 30° |
| f78-10E-03-10 | 18.06 | 78 | (iii) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-4}$ | 0.01 | 1.2 | 0.1 | 1 | 30° |
| f108-100E-X | 25.00 | 108 | (iv) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-3}$ | — | — | — | — | — |
| f108-1E-03-10 | 25.00 | 108 | (iv) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-5}$ | 0.01 | 1.2 | 0.1 | 1 | 30° |
| f108-10E-03-10 | 25.00 | 108 | (iv) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-4}$ | 0.01 | 1.2 | 0.1 | 1 | 30° |
| f108-100E-03-10 | 25.00 | 108 | (iv) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-3}$ | 0.01 | 1.2 | 0.1 | 1 | 30° |
| f108-100E-03-30 | 25.00 | 108 | (iv) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-3}$ | 0.01 | 1.2 | 0.1 | 1 | 6° |
| f108-100E-01-10 | 25.00 | 108 | (iv) | 0.070 | 1.2 | 0.28 | $2.1\times10^{-3}$ | 0.01 | 1.2 | 0.3 | 1 | 30° |

may find that jets operate efficiently to clear away material in this regime.

## 7 CONCLUSIONS

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