How Drag Force Evolves in Global Common Envelope Simulations

Luke Chamandy,∗ Eric G. Blackman, Adam Frank, Jonathan Carroll-Nellenback, Yangyuxin Zou and Yisheng Tu

Department of Physics and Astronomy, University of Rochester, Rochester NY 14627, USA

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ABSTRACT

We compute the forces, torque and rate of work on the companion-core binary due to drag in global simulations of common envelope (CE) evolution for three different companion masses. Our simulations help to delineate regimes when conventional analytic drag force approximations are applicable. During and just prior to the first periastron passage of the in-spiral phase, the drag force is reasonably approximated by conventional analytic theory and peaks at values proportional to the companion mass. Good agreement between global and local 3D “wind tunnel” simulations, including similar net drag force and flow pattern, is obtained for comparable regions of parameter space. However, subsequent to the first periastron passage, the drag force is up to an order of magnitude smaller than theoretical predictions, quasi-steady, and depends only weakly on companion mass. The discrepancy is exacerbated for larger companion mass and when the inter-particle separation reduces to the Bondi-Hoyle-Lyttleton accretion radius, creating a turbulent thermalized region. Greater flow symmetry during this phase leads to near balance of opposing gravitational forces in front of and behind the companion, hence a small net drag. The reduced drag force at late times helps explain why companion-core separations necessary for envelope ejection are not reached by the end of limited duration CE simulations.

Key words: binaries: close – stars: evolution – stars: kinematics and dynamics – stars: mass loss – stars: winds, outflows – hydrodynamics

1 INTRODUCTION

Common envelope evolution (CEE) is the most natural mechanism for rapidly tightening binary orbits and likely facilitates many phenomena, including gravitational wave-emitting mergers and type Ia supernovae. In CEE, the primary and secondary cores inspiral from drag, transferring orbital energy to the envelope until the latter ejects, or the cores merge.

Hydrodynamic simulations of this process generally do not eject the envelope. Although it is possible that the cores should merge for the parameter regime explored in some of the simulations (Iaconi et al. 2018), in other simulations the rate of decay of the inter-particle separation decreases dramatically at values of a too large for a merger during the computation. There may also be missing physics in the simulations. For example, most employ an ideal gas equation of state (EOS), whereas a more sophisticated EOS should account for ionization and recombination. When recombination energy is injected locally, the envelope is found to eject or almost eject in at least some cases (Nandez et al. 2015; Nandez & Ivanova 2016; Prust & Chang 2019). Chamandy et al. (2019) (hereafter Paper II) applied the CE energy formalism (van den Heuvel 1976; Webbink 1984; Livio & Soker 1988) to show that for a reasonable energy parameter αCE ≤ 0.3, theory correctly predicts that the envelope will not eject in our simulation or in any other with very similar initial conditions (Ohlmann et al. 2016) because the simulations do not reach the predicted separation for ejection by the end of the runs. That simulations do not eject the envelope because they do not attain small enough separations is partly supported by observations, exhibiting small final separations (Iaconi et al. 2017; Iaconi & De Marco 2019).

Although extra energy sources (e.g. recombination energy or energy released by accretion onto the companion) may help to eject the envelope, they should also result in larger final separations, since less transfer of orbital energy is then required for ejection. On the other hand, energy sinks, such as loss via radiation, may offset energy gain by the envelope gas (Sabach et al. 2017; Grichener et al. 2018, but see Ivanova 2018).

Separations at late times tend to be overestimated because of inadequate numerical resolution (Ohlmann et al. 2016; Iaconi et al. 2017, 2018; Paper II), but this is unlikely a dominant effect—the slow decrease of a at late times needs to be explained physically. Ricker & Taam (2008, 2012); Staff et al. (2016) and Iaconi et al. (2017, 2018) include some explorations of the drag force in their global CE simulations. And recent work by Reichardt et al. (2019) showed that the decrease in the rate of orbital tightening at late times

∗ lchamandy@pas.rochester.edu

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was consistent with reduction in the drag force on the companion measured in one of their simulations. The reduction was explained qualitatively by a reduction in the angular velocity of the cores relative to the gas in their vicinity.

The goal of this work is to analyze the drag force in three otherwise identical simulations, but each with a different companion mass, and to compare our results with results from analytic theory and local wind tunnel simulations of flow near the secondary. In Sec. 2 we summarize our numerical methods. Sec. 3 contains the results of our simulations for the net force. We compare these results to analytic theory in Sec. 4. The evolution of the flow around the secondary, with a focus on the simulation with largest companion mass, is explored in Sec. 5. The results for the net force and flow properties are then compared to wind tunnel simulations in Sec. 6. We summarize and conclude in Sec. 7.

2 SIMULATION PARAMETERS AND METHODS

We employ the hydrodynamics code astrobear, which includes adaptive mesh refinement (AMR). The primary is an $M_1 = 1.96 M_\odot$ red giant branch (RGB) star with radius $R_1 = 48 M_\odot$ and core mass $M_{1c} = 0.37 M_\odot$, and the secondary has mass $M_2 = 0.98 M_\odot$ (Model A), $M_2 = 0.49 M_\odot$ (Model B) or $M_2 = 0.243 M_\odot$ (Model C). The primary and secondary are initialized in a circular orbit with separation $a_1 = 49 R_\odot$. Aside from the companion mass and initial velocities, the three runs are identical. Model A is the same as Model A of Chamandy et al. (2018) (hereafter Paper I) and Paper II.

RGB core and companion are modeled as point particles ("particle 1" and "particle 2", respectively) that interact with each other and gas via gravity only. The RGB model is adapted from a mesa (Paxton et al. 2015) 1D profile using a similar method to that of Ohlmann et al. (2017) to model the gas profile within the softening radius. The spline softening radius and smallest resolution element are respectively $r_{\text{soft}} = 2.4 R_\odot$ and $\delta = 0.14 R_\odot$ from $t = 0$ to $t = 16.7 d$, and $r_{\text{soft}} = 1.2 R_\odot$ and $\delta = 0.07 R_\odot$ thereafter. Refinement at the highest resolution is applied everywhere within a sphere of dynamically changing radius $r_{\text{refine}}$ (see Fig. 1), centred on the primary core before $t = 16.7 d$, and companion thereafter. The simulation domain size is $L_{\text{box}} = 1150 R_\odot$. An ideal gas EOS with $\gamma = 5/3$ is employed. The ambient density and pressure are $\rho_{\text{amb}} = 6.7 \times 10^{-9}$ g cm$^{-3}$ and $p_{\text{amb}} = 1.0 \times 10^5$ dyn cm$^{-2}$. The simulations are stopped after $t = 40 d$. More details about the setup and methods can be found in Papers I and II.

In Model B of Paper I, the secondary was a sink particle that accreted mass at a rate which was an upper bound to the true accretion rate. Since the orbit, and hence the drag force, were not drastically affected by this accretion, we exclude accretion onto the companion in the present simulations.

3 OVERALL EVOLUTION

3.1 Orbital separation

Fig. 1 shows orbital separation versus time for Models A, B and C in blue, red and black, respectively. The quantities $r_{\text{soft}}$ and $r_{\text{refine}},$ which do not change between runs, are also shown for reference. As the companion mass is lowered, the initial orbital speed and separation decay rate are both reduced. At later times however, the separation decays more rapidly for lower mass, and the curves cross. This behaviour is consistent with other studies (e.g. Passy et al. 2012).

![Figure 1. Inter-particle separation as a function of time for the three runs.](image)

We have computed the tidal shredding radius $r_{\text{shred}}$ for a main sequence secondary using the initial density profile of the primary along with the estimate of Nordhaus & Blackman (2006) and the mass-radius relation from Eker et al. (2018), and find $r_{\text{shred}} < 1 R_\odot$ for all three models. For a white dwarf secondary, $r_{\text{shred}}$ would be smaller still. Thus, the secondary is not expected to tidally shred during any of our simulation runs.

3.2 Drag Force

The centre of mass of the particles accelerates during the simulation (Paper II) due to the gravitational interaction between the gas and each of the particles. To facilitate comparison with theory and local simulations that treat the primary as fixed and non-rotating, we compute the dynamical friction force on particle 2 in the non-inertial rest frame of particle 1, $F_{2,\text{gas}}$, where the subscript '1' after the comma denotes this reference frame. As seen in the lab frame, this frame orbits with particle 1 but does not rotate. This introduces a fictitious force so that the force exerted on particle 2 by gas in this frame is given by

$$F_{2,\text{gas}} = F_{2,\text{gas}} - (M_2/M_1)F_{1,\text{gas}},$$

where the terms on the right are computed in the lab frame (nearly the centre of mass frame of the entire system; see Paper II). Note that a force in the $-\phi$ direction (a drag) on particle 1 in the lab frame contributes a drag on particle 2 in the frame of particle 1. To compute the terms on the right of equation (1), we simply integrate the force per unit volume on each particle, for example: $F_{2,\text{gas}} = GM_2 \sum_V \rho(s)(|s - s_2|/|s - s_2|)^3 |d^2s|$, where $\rho(s)$ is the gas density at position $s$, $V$ is the volume of the simulation domain, and $s_2$ is the position of particle 2. We then compute the $\phi$-component $(s_2 - s_1) \times F_{2,\text{gas}}/|s_2 - s_1|$. Likewise, we compute the projection of the force along the velocity relative to particle 1: $F_{2,\text{gas}} \cdot (v_2 - v_1)/|v_2 - v_1|$. The force on particle 2, multiplied by $-1$, is presented in Fig. 2. We refer to positive values on the plot as 'drag' and negative values as 'thrust'. The $\phi$-component is plotted as a solid black line, and the projection along the relative velocity is plotted as a dash-triple-dotted gold line, for Model A (top), Model B (middle) and Model C.

![Figure 2. Drag force components and projections.](image)
Figure 2. Azimuthal ($\phi$) component of the net force on particle 2 due to the gas in the non-inertial rest frame of particle 1, computed from the simulation (solid black), component of this force along the relative velocity of particle 2 with respect to particle 1 (dash-triple-dotted gold), and contribution to the $\phi$-component from the force on particle 2 in the lab frame, without the fictitious force (dashed grey). The inter-particle separation is plotted on the right axis for reference.
creases from resolution at thrust. The oscillations occur because the gas force exerted on each strongly with orbital separation and oscillates between drag and positive. 

\[ B, \] with the force magnitude greatest (smallest) when respectively. 

\[ \sim \] peak magnitude is roughly proportional to the companion mass: passage, though for Models Band C it happens slightly earlier. The evolution is slower in Model C, so we expect such an estimate would need to consider radiative transfer and is left for future work. The right side of Fig. 3 shows strong agreement between the two different methods, first from computing the rate of work done by gas on particles, 

\[ \dot{W} = F_{1-gas} \cdot v_1 + F_{2-gas} \cdot v_2 \] (black solid line), and second by numerical time-differentiating the total particle energy 

\[ E_{1-2} = \frac{1}{2} M_{1,\phi} v_1^2 + \frac{1}{2} M_2 v_2^2 - \frac{GM_{1,\phi} M_2}{a} \] (dash-triple-dotted magenta line).

### 4 COMPARISON TO ANALYTICAL THEORY

#### 4.1 Estimate for Uniform Density

The dynamical friction force can be estimated from Bondi-Hoyle-Lyttleton (BHL) theory (Hoyle & Lyttleton 1944; Bondi 1952). Here, gas approaching with impact parameter less than the accretion radius

\[ R_a = \frac{2GM}{c_s^2 + v_{\infty}^2} \] (6)

accretes onto the star, where \( c_s \) and \( v_{\infty} \) are the speed of the unperturbed envelope, and its speed relative to the secondary. The accretion rate can be estimated as \( M = \pi R_a^2 \rho_{\infty} (c_s^2 + v_{\infty}^2)^{1/2} \), where \( \rho_{\infty} \) is the unperturbed density, resulting in a drag force 

\[ F = M v_{\infty} \ln \left( \frac{r_{\max}}{r_{\min}} \right) \sim \frac{4\pi G^2 M_2^2 \rho_{\infty} v_{\infty}}{(c_s^2 + v_{\infty}^2)^{3/2}} \ln \left( \frac{r_{\max}}{r_{\min}} \right). \] (7)

Typically, \( r_{\min} \) is taken to be \( R_a \) and \( r_{\max} \) as the radius of the star. Equation (7) was first derived by Dokuchaev (1964) and survives among different estimates (Edgar 2004) subjected to refinements from numerical studies, e.g. Shima et al. (1985). We neglect turbulence (Krumholz et al. 2006) which may be important in general. We do consider the influence of a density gradient, as explained below.

To make contact with previous work, we plot the \( \phi \)-component of the drag force, as in Fig. 2, but now with additional lines representing theoretical predictions or results from local simulations, in Fig. 4. The dash-dotted red line shows the quantity 

\[ F_0 \equiv \frac{4\pi G^2 M_2^2 |v_0| v_0}{(c_0^2 + v_0^2)^{3/2}}, \] (8)

where \( v_0 \equiv |v_2 - v_1| \). In our notation, quantities with a ‘0’ subscript are computed from the initial envelope profile at radius \( a(0) \), with velocity computed assuming a circular orbit with primary mass equal to the mass interior to the orbit, \( r_m(a) = M_{1,\phi} + m_{env}(a) \). We find that replacing \( v_0 \) by its actual value measured in the simulation \( |v_2 - v_1| \) increases the amplitude of the oscillations in \( F_0 \) but otherwise the results are similar, so we opt to use the relative velocity computed from the initial profile.²

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1 The inter-particle separation never differs from its projection in the \( xy \)-plane by more than 0.2%.

2 Defining the Mach numbers \( M = |v_2 - v_1|/c_0 \) or \( M_0 = v_0/c_0 \), these are found to be in the range \( 1.1 < M, M_0 < 5.8 \). Within this range, the...
At early times, $F_0$ is effectively zero due to the small $\rho_0$. Subsequently, $F_0$ rises to be comparable to the $\phi$-component of $-F_{2,\text{gas},1}$ just before the first periastron passage, before continuing to rise, in contrast to the $\phi$-component of $-F_{2,\text{gas},1}$, which decreases and then levels off. Qualitatively similar results were obtained by Staff et al. (2016).

### 4.2 Estimate Including Density Gradient

Using a more refined version of the theory that includes the logarithmic factor of equation (7) and accounts to some extent for gradients in the radial direction might be expected to produce better agreement. Hence, for a more general estimate to the drag force, we multiply $F_0$ by $\ln(r_{\text{max}}/r_{\text{min}})$ and a correction factor Dodd & McCrea (1952) (hereafter DM) 

$$R_{a,\text{DM}} \approx R_{a,0} \frac{\rho_0}{\left(\frac{d\rho}{dr}\right)_0},$$

(9)

where

$$R_{a,0} = \frac{2GM_2}{e_0^2 + v_0^2}$$

(10)

and $H_\rho = -\rho_0/(d\rho/dr)_0$ is the scale height. The modified force magnitude is then

$$F_{\text{DM}} = F_0 \ln\left(\frac{r_{\text{max}}}{r_{\text{min}}}\right) \frac{R_{a,\text{DM}}}{R_{a,0}}.$$  

(11)

We adopt $r_{\text{max}} = R_{a,\text{DM}}$ and $r_{\text{min}} = r_{\text{soft}}|_{t=0} = 2.4 R_\odot$. The dashed purple line shows the resulting corrected estimate.

We see from Fig. 4 that despite some differences, the level of agreement between theory which includes the density gradient (dashed purple) and the simulation results (solid black) is overall comparable to that obtained using $F_0$ (dashed red). The DM correction marginally improves agreement for Models A and B, but marginally worsens agreement for Model C.

3 Radial variations in the density gradient of the initial envelope profile cause the noise. This variation is present in the 1D MESA solution, which was retained for our initial condition outside of $r = 2.4 R_\odot$.

4 We also tried other variations, with only the $\ln(r_{\text{max}}/r_{\text{min}})$ factor or only the DM correction included, and found results that are generally similar to the cases plotted.
Figure 4. Azimuthal component of the net force on particle 2 due to the gas in the non-inertial rest frame of particle 1 (as in Fig. 2), along with model predictions. See text for explanations of the quantities plotted. The dashed green line in the bottom panel is from the fitting formula (15), obtained from local 3D wind tunnel simulation results (M17). This comparison is only carried out for Model C, where $q_{enc}(t)$ is comparable with the value $q_{enc} = 0.1$ used in their local simulations.
4.3 Theory works best at intermediate times

We do not expect good agreement between simulation and theory at early times because of three interrelated factors: (i) tidally drawn envelope material increases the density near particle 2 beyond ambient and outer envelope layer values, (ii) density scale heights are initially small compared to the accretion radius and (iii) the initial condition of a secondary placed just outside the spherically symmetric primary at $t = 0$ is not fully realistic. Point (ii) is seen by comparing solid black and green lines in Fig. 5, where we plot the various length scales as a function of time, for each simulation. The
DM correction in principle helps to account for (ii) but considers only the lowest order effect of the density gradient.

At late times, we also expect poor agreement. In Model A ($q=1/2$), $R_0 \sim a$ shortly after the first periastron passage, as seen in Fig. 5 (compare blue and red dashed lines with black line), so we do not expect good agreement. For Model B ($q=1/4$), $R_0$ remains marginally smaller than $a$, while for Model C ($q=1/8$), $R_0 \sim 0.5a$ by the end of the simulation. Theoretical predictions for late times improve slightly as $q$ decreases to $1/8$, but not dramatically.

At intermediate times, when $R_a \ll a$ and $H_{0,0} \gtrsim R_a$, we expect and find agreement to be much better. If we use $|v_2 - v_1|$ measured directly from the simulation to compute $R_0$ (dashed blue in Fig. 5), then the time range when $R_a(t) < a(t)$ at the previous periastron passage becomes $12d \leq t \leq 14d$ for Model A, $13d \leq t \leq 24d$ for Model B, and $t \gtrsim 16d$ for Model C. BHL/DM theory approximates the numerical results reasonably well in these time ranges. In particular, during the broad force peak, theory (equation 8 or 11) correctly predicts the force to within a factor of ~ 2 for all models.

4.4 Improved theory is needed for late times

Reichardt et al. (2019) suggested that a reduction in the relative velocity between the particles and gas at late times in their simulation with $q = 0.68$ might help explain the reduction of the drag force. Might replacing our initial values of the gas density, velocity with $v_0$, might help explain the reduction of the drag force. At late times, we also expect poor agreement. In Model A, the $R_a(t)$ is still much too large to explain the force measured in the simulation. However, it is not clear whether equation (12) is even applicable in the present context.

A more promising possibility is to note that at late times the particle’s relative velocity is approximately zero (consistent with the top-left panel of Fig. 6), then the time range when $R_a(t) < a(t)$ at the previous periastron passage becomes $12d \leq t \leq 14d$ for Model A, $13d \leq t \leq 24d$ for Model B, and $t \gtrsim 16d$ for Model C. BHL/DM theory approximates the numerical results reasonably well in these time ranges. In particular, during the broad force peak, theory (equation 8 or 11) correctly predicts the force to within a factor of ~ 2 for all models.

5 EVOLUTION OF FLOW PROPERTIES

Fig. 6, shows snapshots of various quantities, sliced through $z = 0$, for Model A. The snapshots are taken at $t = 6.9$, 11.1, 16.7, and 22.0 d. Defining the end of the dynamical plunge-in phase as the time of first periastron passage (Paper II) the four times represent, roughly speaking, the flow near the beginning of plunge-in, the end of plunge-in, the transition to slow spiral-in, and at the beginning of slow spiral-in. The orbital motion is counter-clockwise. In each panel, particle 2 is at the centre and the view is rotated so that particle 1 is on the negative $y$-axis. Circles show the softening spheres around the particles. We focus on Model A because it displays the strongest deviation from theory, and because other aspects of the run were extensively studied in Papers I and II.

5.1 Force density

The top row shows the magnitude of the $\phi$-component of the force per unit volume exerted by gas on particle 2 in the co-orbiting but non-rotating rest frame of particle 1. Positive (negative) drag contributions are indicated by solid (dashed) contours, spaced by $\rho_{\infty}$, the values on the color bar. As there are positive and negative contributions from both terms in equation (1), the plot contains four sets of contours. Forces between gas and particle 2 dominate the contours in the upper part of the plot, while forces between gas and particle 1 (fictitious forces on particle 2) dominate the lower sets of contours. A drag (thrust) on particle 1 in the lab frame produces a fictitious drag (thrust) on particle 2 in the reference frame orbiting with particle 1. The black arrow shows the relative magnitude and direction of $\vec{F}_{\phi 1}$, which is just the order of magnitude needed. We leave further exploration of the force at late times for future study.
Figure 6. Snapshots in the orbital plane $z = 0$ for Model A. From left to right, columns show the times $t = 6.9, 11.1, 16.7$ and $22.0 \, d$. Rows from top to bottom are: Force density on particle 2 due to gas in the accelerating reference frame of particle 1; mass density normalized to $\rho_0(a)$ with velocity vectors in the corotating frame of particle 2 (note the difference in color bar range from Fig. 7); Mach number in the corotating frame of particle 2; $-\phi$-component of gas velocity with respect to particle 1, in the corotating frame of particle 2, normalized to $v_{0\phi}$ and sound speed normalized to $c_0$.

Correspondingly, the contours show a high degree of left-right symmetry. The force $F_{2-gas,1}$ now has comparable contributions from $F_{2-gas}$ and $-(M_2/M_1 c) F_{1-gas}$.

For the final snapshot at $t = 22.0 \, d$ (column 4), the $-\phi$-component of $F_{2-gas,1}$ is quasi-steady. The force remains small, owing to the high degree of symmetry in the force density, so that the thrust and drag contributions balance except for a small net drag. The force density pattern is quasi-steady thereafter, consistent with the net force being quasi-steady.
5.2 Gas density evolves toward symmetry

The second row of Fig. 6 shows the gas density normalized to $\rho_0(a)$ of the initial density profile of the RGB star. Vectors show the gas velocity in the frame co-orbiting and co-rotating with particle 2. As this is the appropriate reference frame for comparison with theory and local simulations. The second to fifth rows are zoomed in by a factor of four compared to the top row. At $t = 6.9\, d$, the density is $\sim 10^5$ times larger than $\rho_0(a)$ as deeper gas is pulled tidally around particle 2. The value of $\rho$ then reduces to $\sim 10$ at $t = 22.0\, d$ and by $1\, t = 40\, d$. The flow around particle 2 becomes more axisymmetric, rotating $\sim 20\%$ of the Keplerian value at late times (Paper I).

5.3 Mach number and turbulence

In the third row, we plot the gas Mach number computed in the frame co-orbiting and co-rotating with particle 2. In this frame, the gas around particle 2 is mostly supersonic during plunge-in, except in the bow shock. For these snapshots we obtain, from earliest to latest, $M_0 = v_0/v_0 = 5.3, 2.1, 1.7$, and $1.7$. At $t = 16.7\, d$, a shock is still seen, now above particle 2 in the plot. By $t = 22.0\, d$, the gas about the particles and within the orbit is not only subsonic, but turbulent. The turbulence is well-developed by $t = 18\, d$.

To verify that the turbulence is not produced by the sudden change in softening length and resolution at $t = 16.7\, d$, we compared the 2D snapshots to a run (Model F of Paper II) for which the softening length and maximum AMR level are not changed in this way. Turbulent eddies are conspicuous by $t = 18\, d$ in that run as well, even though the smallest scales of the turbulence are larger.

The onset of turbulence roughly coincides with the transition from plunge-in to slow spiral-in once $R_2 = a$, as shown in Fig. 5, and the particles have completed a full orbit since the first periastron passage. The gas they encounter no longer moves out supersonically due to the deeper potential and confinement by overlying layers (Paper II) so is continually being ‘reprocessed’.

5.4 Azimuthal velocity and sound speed

Finally, we present plots of the velocity and sound speed, which were used above to obtain modified parameter values for theoretical estimates (Sec. 4.4). The vectors in the fourth row of Fig. 6 show the gas velocity in the corotating frame of particle 2 as in the third row. The color shows the $-\phi$-component of this velocity with respect to particle 1, normalized to $v_0$. A value of unity (orange) corresponds to the relative tangential velocity estimated from the initial stationary envelope profile, while negative values (yellow to purple) denote oppositely moving gas. In all snapshots, the streamlines curl counterclockwise around particle 2 so that the $\phi$-component of the velocity reverses sign. The speed of gas approaching particle 2 is of order $v_0$ in the first three snapshots, but only about $\frac{1}{2} v_0$ by the fourth snapshot (Sec. 4.4).

Finally, in the fifth row we plot the sound speed normalized to $c_0$, along with the same velocity vectors plotted in rows 2 and 4. The gas flowing toward and deflected by the secondary has sound speed $\sim 2c_0$ (blue).

### 6 COMPARISON TO WIND TUNNEL SIMULATIONS

6.1 Drag force comparison

Here we compare our results with the local CE wind tunnel simulations of MacLeod et al. (2017) (hereafter M17) for which a particle representing the secondary was fixed at the centre of the grid and a wind was launched from the $-x$ boundary with a prescribed $x$-velocity and density gradient in the $-y$ direction. By approximating the gas as a polytrope and assuming that the upstream wind velocity equals the local Keplerian orbital speed, the upstream Mach number is determined once the dimensionless density gradient parameter

$$\epsilon_p = \frac{2GM_2}{v_0^2 H_p}$$

(14)

and the mass ratio $q_{enc} = M_2/m_1(a)$ are specified. M17 chose $q_{enc} = 0.1$ and explored the dependence on $\epsilon_p$. In our simulations, $q_{enc} = q = 1/2, 1/4$ or $1/8$ at $t = 0$, but then increases with time as $m_1(a)$ decreases: computing $m_1(a)$ from the initial envelope profile, we obtain $q_{enc, 0} = 2.0, 1.2$ and $0.6$ at $t = 40\, d$ for Models A, B and C, respectively. M17 results are likely to be sensitive to their fixed choice of $q_{enc}$; nevertheless we proceed with the comparison for Model C, which proves to be fruitful.

We first fit the drag force in M17 for $\gamma = 5/3$ in their Fig. 10. Replacing $\rho_\infty$ and $v_0$ by $\rho_0$ and $v_0$ we obtain

$$F_{M17} \approx 0.6 v_0^2 \epsilon_p^{1.6} \frac{4 \pi G^2 M_2^3 \rho_0}{v_0^3}.$$  (15)

We apply this for $0.4 < \epsilon_p < 2.7$ (consistent with the range of parameter space explored by M17) and plot the resulting force only for times in our simulation when $\epsilon_p > 2GM_2/(v_0^2 H_p a)$ is within this range. The result is the dashed green line in the bottom panel of Fig. 4.

At intermediate times, between $t = 12$–$26\, d$, the agreement is excellent. At $t = 26\, d$, when $-\phi$ attains its second maximum (the first having occurred between $t = 13$–$14\, d$), the $\phi$-component of $F_{\phi \text{-gas}, 1}$ decreases from its peak value, but equation (15) predicts the force to continue rising. At this time, $q_{enc, 0} = 0.28$, or almost three times larger than that assumed by M17, which likely contributes to this discrepancy.

6.2 Flow structure comparison

Flow structure of global and local simulations can also be compared. For Model C, we choose the time $t = 20\, d$, at which $\epsilon_p = 0.80$ (and $q_{enc} = 0.15$), to compare with the lower left panels of Fig. 2 of M17. We plot the mass density normalized to $\rho_0(a)$ and velocity vectors in the corotating frame of particle 2 in the top panel of Fig. 7, and the Mach number in the corotating frame of particle 2 in the bottom panel. The unit of the M17 axes is $2GM_2/v_0^2 = 7.4\, R_0$, so our plotting region is slightly larger than theirs. The level of agreement is remarkable. All of this suggests that the local simulations approximate global simulations for this window of parameter space.

Curiously, there is also some correspondence between the flow in Model A and that of the local simulations, even though the mass ratio of the former is much larger. Whereas M17 adopted $q_{enc} = 0.1$ and $\epsilon_p = 0.2$–$2$, Model A has $q_{enc, 0} = 0.50, 0.75, 1.23$ and $1.53$ and $\epsilon_p, 0 = 20.3, 2.1, 1.7$ and $1.4$ at $t = 6.9, 11.1, 16.7$ and $22.0\, d$, respectively. Despite differences in $q_{enc}$ and the force seen in Fig. 4, the panels of Fig. 6 showing $\rho/\rho_0$ and $M$ in Model A at $11.1\, d$ show similarities to those of $\epsilon_p = 2.00$ in Fig. 2 of M17, as seen by comparing the second column, third and fourth rows of Fig. 6 with Fig. 2 of M17. The flow pattern is similar and both methods exhibit a thin spiral shock. However, the normalized gas density in Fig. 6 is $1$–$1000$ (whereas in Fig. 7 we used $0.1$–$100$, as in M17).

Thus in Model A our normalized densities are almost an order of magnitude larger than those of M17, likely because our $q_{enc}$ is $7.5$ times larger than theirs at that time. The size of the region...
plotted in units of $2GM_2/v_{\infty}^2$ differs from M17: for Model A we obtain $2GM_2/v_{\infty}^2 = 29, 19, 16$ and $14 R_\odot$, respectively, for the four snapshots.5

As expected, snapshots at other times hardly resemble those of M17. At $t = 6.9$ d, $\epsilon_r$ is an order of magnitude larger than that explored by M17. We do see increasing density contrast and larger rotation angle of the bow shock with increasing $\epsilon_r$, as in M17, but our shock is thick and morphologically complex. By $t = 16.7$ d, $R_s$ has already become comparable to $a_s$ as shown in the top panel of Fig. 5. The assumptions of M17, namely that (i) the envelope gas encountered by the secondary had not been previously affected; (ii) their $\rho_{enc}$ smoothly and monotonically decreases with distance from the RGB core, and (iii) the gravity force from the RGB core can be approximated as everywhere downward, are no longer valid. Moreover, in our final snapshot, turbulence likely affects the dynamics.

Thus, we would not expect wind tunnel simulations to approximate the results of Model A at late times even if several wind tunnel simulations of different $q_{enc,0}$ and $\epsilon_{r,0}$ were patched together to accommodate dynamically changing values of these parameters in the global simulation. However, given the excellent agreement at intermediate times for Model C, it would be interesting to compare local and global simulations using such dynamical patching of the local simulations to refine the temporal range over which this approach could be useful and computationally efficient.

7 CONCLUSIONS

We computed the drag force in three global CE simulation runs of 40 d in which a companion point particle is placed in circular orbit around a $2M_\odot$ RGB star. The runs are identical except for the value of the companion mass, $M_2 = \frac{1}{2} M_\odot$ or $\frac{1}{4} M_\odot$. We found that:

- The drag force on the particles at late times, during the slow spiral-in phase, has mean magnitude $\sim 7 \times 10^{13}$ dyn, depending only weakly on companion mass, and varies periodically with the orbit (Figs. 2, A1).
- BHL/DM theory overestimates the drag force at late times by at least an order of magnitude for the run with initial mass ratio $q = 1/2$ (Fig. 4 top panel), and cannot reproduce the late time force characteristics for any of the three runs.
- BHL/DM theory and local wind tunnel simulations are particularly inapplicable at late times for large $q_{enc} = M_2/m_1(a)$ because the accretion radius becomes comparable to the inter-particle separation. The gas encountered by the particles forms a turbulent, thermalized, highly symmetric region around the particles (Fig. 6 rightmost column). Hydrodynamic drag may even dominate over dynamical friction during this phase, but further work is needed.
- At earlier times, the drag force peaks at or just before the first periastron passage with value approximately proportional to the companion mass (Fig. 2). Near this peak, the drag force is reasonably well matched by BHL/DM theory and particularly well matched by local wind tunnel simulations (Fig. 4 bottom panel), which also reproduce various features of the 2D slices at that time (c.f. Fig. 7 of this work and Fig. 2 of M17).

Thus, for low $q_{enc}$, BHL/DM theory and local wind tunnel simulations approximate the drag in global simulations during the intermediate plunge-in phase, but not before or after. Since $q_{enc}$ evolves temporally in global simulations, different fixed $q_{enc}$ wind tunnel simulations must be patched together to increase the fidelity of comparison with global simulations over a larger temporal range. This has not yet been done.

Finally, more general theoretical approaches are needed to account for the high degree of symmetry and turbulence in the flow once $R_s \sim a$, and the associated reduced drag at late times. This reduced drag dramatically slows the inward evolution and explains why numerous CE simulations do not reach tight enough orbits by the end of runs to eject the CE envelope.

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\footnotetext[5]{When $\epsilon_r$ and $2GM_2/v_{\infty}^2$ are estimated using the actual velocity $v_2 - v_1$, rather than $v_0$, the values are larger by 37% for $t = 6.9$ d but hardly differ for the other snapshots of Model A.}
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APPENDIX A: EFFECT OF CHANGING SOFTENING LENGTH AND RESOLUTION

Here we compare the $-\phi$-component of the force exerted on particle 2 by the gas in the frame of particle 1 in Model A and Model F of Paper II. Model F restarts from Model A at $t = 16.7 \, d$ but the softening radius and smallest resolution element are not halved as in Model A. The evolution of the force is very similar, confirming that the halving of $r_{soft}$ and $\delta$ does not importantly affect the overall evolution of the force.

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Figure A1. Comparison between the $\phi$-component of the force exerted by gas on particle 2 in the reference frame of particle 1, for Model A and Model F of Paper II. In Model F, the softening radius and smallest resolution element were kept constant during the simulation rather than being halved at $t = 16.7 \, \text{d}$, as in Models A, B and C.