

3D models of radiatively driven colliding winds in massive O+O star binaries – I. Hydrodynamics

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ABSTRACT

The dynamics of the wind–wind collision in massive stellar binaries are investigated using 3D hydrodynamical models which incorporate gravity, the driving of the winds, the orbital motion of the stars and radiative cooling of the shocked plasma. In this first paper, we restrict our study to main-sequence O+O binaries. The nature of the wind–wind collision region is highly dependent on the degree of cooling of the shocked plasma, and the ratio of the flow time-scale of the shocked plasma to the orbital time-scale. The pre-shock wind speeds are lower in close systems as the winds collide prior to their acceleration to terminal speeds. Radiative inhibition may also reduce the pre-shock wind speeds. Together, these effects can lead to rapid cooling of the post-shock gas. Radiative inhibition is less important in wider systems, where the winds are accelerated to higher speeds before they collide, and the resulting collision region can be largely adiabatic. In systems with eccentric orbits, cold gas formed during periastron passage can persist even at apastron, before being ablated and mixed into its surroundings and/or accelerated out of the system.

Key words: shock waves – hydrodynamics – binaries: general – stars: early-type – stars: mass-loss – stars: winds, outflows.

1 INTRODUCTION

The collision of the winds in massive star binary systems can produce a rich array of phenomena. Energetic particles are accelerated at the wind–wind collision region (WCR; see e.g. Eichler & Usov 1993; Dougherty et al. 2003; Pittard & Dougherty 2006; Pittard et al. 2006), producing non-thermal radio emission via the synchrotron process (see e.g. Dougherty et al. 2005), and X-ray and γ -ray emission via the inverse Compton and pion decay processes which should extend to TeV energies (Pittard & Dougherty 2006; Reimer, Pohl & Reimer 2006). Dust can be formed either episodically producing transient infrared outbursts (Williams 1996), or continuously producing spiral-shaped structures on the sky (e.g. Tuthill, Monnier & Danchi 1999; Marchenko et al. 2002). Emission-line profiles from the WCR show variable Doppler shifts and broadening as sight lines relative to the WCR change (e.g. Lührs 1997; Henley, Stevens & Pittard 2003). Shock heating of the winds produces bright thermal X-ray emission, which may exhibit signs of non-equilibrium ionization in wide systems (Pollock et al. 2005).

The hydrodynamics of colliding wind binaries (CWBs) have usually been investigated using 2D (axisymmetric) models with terminal velocity winds (e.g. Stevens, Blondin & Pollock 1992; Pittard &

Stevens 1997). 3D simulations, which include orbital effects, have been presented by Walder (1998), Pittard (1999) and Lemaster, Stone & Gardiner (2007). In close binaries, the winds collide before they reach terminal velocity, and their dynamics may be altered by the companion star’s radiation field (Stevens & Pollock 1994; Gayley, Owocki & Cranmer 1997, 1999). The driving of the winds and the dynamical effect of the companion’s gravitational and radiation fields have been included in 2D models of V444 Cygni (Gayley et al. 1997), ι Orionis (Pittard 1998), η Carinae (Pittard et al. 1998) and Sanduleak 1 (St-Louis et al. 2005). The only published 3D simulation with radiative driving is of V444 Cygni (Pittard 1999). Other approaches based on solutions to the ram-pressure balance have been presented by Antokhin, Owocki & Brown (2004) and Parkin & Pittard (2008).

In this work, we examine the hydrodynamic properties of the wind–wind collision in short period O+O binaries. We perform 3D calculations, so that orbital effects can be included, and calculate the radiative driving of the winds, so that the winds collide at realistic velocities and some effects of the companion’s radiation field can be accounted for. In some of the simulations, the winds collide at only a fraction of their terminal velocities, and the lower post-shock temperatures and higher post-shock densities which result enhance the radiative cooling of the post-shock gas. We examine the dynamics of the wind–wind collision in systems with circular and eccentric orbits, and with equal and unequal winds. In Section 2, we

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describe the details of our simulations and in Section 3 we present our results. Section 4 summarizes and concludes this work.

2 THE NUMERICAL SET-UP

2.1 Details of the hydrodynamics

Our 3D simulations were conducted on a Cartesian grid using Eulerian hydrodynamics with piecewise parabolic interpolation of the fluid variables. The code solves a Riemann problem at each zone interface to determine the time-averaged values at the zone faces, and then solves the equations of hydrodynamics:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (1)$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u} + P) = \rho \mathbf{f}, \quad (2)$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot [(\rho \varepsilon + P) \mathbf{u}] = \left(\frac{\rho}{m_H} \right)^2 \Lambda(T) + \rho \mathbf{f} \cdot \mathbf{u}, \quad (3)$$

where $\varepsilon = \mathbf{u}^2/2 + e/\rho$ is the total specific energy, ρ is the mass density, e is the internal energy density, P is the pressure and T is the temperature. We adopt an ideal gas equation of state, $e = P/(\gamma - 1)$, with $\gamma = 5/3$ as the ratio of specific heats. $\mathbf{f}$ is the force per unit mass and includes gravity and radiative driving terms.

The radiative cooling term, $\Lambda(T)$, is calculated from the MEKAL thermal plasma code (Kaastra 1992; Mewe, Kaastra & Liedahl 1995) distributed in XSPEC (v11.2.0). The plasma is assumed to be in collisional ionization equilibrium (but see Section 2.2). The temperature of the pre-shock stellar winds is assumed to be maintained at $\approx 10^4$ K through photoionization heating by the stars. Gas in the WCR, which rapidly cools, is prevented from cooling below this temperature. Because of the high Mach numbers involved, the density contrast of the hot plasma and cooled regions can be very high (the density contrast across an isothermal shock of Mach number M is γM^2). In reality, magnetic pressure may halt the compression before this ratio is reached (e.g. Kashi & Soker 2007), but this is an additional complication which is not considered here. The code also contains several advected scalars which allow tracking of which wind material is in which cell, and the ionization age and temperature equilibration of the post-shock gas (see Section 2.2).

The body forces acting on each hydrodynamic cell are the vector summation of gravitational forces from each star, and continuum and line-driving forces from the stellar radiation fields. The computation of the line acceleration is based on a local Sobolev (1960) treatment of the line transport, following the standard Castor, Abbott & Klein (1975, hereafter CAK) formalism developed for single O and B-type winds, augmented by the finite disc correction factor developed by Pauldrach, Puls & Kudritzki (1986). The vector radiative force per unit mass, $\mathbf{g}^{\text{rad}}$, is computed from an integral of the intensity $I(\hat{\mathbf{n}})$ times the projected velocity gradient along directional vectors $\hat{\mathbf{n}}$ within the solid angle covering the stellar disc,

$$\mathbf{g}^{\text{rad}} = \frac{\sigma_e^{1-\alpha} k}{c} \oint I(\hat{\mathbf{n}}) \left[\frac{\hat{\mathbf{n}} \cdot \nabla(\hat{\mathbf{n}} \cdot \mathbf{v})}{\rho v_{\text{th}}} \right]^\alpha \hat{\mathbf{n}} d\Omega. \quad (4)$$

The integration over solid angle is performed with eight directional vectors. α and k are the standard CAK parameters, σ_e is the specific electron opacity due to Thomson scattering and v_{th} is a fiducial

thermal velocity calculated for hydrogen.¹ Shadowing by the companion star is accounted for in our calculations, and in such cases only the visible part of the stellar disc contributes to the radiative driving force. The line driving is set to zero in cells with temperatures above 10^6 K, since this plasma is mostly ionized. Further details concerning the line force calculations can be found in Gayley et al. (1997).

A companion star influences the driving of a wind in a number of distinct ways. Very close to the surface of the star, reflection of the companion's starlight from the stellar photosphere can actually enhance the wind driving and mass loss, and the angular asymmetry in the line-scattering probability can induce significant tilting of the direction vector of the wind away from the surface normal (Gayley et al. 1999). Reflection effects become less important further from the star. At this point, the main effect of the companion's radiation field is to reduce the net radiative flux, slowing the remaining acceleration and producing a lower terminal velocity – this effect is known as radiative inhibition (Stevens & Pollock 1994). The gravity of the companion star also has an effect – it alters the net force on the wind, and can distort the shape of the other star, which may lead to gravity darkening of the stellar surface and thus again affect the wind.

Outflow boundary conditions are used for all of the simulations. The fluid values on the grid are initialized by mapping 1D solutions of the CAK equations on to the grid. The wind velocities are modified to account for the velocity of each star on the grid [i.e. $\mathbf{v} = \mathbf{v}_w(\mathbf{r}) + \mathbf{v}_*$]. We assume that the stars remain closely spherical and are not subject to significant deformations due to the companion's gravity. To generate the winds, we re-initialize density, pressure and velocity values within a shell of three-cell thickness around each star at the start of every time-step. This procedure means that the stars maintain a constant mass-loss rate, and have a wind which is initially directed radially outwards. Because our models do not resolve the wind acceleration regions very close to the stars, we are unable to investigate reflection effects on the mass loss and wind dynamics. Instead, the focus is on exploring the latter stages of the wind acceleration and the effects this has on the resulting wind–wind collision.

Our treatment of the wind initiation also means that the winds effectively feel no radiative inhibition effects until outside the three-cell remap radius. While this is not entirely satisfactory, our attempts to self-consistently accelerate the winds from the stellar surfaces have to date always resulted in unacceptable wind structure due to a ‘staircase’ effect introduced by the grid zones which straddle the surfaces of the stars. This problem is very much reduced in 2D $r - \theta$ simulations of single stars when the sonic point of the winds is resolved (see e.g. Owocki, Cranmer & Blondin 1994). To resolve this problem in 3D simulations with more than one star may require adaptive-mesh-refinement calculations, and/or sophisticated grid geometries. For the time being, we proceed with the above limitations, with the aim of reducing/eliminating this problem in future work.

We specify the initial boundary between the winds as a flat 2D plane which is normal to the line-of-centres through the stars and

¹ While we use the standard CAK α and k description, we note that the k parameter does not represent a physically meaningful quantity in its own right, and has an artificial dependence on v_{th} . A more meaningful description of the strength of line driving was given by Gayley (1995), who introduced the $\bar{Q}$ parameter. α and k values can easily be converted into $\bar{Q}$ values, and are noted alongside the α and k values for each of our model stars in Table 2.

passes through the stagnation point where momentum balance is achieved. This position is calculated assuming the winds instantaneously reach terminal velocity. The simulations are evolved until the effects of the initial conditions have been driven off the grid, following which we start our analysis. For numerical reasons, the orbital plane was aligned with the yz plane on the grid, with the x -axis perpendicular to this.

2.2 Post-shock equilibration

There is now strong evidence from studies of supernova remnants that the post-shock thermalization of electrons lags behind that of ions in high-speed collisionless shocks, with the ratio of post-shock electron to proton temperature, T_e/T_p , substantially below unity for shock velocities $\gtrsim 1000 \text{ km s}^{-1}$ (Rakowski 2005; van Adelsberg et al. 2008). Temperature equilibration through Coulomb collisions and plasma instabilities then occurs some distance downstream. One may expect these findings to be of relevance to collisionless shocks in general and thus also to CWBs. In fact, the post-shock thermalization of electrons has already been examined in the prototypical colliding winds binary WR 140 by Zhekov & Skinner (2000) and by Pollock et al. (2005), and can naturally account for the softer-than-expected X-ray continuum emission (see also Pittard et al. 2006).

Despite an increased understanding of the need to consider slow electron heating, the physics of the heating process in the shock layer remains poorly understood. For instance, the appropriate value of T_e/T_p immediately downstream of the subshock is not clear, with observations yielding a minimum value of ~ 0.03 at shock velocities $\gtrsim 1500 \text{ km s}^{-1}$ which is greater than the theoretical minimum (m_e/m_p) by two orders of magnitude, but smaller than the predictions of some collisionless heating models (e.g. Cargill & Papadopoulos 1988). Faced with this situation, we have therefore assumed in our models that $T_e/T = 0.2$ immediately post-shock, where T is the mean plasma temperature (see also Zhekov & Skinner 2000). The change in the downstream electron temperature is then given by (Spitzer 1978)

$$\frac{d(T_e/T)}{dt} = 3.8 \times 10^{-12} (n_e + n_i) \left(1 - \frac{T_e}{T}\right) \times \frac{\ln \Lambda}{30} \left(\frac{T_e}{10^7 \text{ K}}\right)^{-3/2} \text{ s}^{-1}, \quad (5)$$

where the numerical constant assumes cosmic abundances and $\ln \Lambda \approx 30$ (cf. Borkowski, Sarazin & Blondin 1994). Equipartition requires that the product of the post-shock time-scale and the density exceed $nt \gtrsim 3 \times 10^{11} \text{ cm}^{-3} \text{ s}$. Clumping in the winds will also affect the electron thermalization time-scale (Pittard 2007). Equation 5 is solved along with the other hydrodynamical equations.

The time-scale for the post-shock ionization to approach equilibrium will also be an important factor in some CWBs. For instance, non-equilibrium ionization may explain why line-profile models, which assume rapid ionization equilibrium (Henley et al. 2003), are unable to reproduce the observed correlation of X-ray line widths with ionization potential in the Wolf-Rayet system γ -Velorum (Henley, Stevens & Pittard 2005). Although the post-shock ionization depends on the thermal history of the plasma, to zeroth order the ionization is independent of the temperature history and the specific ionic species in the plasma (Masai 1994), and can be characterized by the so-called ionization age, $n_e t$. For example, the ionization of oxygen and iron in plasma at $T = 10^{6.5} \text{ K}$ as a function of $n_e t$ is shown in figs 1 and 2 of Hughes & Helfand (1985).

Table 1. Assumed binary parameters for the models investigated. The semimajor axis is $34.26 R_\odot$ in model cwb1, $76.3 R_\odot$ in models cwb2 and cwb3, and $55 R_\odot$ in model cwb4.

Model	Stars	Period (d)	Eccentricity (e)	Wind mtm. ratio (η)
cwb1	O6V+O6V	3	0.0	1
cwb2	O6V+O6V	10	0.0	1
cwb3	O6V+O8V	10.74	0.0	0.4
cwb4	O6V+O6V	6.1	0.36	1

Table 2. Assumed stellar parameters for the models investigated. Note that the value of $\bar{Q}$ is fairly constant, and shows less variation than k in the two stellar models constructed for this work.

Parameter/star	O6V	O8V
Mass ($M_\odot$)	30	22
Radius ($R_\odot$)	10	8.5
Effective temperature (K)	38 000	34 000
Mass-loss rate ($M_\odot \text{ yr}^{-1}$)	2×10^{-7}	10^{-7}
Terminal wind speed (km s^{-1})	2500	2000
CAK α	0.57	0.52
CAK k	0.12	0.24
$\bar{Q}$	258	308

The oxygen reaches ionization equilibrium at $n_e t \approx 10^{12.5} \text{ cm}^{-3} \text{ s}$, while the iron reaches equilibrium at $n_e t \approx 10^{11.5} \text{ cm}^{-3} \text{ s}$. At higher temperatures, iron is ionized to higher stages, and requires a greater ionization age to reach equilibrium. However, in general a plasma will be close to ionization equilibrium when $n_e t \gtrsim 10^{12.5} \text{ cm}^{-3} \text{ s}$. We therefore advect a scalar variable in the hydrodynamical code to track the post-shock value of $n_e t$.

2.3 Models investigated

In this work, we do not attempt to model particular systems. Instead, the aim is to achieve an understanding of how the dynamics of the collision region depend on some key parameters. We have therefore computed four different models with a range of binary and stellar parameters, as summarized in Tables 1 and 2. In the present work, we consider systems with dwarf O-stars, so that tidal distortions are minimized, and in this first study can be ignored. The stellar parameters are consistent with recent observations presented in Repolust, Puls & Herrero (2004), Martins, Schaerer & Hillier (2005), Bouret, Lanz & Hillier (2005) and Fullerton, Massa & Prinja (2006), in which clumping within the winds is considered. The CAK parameters (α and k), which are needed to drive the desired winds from the stars, are noted in Table 2, along with the value of $\bar{Q}$ calculated from them. We assume that the mass loss from the stars is isotropic. Solar abundances are assumed for each star/wind, and all simulations are performed in the centre of mass frame.

The nature of the WCR is largely governed by the ratio of the cooling time-scale for the shocked gas to the dynamical time-scale for it to flow out of the system, which is given by $\chi = v_8^4 d_{12} / \dot{M}_{-7}$, where v_8 is the pre-shock velocity in units of 1000 km s^{-1} , d_{12} is the stellar separation in units of 10^{12} cm and $\dot{M}_{-7}$ is the stellar mass-loss rate in units of $10^{-7} M_\odot \text{ yr}^{-1}$ (Stevens et al. 1992). Another key parameter governing the nature of the WCR is the ratio of the orbital speed to the pre-shock wind speed, v_{orb}/v_w . This ratio affects the

aberration angle of the WCR [$\theta \sim \tan^{-1}(v_{\text{orb}}/v_w)$] and its degree of downstream curvature due to coriolis forces.

In this work, we consider systems with identical or similar wind momenta. This means that radiative braking (Gayley et al. 1997) effects are negligible, and in all cases a normal wind–wind pressure balance exists. In future work, we will extend our investigation to systems with higher wind momentum ratios, to study the effects of braking and the dynamics of the WCR when the more powerful wind overwhelms the weaker wind and the WCR collapses on to the surface of one of the stars.

In model cwb1, we suppose that two identical O6V stars move around each other in a circular orbit with a period of 3 days. The stellar separation is $34.26 R_\odot$, and each star has an orbital velocity $v_{\text{orb}} = 290 \text{ km s}^{-1}$. A rough estimate of χ can be obtained by determining the speed of the winds at the stagnation point where momentum balance is achieved. Ignoring for the moment effects due to the orbital motion of the stars and the presence of two radiation fields, one finds that the winds accelerate to a speed of 1250 km s^{-1} prior to their collision at the stagnation point. This implies that $\chi = 2.9$, and the post-shock gas would not be expected to cool back to $T \sim 10^4 \text{ K}$ until it had left the central regions of the system. In fact, we shall see that once the simulation starts, the reduction in the net radiative flux due to the presence of the companion star reduces the acceleration of each wind towards its companion. This ‘radiative inhibition’ (Stevens & Pollock 1994) reduces the pre-shock velocities below 1250 km s^{-1} , which increases the cooling in this model (see Table 4, which summarizes some of the salient features directly obtained from the hydrodynamical simulations). Neglecting radiative inhibition again, we also find that $v_{\text{orb}}/v_w = 0.23$, indicating that the WCR will display a reasonably large aberration angle and downstream curvature due to coriolis forces. These effects become more pronounced if there is a significant reduction in wind speeds along the line-of-centres due to radiative inhibition. Note also that unphysical masses are required in some of the models of Lemaster et al. (2007), including their main large-box simulation C2.5.

Model cwb1 is similar to many real systems, including DH Cep (see Linder et al. 2007, and references therein), HD 165052 (Arias et al. 2002; Linder et al. 2007) and HD 159176 (De Becker et al. 2004b; Linder et al. 2007). All of these systems have near-identical main-sequence stars of spectral type O6–O7, and circular or near-circular orbits with periods near 3 days. Hence the hydrodynamics of and emission from the WCR in model cwb1 will be a reasonable approximation to the situations in these systems. In some of these systems, it may be difficult for the winds to attain a normal ram–ram pressure balance, and the stronger wind may push the WCR on to the surface of the star with the weaker wind. Detailed simulations of each individual system are needed to ascertain whether, in fact, this occurs. Reflection and distortion effects may also well be important in these systems, but are beyond the scope of the present work.

Model cwb2 uses the same stars as model cwb1, but increases the orbital period to 10 days (the stellar separation becomes $76.3 R_\odot$). The pre-shock collision speed on the line-of-centres (neglecting radiative inhibition) increases to 1970 km s^{-1} , as the winds now have more room to accelerate. The higher collision speed leads to higher post-shock temperatures, and together with the increased stellar separation produces lower post-shock densities. The result is that cooling within the WCR is dramatically reduced ($\chi \approx 40$), and the post-shock gas behaves largely adiabatically. The reduced orbital speed and higher pre-shock wind speeds also means that the aberration and curvature of the WCR will be smaller in this model than in model cwb1. Taking account of radiative inhibition, we again find slightly increased cooling and orbital effects (see Table 4).

Table 3. Details of the hydrodynamical grid of each model. The length of the sides of the grid in model cwb4 corresponds to $3.2 - 6.86 D_{\text{sep}}$ as the stars progress in their orbit from apastron to periastron.

Model	No. of cells	Length of sides		Resolution ($R_\odot$)
		($R_\odot$)	(a)	
cwb1	480 ³	240	7	0.5
cwb2	456 ³	570	7.46	1.25
cwb3	456 ³	570	7.46	1.25
cwb4	480 ³	240	4.34	0.5

Model cwb2 is similar to HD 93161A, an O8V + O9V system with a circular orbit and an orbital period of 8.566 days (Naze et al. 2005), albeit with slightly more massive stars and powerful winds. Another system with not too dissimilar properties is Plaskett’s star (Linder et al. 2006, 2008), though this object contains stars which have evolved off the main sequence. The wider separation of the stars in these systems means that the dominant dynamical effect of the companion starlight will be radiative inhibition, with reflection effects minimized.

In model cwb3, we examine the interaction of unequal winds in a hypothetical O6V + O8V binary. We keep the same stellar separation as model cwb2, which gives a period of 10.74 days from the total system mass of $52 M_\odot$. The orbit is circular, with the O8V star further from the centre of mass. An initial estimate of the pre-shock wind speeds can be obtained by considering the location of the stagnation point. The terminal speed wind momentum ratio, $\eta = \dot{M}_2 v_{\infty,2} / \dot{M}_1 v_{\infty,1} = 0.4$, indicating that the stagnation point occurs at a distance of $0.39 a$ from the O8V star. At this distance, the secondary wind speed is 1570 km s^{-1} , giving $\chi_2 \approx 32$. The primary wind collides at higher speed (2070 km s^{-1}), and its post-shock plasma is slightly more adiabatic ($\chi_1 \approx 50$). Again, radiative inhibition reduces the pre-shock wind speeds and post-shock cooling parameters below these simple estimates (see Table 4).

Model cwb4 explores the effect of an eccentric orbit which takes the stars through separations of $34.26 - 76.3 R_\odot$ (i.e. the separations of the stars in the circular orbits of models cwb1 and cwb2). The required eccentricity is $e = 0.36$, and the resulting orbital period is 6.1 days. This model allows us to investigate whether the WCR properties at a specific stellar separation are similar to those obtained with a circular orbit. Some well-known O+O binaries with eccentric orbits include (in order of increasing orbital period) HD 152248 ($e = 0.127$; Sana et al. 2004), HD 93205 ($e = 0.46$; Morrell et al. 2001), HD 93403 ($e = 0.234$; Rauw et al. 2002), Cyg OB2#8A ($e = 0.24$; De Becker, Rauw & Manfroid 2004a; De Becker et al. 2006) and ι Orionis ($e = 0.764$; Bagnuolo et al. 2001).

The hydrodynamical grid is half-cubic in all simulations, and is reflected in the orbital plane for further analysis. The grid is large enough to capture, for example, the majority of the X-ray emission from each model. Details of the grids are noted in Table 3. As a comparison, most of the simulations run by Lemaster et al. (2007) used a grid with sides of length $2.5a$, with their large grid simulations having sides of length $6.25a$.

3 RESULTS

3.1 Model cwb1

Fig. 1(a) shows a density snapshot in the orbital plane of model cwb1. The post-shock gas in the WCR between the stars has cooled

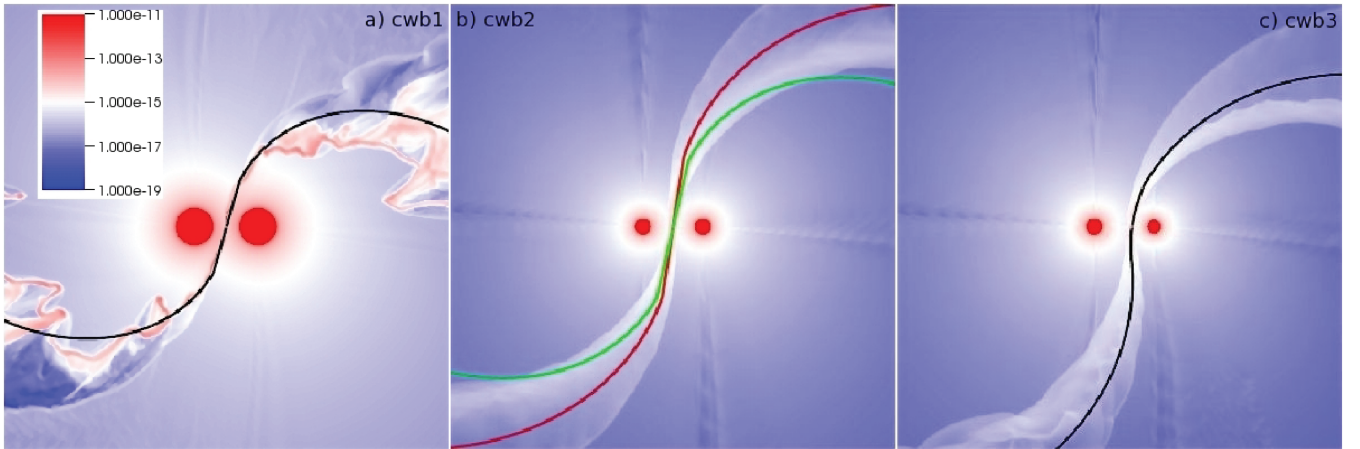


Figure 1. Density plots of models cwb1 (a), cwb2 (b) and cwb3 (c). The colour scale is logarithmic, spanning $10^{-19} \text{ g cm}^{-3}$ (blue) to $10^{-11} \text{ g cm}^{-3}$ (red). Panel (a) has sides of length $240 R_{\odot}$, while panels (b) and (c) have sides of length $570 R_{\odot}$. The black, red and green lines marked on the figures show the position of the CD as calculated by the model described in Parkin & Pittard (2008) – see the text for further details.

into a thin, dense sheet, which is subject to the non-linear thin-shell instability (Vishniac 1994; Blondin & Marks 1995). Clearly, our initial estimate of χ in Section 2.3 was too high. Examination of the dynamics reveals that the winds, in fact, collide at $\approx 730 \text{ km s}^{-1}$, rather than the 1250 km s^{-1} obtained from considering the acceleration of the wind of an isolated star. This is caused by a significant reduction in the acceleration of the stellar winds towards the centre of mass of the system due to strong radiative inhibition (in reality, reflection effects could also be important, though this process is not examined in this work). The cooling parameter, χ , is reduced to ≈ 0.3 , which gives rise to the severe radiative cooling of the post-shock gas seen in Fig. 1(a).

As previously noted, the nature of the WCR is also determined by the ratio of the pre-shock wind speed to the orbital speed of the stars, since this affects its angle of aberration and downstream curvature. The aberration angle of the WCR in Fig. 1(a) is $\approx 17^\circ$, which compares to an expected value of 22° if $v_w = 730 \text{ km s}^{-1}$ is used in the formula in Section 2.3. That the expected value is overestimated is entirely anticipated, of course, since the pre-shock wind speed is higher off-axis than it is along the line-of-centres, so that using speeds along the line-of-centres biases the calculation to larger angles.

Downstream the WCR spirals around the stars as a result of their orbital motion. Analyses of the so-called ‘pinwheel nebulae’ have compared such morphologies to an Archimedean spiral, which in polar coordinates is specified by $r = \alpha_{\text{cor}} \theta$ (see Tuthill et al. 2008, and references therein). The curvature of the spiral is governed by the distance which the plasma in the WCR moves during one orbital period. The gas in the denser parts of the WCR near the right-hand edge of the grid shown in Fig. 1(a) has a speed of about 2050 km s^{-1} . Hence, in 3 days this travels a distance of 3.55 au ($763 R_{\odot}$). The minimum distance from the centre of the grid to its edge is $120 y R_{\odot}$, so we expect the WCR to curve through 16 per cent of a full rotation, or about 57° . Fig. 1(a) actually displays greater curvature than this estimate, though this is expected because the speed of gas near the apex of the WCR is much slower than further downstream.

Overplotted in Fig. 1(a) is the contact discontinuity (CD) in the orbital plane as calculated by the dynamical model described in Parkin & Pittard (2008). The model assumes that the winds collide at terminal velocity, which is obviously not the case here. Nevertheless, the model is able to match remarkably well the position

of dense gas in the WCR, if the wind speeds are assumed to be 2000 km s^{-1} and the flow in the WCR behaves ballistically once accelerated to 75 per cent of its terminal speed (for further details, see Parkin & Pittard 2008). Adopting a 2500 km s^{-1} terminal wind speed in the dynamical model results in slightly less aberration and downstream curvature, while specifying a 750 km s^{-1} terminal wind speed results in much greater aberration and a much tighter downstream curvature compared to the hydrodynamical models. Clearly, there is scope for the dynamical model to be ‘calibrated’ against full hydrodynamical models. A major advantage of the dynamical model over full hydrodynamical calculations is its low computational cost.

From movies of the simulation it is clear that the radiative over-stability occurs in model cwb1. High Mach number shocks are susceptible to a global oscillation if the slope, α , of the cooling function (where the cooling function, $\Lambda(T)$, is approximated as $\Lambda_0 T^\alpha$), is less than a critical value (i.e. $\alpha \lesssim 0.4$ – see e.g. Strickland & Blondin 1995; Pittard et al. 2005). In this model, the post-shock gas temperature $T \approx 7 \times 10^6 \text{ K}$ corresponds to a local slope $\alpha \approx 0$ on the cooling function. This is less than the critical value $\alpha_{\text{cr}} = 0.4$, below which the over-stability occurs. As the gas cools below $\approx 3 \times 10^6 \text{ K}$, very low values of α are encountered (see Pittard et al. 2005). Mass loading (from clump ablation and evaporation) can moderate or even prevent thermal instabilities (Pittard, Hartquist & Ashmore 2003b), but clearly is not a significant effect here.

Further downstream, the leading edge of the WCR becomes shadowed by upstream regions of the WCR, leading to very low post-shock densities, and very weak oblique shocks. In contrast, the trailing edge of the WCR is very much denser, and remains much more normal to the wind. The WCR remains denser on the trailing side because of the high inertia of the dense gas, which causes it to respond slowly to the movement of the stars in their orbits. The dense sheet of cooled material between the stars is broken up into numerous small clumps in the downstream flow on the trailing side of the WCR, as shown in Fig. 2(a) which shows 3D isosurfaces of the density and temperature in model cwb1. In contrast, the trailing edge of the WCR is far smoother and less structured.

Fig. 3(a) shows the wind speeds in the orbital plane. The driving of the winds off the back of the stars produces wind speeds which are lower in the centre of mass frame than off the front of the stars. Inspection of the model also reveals that the winds accelerate more slowly when in the shadow of one of the stars. Remarkably,

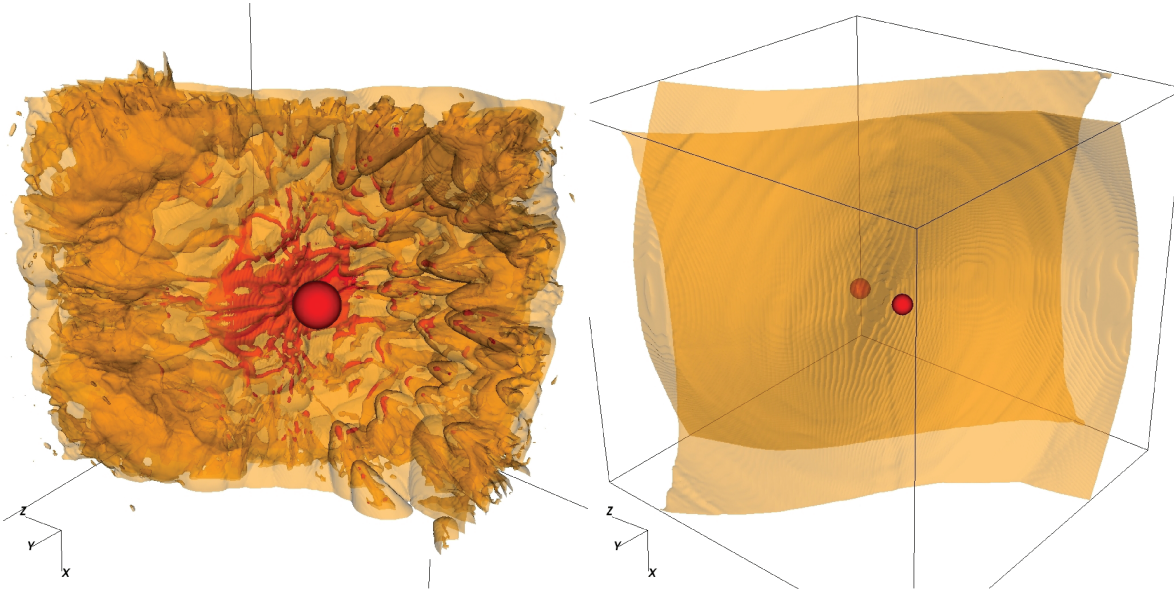


Figure 2. (a) 3D density contours from model cwbl. The orange contour shows the surface at a temperature of 3×10^5 K, while the red contour shows the surface at a density of 10^{-14} g cm $^{-3}$. The density contour highlights the stellar positions, plus the densest regions of the WCR (the other star is hidden behind this). The WCR readily breaks up into small dense clumps on the trailing edge of each arm. These clumps are often surrounded by high-temperature bow shocks as revealed by the temperature surface. (b) As Fig. 2(a) but for model cwbl2. The shocks trace a double helix, in a similar manner to the DNA molecule.

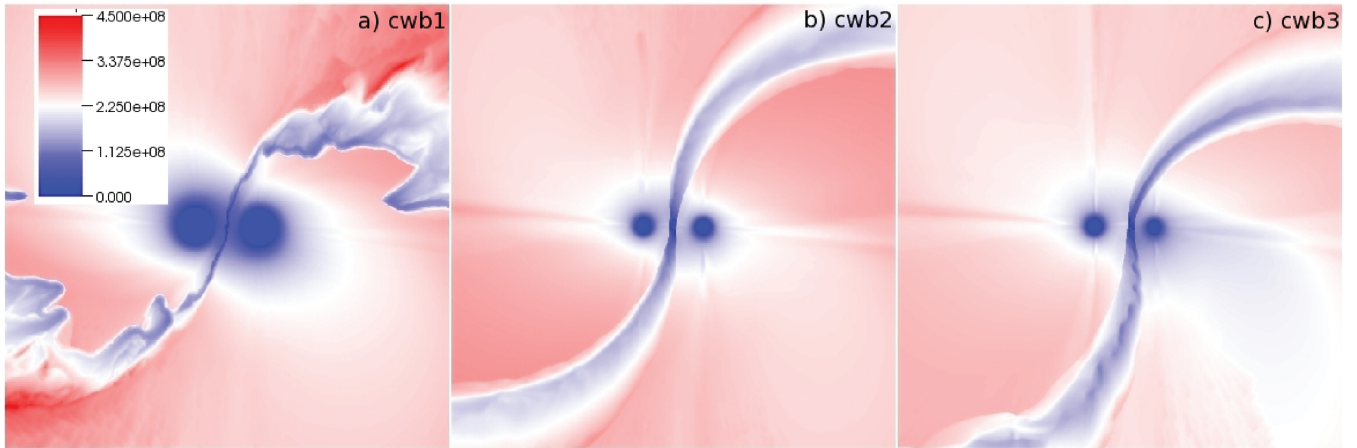


Figure 3. Velocity plots of models cwbl (a), cwbl2 (b) and cwbl3 (c) in the orbital plane. The colour scale is linear, spanning 0 km s $^{-1}$ (blue) to 4500 km s $^{-1}$ (red).

the maximum speed of material on the computational grid in the orbital plane is ≈ 4650 km s $^{-1}$, almost double the terminal velocity of the single star wind. However, these speeds occur in extremely rarefied gas within the WCR and are atypical of the highest speeds seen. It is unlikely that such high speeds would be easily detected since they are tied to such small amounts of material. A more representative speed of the high-velocity gas is 3000–3500 km s $^{-1}$ (see Fig. 7b) – such speeds are typically seen in the shadow of the leading shocks of the WCR. The direction of the lowest wind speeds is towards the top-left and bottom-right of the density plot in Fig. 1(a), where the typical wind speed is ≈ 2750 km s $^{-1}$. The winds are slower in these directions because of the oppositely directed stellar motions. The winds are still accelerating in these regions, albeit gradually.

Fig. 4(a) shows the temperature in the orbital plane of model cwbl. The expected post-shock temperature behind a high Mach number shock, which is normal to the pre-shock flow, is given by

$T = \frac{3}{16} \frac{\bar{m}}{k} v^2$ K, where $\bar{m}$ is the average mass per particle. Given the observed pre-shock wind speeds along the line-of-centres we expect a post-shock temperature $T = 7.2 \times 10^6$ K, which is indeed what is seen.

In wide CWBs where the winds collide at their terminal speeds the maximum post-shock temperature is produced at the apex of the WCR where the shocks are normal to the flow. For a given pre-shock speed, oblique shocks are less efficient at thermalizing the flow and produce lower post-shock temperatures. However, in systems where the winds collide prior to reaching their terminal speeds the hottest temperatures in the WCR can in fact be obtained far downstream of the WCR apex, as we now explain. The increased distance from the stars to the shocks means that the winds have more time to accelerate and collide at higher speed. While these increased speeds may be offset by the increasing obliquity of the shocks, in cases where the WCR is strongly radiative and thus susceptible to kinking by thin shell instabilities, some parts of the WCR surface (and thus the

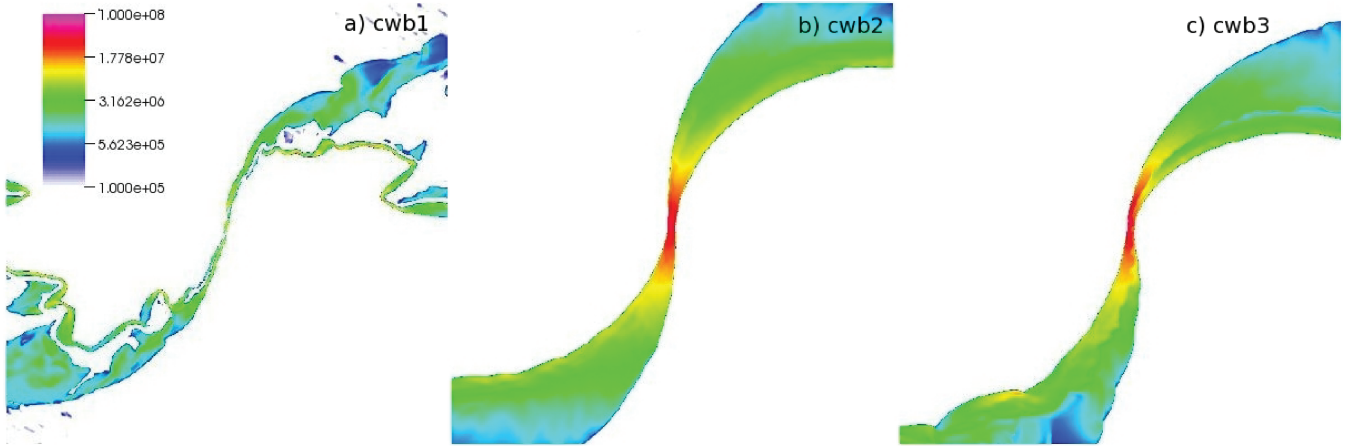


Figure 4. Temperature plots of models cwb1 (a), cwb2 (b) and cwb3 (c) in the orbital plane. The colour scale is logarithmic, spanning $\leq 10^5$ K (white) to 10^8 K (pink).

shocks) can be normal to the pre-shock flow. This combination of high pre-shock speeds and normal shocks can result in the hottest plasma temperatures actually occurring far downstream. This is in fact the case in model cwb1, where temperatures reach as high as 4.5×10^7 K at the apex of bow shocks around downstream clumps, indicating a relative speed of $\approx 1800 \text{ km s}^{-1}$ between the dense clumps and the pre-shock winds at such points (though the typical temperature in these bow shocks is somewhat lower – see Fig. 7b). Note that the maximum temperature is actually higher than the corresponding value from model cwb2 (see Section 3.2), despite the latter models wider stellar separation and higher pre-shock wind speeds along the line-of-centres (at first glance Fig. 7b would seem to contradict this statement, but this is only because the ordinate as plotted does not extend to low enough values).

In model cwb1, the densities between the stars are sufficiently high for the shocks to be collisional. Hence, the electron and ion temperatures rapidly come into equilibrium. The post-shock density (prior to cooling) along the line-of-centres is $n \sim 10^{10} \text{ cm}^{-3}$ (this increases to a maximum of $2.4 \times 10^{12} \text{ cm}^{-3}$ after cooling – see Fig. 7a). Hence the electron and ion temperatures reach equilibrium about 30 seconds after passing through the shocks. The equilibration time-scale is longer for gas-shocked downstream of the WCR apex, but still very rapid.

Similarly, the ionization age of the shocked plasma, $n_e t$, exceeds $10^{13} \text{ cm}^{-3} \text{ s}$ near the apex of the WCR, indicating that the post-shock gas is in collisional ionization equilibrium. Lower ionization ages are seen further downstream (e.g. in the bow shocks surrounding the protrusions of cold post-shock gas seen downstream in the trailing edge of the WCR in Fig. 2a; $n_e t \sim 10^{11.5-12} \text{ cm}^{-3} \text{ s}$). While the ionization will not be in equilibrium in such regions, their densities are sufficiently low that their emission will be a very minor contribution to the total from the system, so, for instance, it is likely that there will be no discernible effect on the global X-ray emission (though, as already noted, these regions are also the hottest parts of the WCR and thus produce the hardest emission).

Figs 5 and 6 show various slices through the simulation of model cwb1, which allow one to more fully appreciate the complex 3D structure of the winds and their collision. In systems with equal wind momenta, like model cwb1, the WCR twists like a helix out of the orbital plane. The WCR thickens above and below the orbital plane, and its orientation increasingly lags that within the orbital plane as one moves further from the orbital plane. The dense gas

remains clumpy and fragmented, and is gradually accelerated as it moves out of the orbital plane.

Fig. 7(a) shows histograms of the mass within $120 R_\odot$ of the system centre of mass, divided into density bins of width 0.1 in log. Gas at all temperatures is included, but the densest gas within 1.2 stellar radii is excluded. The highest density then obtained is $2.4 \times 10^{-12} \text{ g cm}^{-3}$, which occurs in the cold post-shock gas between the stars. The mass as a function of density rises rapidly as the density decreases until $\rho \approx 2 \times 10^{-14} \text{ g cm}^{-3}$, after which it is roughly constant until the density is approximately 2.5 dex lower. A low-density tail extends to $\rho \approx 2 \times 10^{-18} \text{ g cm}^{-3}$. Such rarefied gas exists in downstream regions of the WCR which are ‘shadowed’ by the cool dense ribbon of gas closer to the WCR apex (cf. Fig. 1a).

To better understand Fig. 7(a), we also plot the mass distribution between radii of $12\text{--}120 R_\odot$ from a single O6 star. If material leaves the surface of the star at terminal velocity the slope of the resulting mass distribution (labelled as ‘vinf’ in Fig. 7a) is -0.5 . An accelerating wind induces curvature into this slope, such that there is relatively more mass at higher densities (this distribution is labelled as ‘CAK’ in Fig. 7a). Comparing the ‘CAK’ and ‘cwb1’ profiles we see that the overall effect of a WCR is to create much more higher density gas in the immediate circumstellar environment than would otherwise be the case.

Fig. 7(b) shows the mass within radii $12\text{--}120 R_\odot$ as a function of speed, in bins of 50 km s^{-1} width. The ‘CAK’ profile shows that most of the mass in the single-star case has been accelerated to nearly the terminal wind speed. In contrast, in model cwb1 the distribution is reasonably flat between 1000 and 3000 km s^{-1} , with less mass at lower speeds. Fig. 7(b) also reinforces the point that there is significant mass moving at speeds up to 500 km s^{-1} faster than the terminal speeds of the individual stars, while a smaller proportion of mass exceeds the terminal wind speed by $\sim 1000 \text{ km s}^{-1}$.

Fig. 7(c) shows the mass in model cwb1 as a function of temperature, in bins of width 0.1 in log. Most of the mass (unshocked plus shocked material) is cold ($\approx 10^4$ K). Some material is shock heated above 10^7 K, with the majority of the hot ($T > 10^5$ K) gas at temperatures of a few million degrees. Note that the mass distribution between a few times 10^4 K and a few times 10^7 K bears some resemblance to an inverted ‘cooling curve’, with less gas at temperatures where cooling is very rapid. This behaviour is quite different to the mass distributions of adiabatic wind–wind collisions plotted in Lemaster et al. (2007).

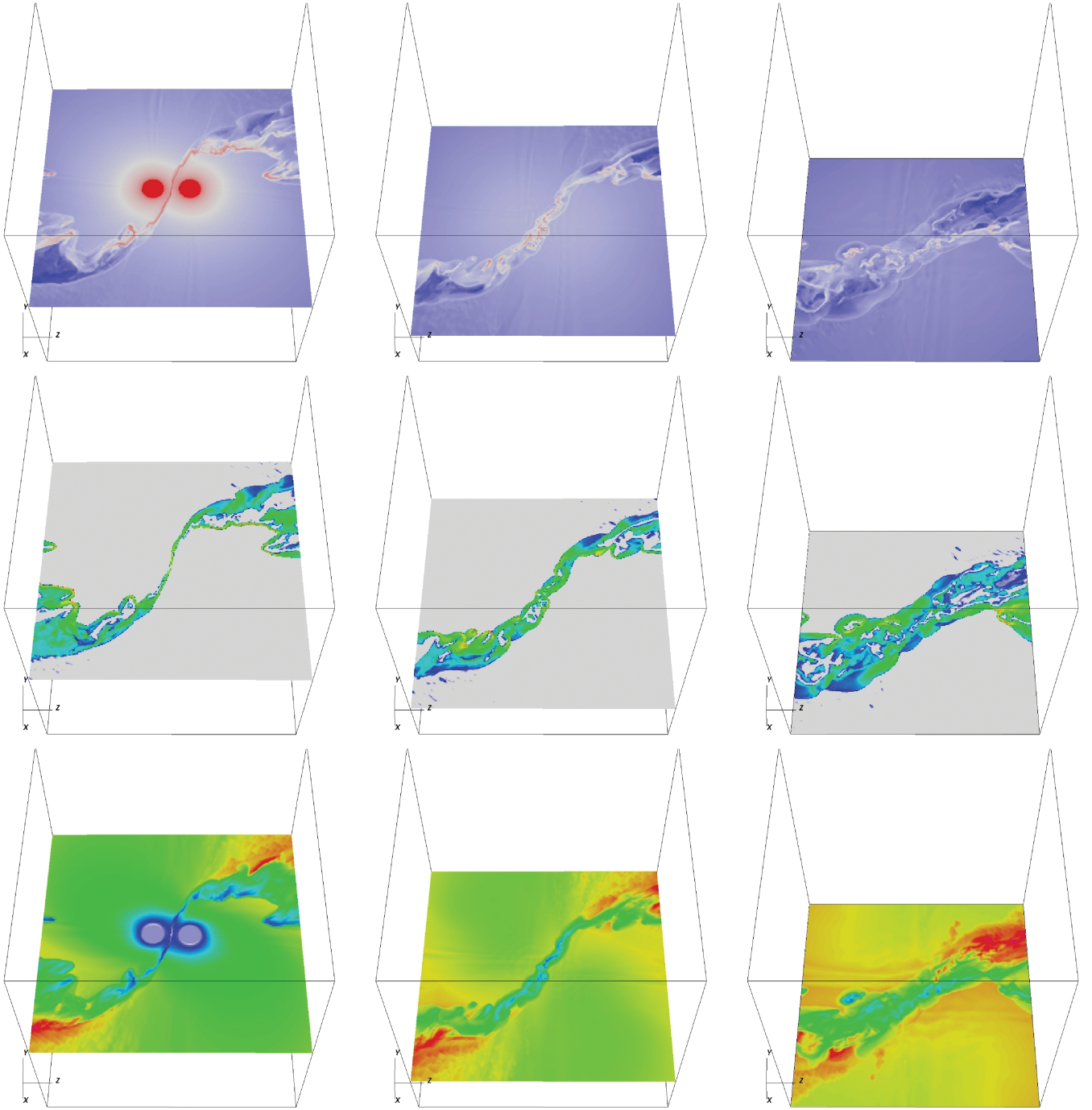


Figure 5. Density (top), temperature (middle) and speed (bottom) slices of model cwb1 in the orbital plane (left), and below the orbital plane (middle and right). The density and temperature colour scales are the same as in Figs 1 and 4, while the colour scale for the speed plots is the same as the temperature scale though is linear and covers the range $0\text{--}4500\text{ km s}^{-1}$ (i.e. stationary/low-speed gas is white/blue, while the high-speed gas is red).

The volume of gas as a function of temperature is shown in Fig. 7(d). Most of the volume within the investigated region contains cold gas.

3.2 Model cwb2

A density snapshot of model cwb2 is shown in Fig. 1(b) where it can be seen that the character of the WCR is completely different to that of model cwb1. The most striking difference is that the post-shock gas remains largely adiabatic, flowing out of the system while

still relatively hot. This was anticipated since the estimated value of χ is substantially larger than unity. The greater distance between the stars allows the winds to accelerate along the line-of-centres to $\approx 1630\text{ km s}^{-1}$ before their collision (cf. a speed of 1820 km s^{-1} at the same distance in the single star case). This results in post-shock temperatures up to $\approx 4 \times 10^7\text{ K}$ (Fig. 7g), while the maximum post-shock density is $\approx 4 \times 10^{-15}\text{ g cm}^{-3}$ (Fig. 7a), compared to $\approx 2.4 \times 10^{-12}\text{ g cm}^{-3}$ in the cool, dense post-shock gas in model cwb1.

The predicted aberration angle is $\approx 7^\circ$. This is again higher than is observed ($\approx 3\text{--}4^\circ$) for the same reasons as mentioned for model

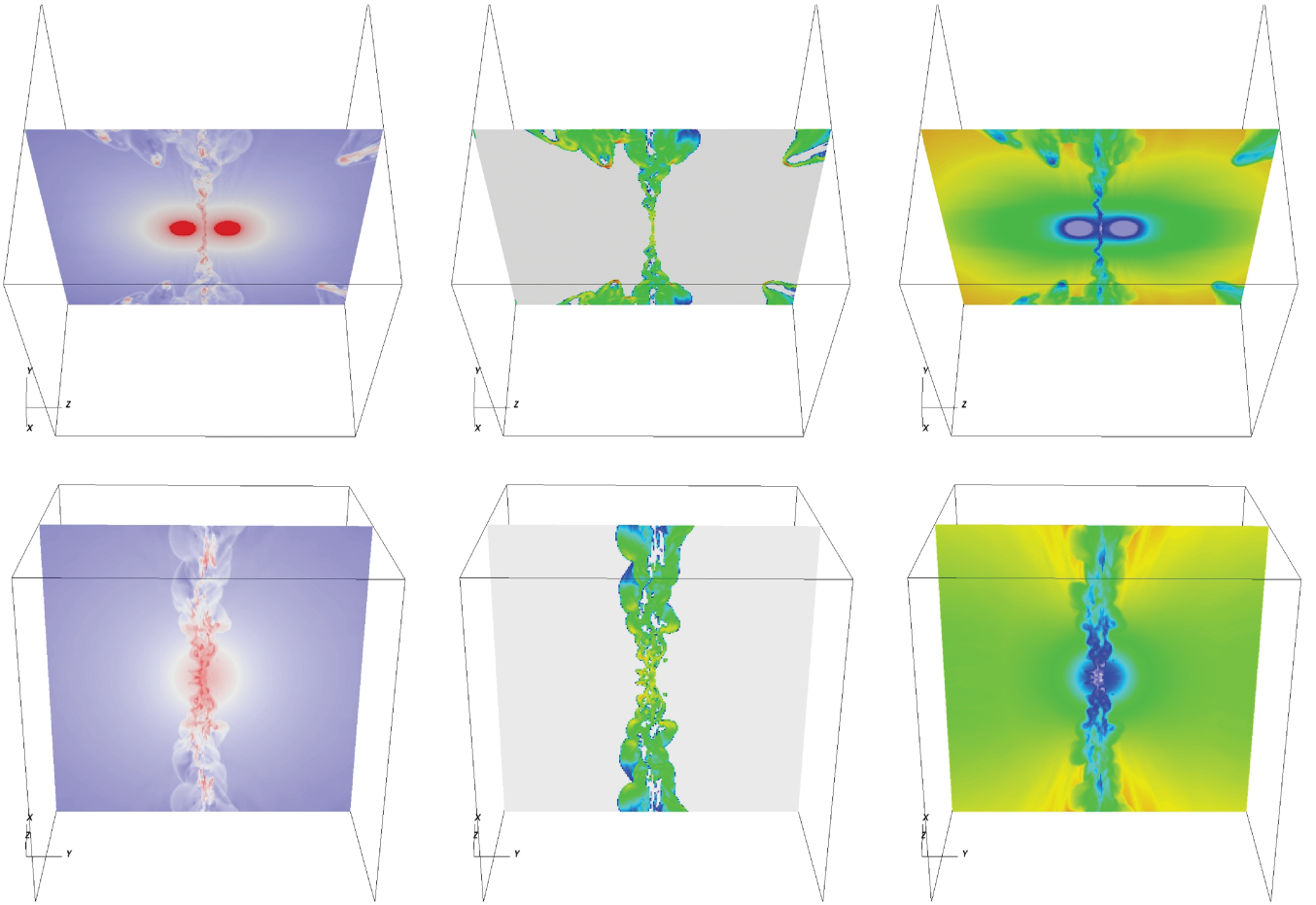


Figure 6. Density (left), temperature (middle) and speed (right) slices of model cwb1 in the plane orthogonal to the orbital plane containing the stars (top), and in the plane orthogonal to this and the orbital plane (bottom). The colour scales are the same as in Fig. 5.

cwb1. Fig. 1(b) also shows that there is a density gradient across the flow direction in the downstream parts of the WCR (i.e. there is a reduction in density from the CD towards the leading shock, and an increase towards the trailing shock). This is similar to the behaviour already noted in model cwb1, being caused by the slower exit out of the system of the gas in the WCR than in the winds, and the shadowing introduced by the curvature of the WCR which results in low densities ahead of the leading shock, and therefore seems to be a general property of CWBs with equal winds (the unequal winds case, discussed in Section 3.3, is more complicated).

The typical speed of gas in the WCR as it leaves the hydrodynamical grid in the orbital plane as shown in Fig. 1(b) is about 2500 km s^{-1} . In 10 days, this gas travels a distance of 14.4 au ($3100 R_{\odot}$). The minimum distance from the centre of the grid to its edge is $285 R_{\odot}$, so we expect the WCR to curve through 9 per cent of a full rotation, or about 33° . At a distance of $285 R_{\odot}$ from the centre of mass, the WCR in Fig. 1(b) actually displays a curvature of just over 60° , again indicating that the speed of gas near the apex of the WCR is much slower than further downstream. Hence the shape of the WCR near its apex is not very well approximated by an Archimedean spiral since the speed within the WCR is not constant.

We again overplot results from the dynamical model of Parkin & Pittard (2008). The CD traced by the red line was calculated assuming terminal wind speeds of 2500 km s^{-1} , while the green

line is from a model with wind speeds of 1650 km s^{-1} . Both models assumed that the shocked wind flowed ballistically once it had reached 85 per cent of its terminal speed. Clearly, the model which assumes the higher terminal wind speeds is a better match to the hydrodynamical calculation, which indicates that the downstream morphology of the WCR is not solely dependent on the pre-shock wind speeds along the line-of-centres.

Lemaster et al. (2007) noted that due to the curvature of the WCR by the orbital motion of the stars, Kelvin–Helmholtz (KH) instabilities occurred even when the winds had equal speeds. There is no sign of this in our model, but this could be because of the higher ratios of v_{orb}/v_w in some of Lemaster et al.’s models. The fastest wind speed attained in model cwb2 in the orbital plane is $\approx 3200 \text{ km s}^{-1}$, near the trailing shocks of the WCR as in model cwb1. The lowest wind speeds in the orbital plane occur in the top-left and bottom-right of the panel shown in Fig. 3(b), where the speed is limited to $\approx 2400 \text{ km s}^{-1}$. Both these values are lower than the corresponding values obtained from model cwb1, indicating that the boosts to the acceleration of certain regions of the winds are greater, the closer the two stars (and the centres of their radiation fields) are to each other.

Fig. 4(b) displays the temperature of the WCR in the orbital plane. The gas near the trailing shocks cools to $\approx 5 \times 10^6 \text{ K}$ as it reaches the edge of the grid, but close to the leading shocks the post-shock temperature is $\approx 7 \times 10^5 \text{ K}$ near the edge of the

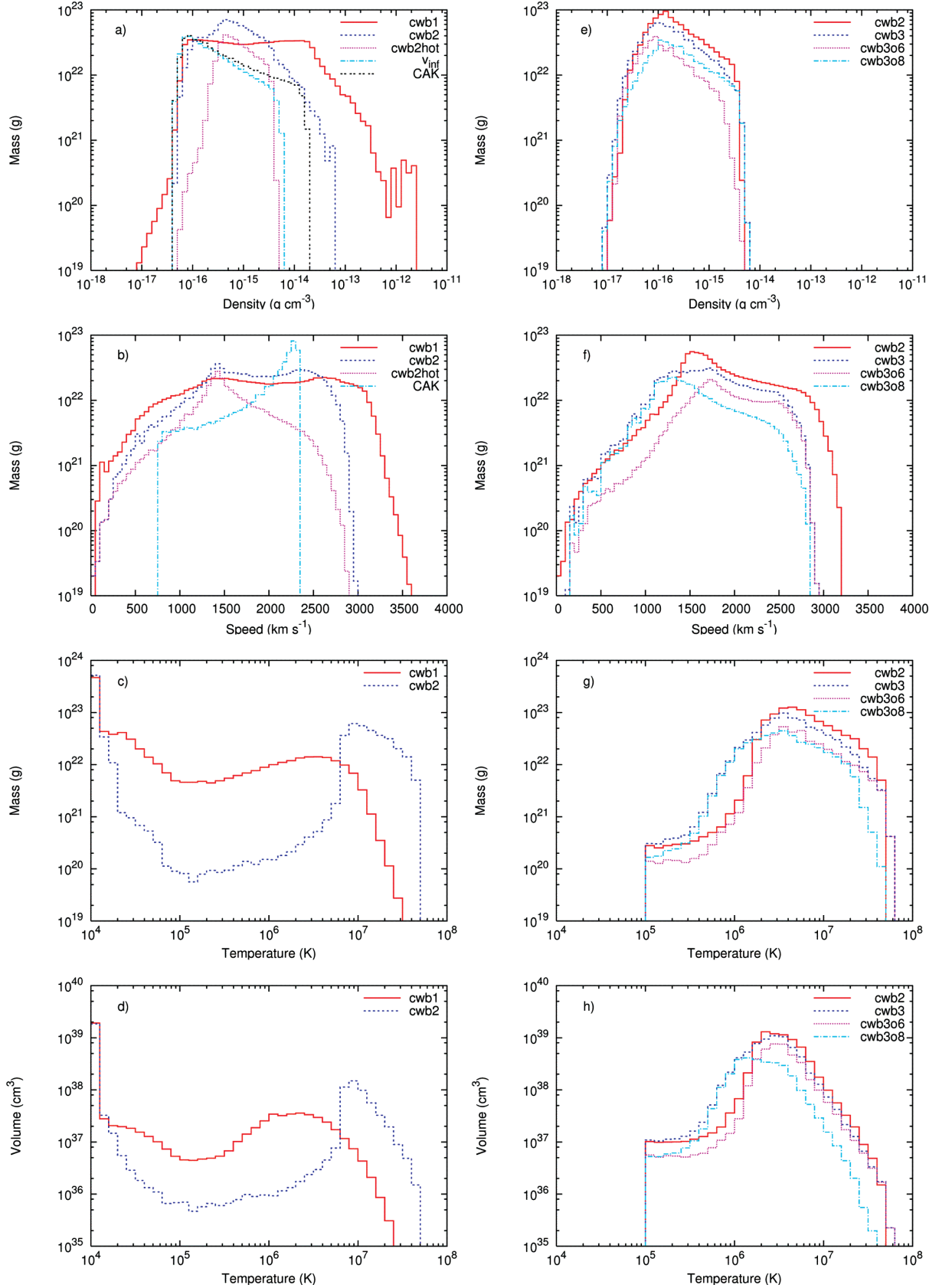


Figure 7. Histograms of various quantities in the models. The left-hand column shows data from models cwb1 and cwb2 within a radius of $120 R_{\odot}$ of the system centre of mass, while the right-hand column shows data from models cwb2 and cwb3 within $285 R_{\odot}$ of the centre of mass. Plot (a) shows mass versus density, plot (b) mass versus speed, plot (c) mass versus temperature and plot (d) volume versus temperature. Plots (e)–(h) show the equivalent analysis of models cwb2 and cwb5.

grid. The lower temperatures near the leading shocks arise because the leading shocks are more oblique at a given downstream distance than the trailing shock. Hence, in systems with identical winds the gas near the leading shocks is both less dense and cooler than gas near the trailing shocks, and vice versa. The situation changes slightly in systems with unequal winds, as noted in Section 3.3.

In model cwb2, the post-shock ion and electron temperatures at the apex of the WCR equilibrate in about 2 hours. This is about an order of magnitude faster than the flow time of this gas out of the system ($t_{\text{flow}} \sim (D_{\text{sep}}/2)/(v_w/4) \sim 7 \times 10^4$ s). Further downstream there is a thin post-shock region where there is a notable delay for the electrons to heat to the same temperature as the ions. However, the thickness of these regions is typically only a few per cent of the width of the WCR at these positions. Given this and the reduced plasma emissivity compared to the apex of the WCR, it is not expected that there will be any observable effects revealing $T_e < T_{\text{ion}}$ in systems similar to this model. However, slow electron heating is certainly important in wider systems, such as WR 140, as other work has already pointed out (Zhekov & Skinner 2000; Pollock et al. 2005).

The ionization age, $n_e t$, is $\approx 2 \times 10^{12} \text{ cm}^{-3} \text{ s}$ in the post-shock gas near the apex of the WCR, and reaches $4 \times 10^{13} \text{ cm}^{-3} \text{ s}$ at the CD in the densest part of the WCR (i.e. near the stagnation point). Further downstream, the post-shock flow does not quickly reach ionization equilibrium. However, the central part of the WCR (close to the CD) remains in collisional ionization equilibrium, as this gas originates from close to the WCR apex.

Figs 8 and 9 show various slices through the simulation of model cwb2, again to allow one to more fully appreciate the 3D structure of the winds and their collision. Compared to model cwb1, we once again see that the interaction region is much smoother and more stable. The top-right panel of Fig. 9 reveals that the winds accelerate faster out of the orbital plane than regions within it where one of the stars shadows the other, due to the more effective combination of the stellar radiation fields.

Fig. 7(a) shows a histogram of mass versus density within $120 R_{\odot}$ of the centre of mass of model cwb2 (excluding material within $14 R_{\odot}$ of the centres of the stars). The distribution outlined in blue shows that most of the mass is at a density of $\approx 5 \times 10^{-16} \text{ g cm}^{-3}$, and extends to $\approx 4 \times 10^{-17} \text{ g cm}^{-3}$ at the low-density end and $\approx 6 \times 10^{-14} \text{ g cm}^{-3}$ at the high-density end, the latter representing unshocked wind material close to the stars. Compared to model cwb1, the distribution is not as flat or as wide.

Fig. 7(a) also shows the mass–density distribution for only the hot ($T > 10^5 \text{ K}$) gas. The maximum density is now $\approx 4 \times 10^{-15} \text{ g cm}^{-3}$. The full (blue) distribution is a rough combination of two ‘CAK’ distributions (one for each star) plus the hot (pink) distribution. However, it is clear that the sum of these distributions would lead to more mass at densities below $\approx 2 \times 10^{-16} \text{ g cm}^{-3}$ than is actually seen in model cwb2. The excess mass at higher densities in model cwb2 is because the WCR gas flowing through the spherical surface of radius $120 R_{\odot}$ has $\rho \gtrsim 2 \times 10^{-16} \text{ g cm}^{-3}$.

The mass–speed distribution is shown in Fig. 7(b). Compared to model cwb1, we find a reduced maximum speed attained by the gas (with the distribution turning over at $\approx v_{\infty}$, rather than at $\approx 500 \text{ km s}^{-1}$ above the single star terminal wind speed). There is also less gas moving at speeds below 1250 km s^{-1} , and more mass moving at speeds between 1250 and 2600 km s^{-1} . Limiting our analysis to only hot ($T > 10^5 \text{ K}$) gas we see that there is a peak in the distribution near 1500 km s^{-1} . The maximum speed of hot gas in the orbital plane is 2500 km s^{-1} , increasing to nearly 3000 km s^{-1} out of the orbital plane.

Fig. 7(c) shows the distribution of mass versus temperature. The majority of the gas mass is predominantly cold (since the gas in the WCR stays hot in model cwb2 as it flows out of the system, the cold material represents the unshocked winds). However, there is also significant mass at temperatures $\sim 10^7 \text{ K}$. The amount of mass at intermediate temperatures ($\sim 10^4$ – $7 \times 10^5 \text{ K}$) should be treated cautiously, since it mostly represents gas in cells at the unresolved shocks, and will therefore be sensitive to the numerical scheme. The bi-modal nature of the mass–temperature distribution of model cwb2 is also reflected in Fig. 7(d), which shows the volume–temperature distribution. 76 per cent of the volume within $120 R_{\odot}$ of the system centre of mass contains the unshocked winds, while 20 per cent contains gas at temperatures exceeding $5 \times 10^6 \text{ K}$.

Figs 7(e)–(h) show mass and volume distributions of the hot gas in model cwb2 out to a radius of $285 R_{\odot}$ from the system centre of mass. The distributions are similar to those in Figs 7(a)–(d), but extend to lower densities and temperatures, and greater speeds, as expected.

3.3 Model cwb3

A distinct difference between the WCR in model cwb3 compared to the other models is that its apex occurs closer to one star (the O8V secondary star which has the weaker wind) than the other star (the O6V primary star) due to the unequal wind momentum ratio (see Fig. 1c). The gas downstream of the WCR apex is also pushed closer to the secondary star, due to the greater momentum flux of the primary wind. These effects, together with the fact that the winds are still accelerating when they collide, plus the enhanced terminal wind speed of the O6V star, lead to higher pre-shock and post-shock speeds in the primary wind relative to the secondary wind. This has three major consequences: (i) there is a velocity shear along the CD between the winds, which excites KH instabilities; (ii) to maintain pressure balance, the pre-shock and post-shock density of the secondary wind exceeds that of the primary wind; (iii) higher post-shock densities, together with reduced post-shock speeds, results in the gas on the secondary side of the WCR radiating more efficiently (this is discussed in more detail in a forthcoming paper on the X-ray emission).

There is also a clear signature of radiative inhibition: at the primary wind shock on the line-of-centres, the pre-shock speed is 1800 km s^{-1} , whereas without the companion star it is 2010 km s^{-1} at this distance. Hence the radiation field of the secondary star reduces the net acceleration of the primary wind towards it by ≈ 10 per cent. Likewise, the pre-shock speed of the secondary wind on the line-of-centres is 1270 km s^{-1} , whereas the single star solution has a speed of 1450 km s^{-1} at this distance, indicating a reduction in the acceleration of ≈ 12 per cent. Radiative inhibition thus has a greater effect on the secondary wind, as expected. There is no sign of radiative braking (Gayley et al. 1997), though this is not surprising given the low wind momentum ratio (hence wind opacity ratio) in our model.

Also overplotted in Fig. 3(c) is the comparison with the dynamical model of Parkin & Pittard (2008). The match is again very good, with the main differences between the models occurring in the leading arm where the CD in the hydrodynamical model shows slightly greater curvature.

Fig. 3(c) shows the speed of gas in the orbital plane. The maximum speeds reached in the O6 and O8 winds are 2910 km s^{-1} and 2840 km s^{-1} , respectively. These values are attained near the trailing edges of the WCR at the boundaries of our hydrodynamic grid. More typically, the O6 and O8 winds reach speeds of $\approx 2550 \text{ km s}^{-1}$ and

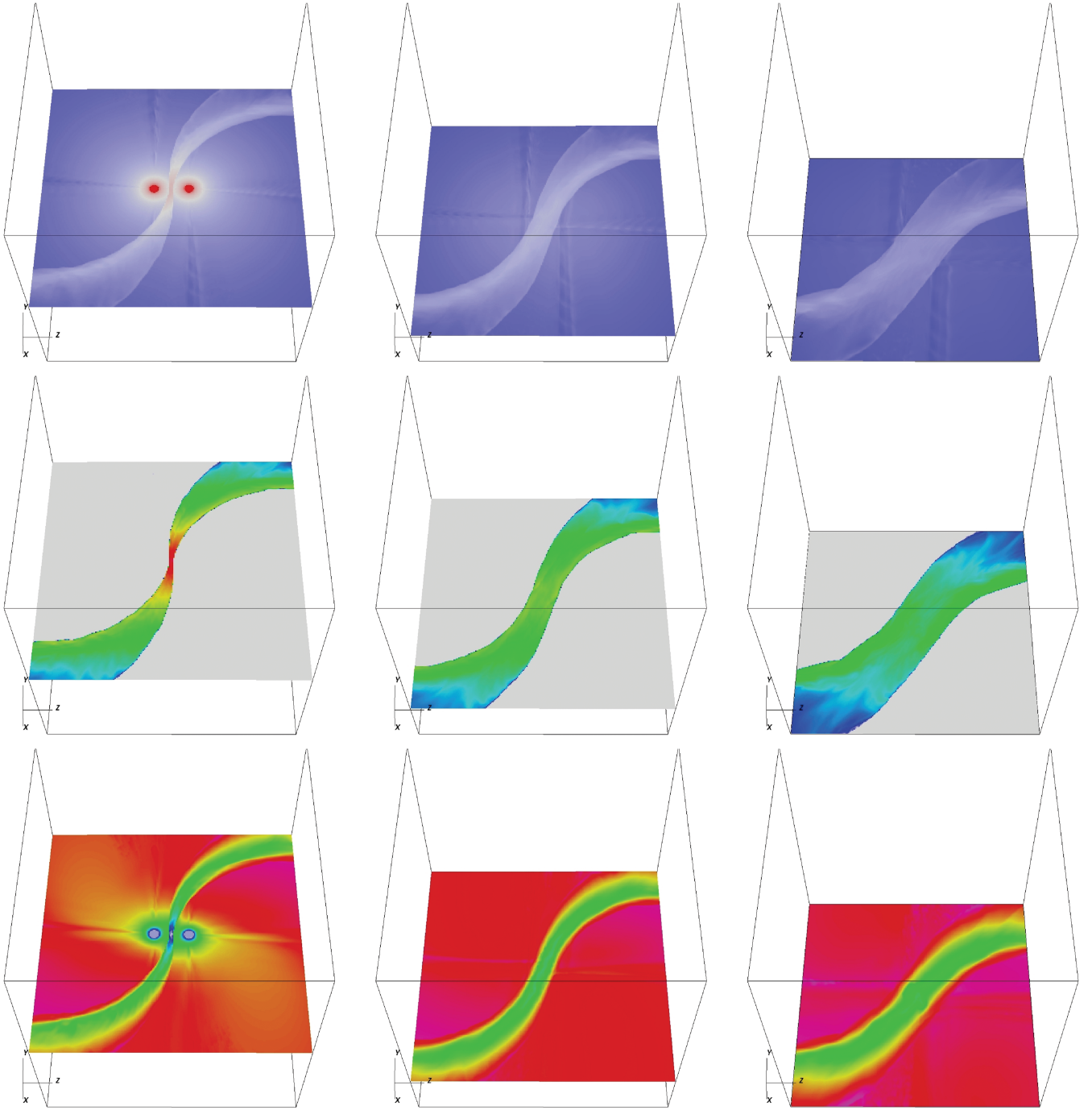


Figure 8. Density (top), temperature (middle) and speed (bottom) slices of model cwb2 in the orbital plane (left), and below the orbital plane (middle and right). The colour scales are the same as in Fig. 5.

2300 km s^{-1} (again in directions towards the top-left and bottom-right of the hydrodynamic grid), respectively. Gas in the denser parts of the WCR typically reaches speeds of 1600 km s^{-1} in the orbital plane by the time it leaves the hydrodynamic grid.

Using the measured pre-shock velocities along the line-of-centres to determine the cooling parameter χ , we find that $\chi_1 \approx 28$ and $\chi_2 \approx 14$. Thus, the post-shock winds remain largely adiabatic, as is indeed seen. The post-shock winds reach maximum temperatures of $\approx 5 \times 10^7 \text{ K}$ (for the shocked O6 wind) and $\approx 3 \times 10^7 \text{ K}$ (for the shocked O8 wind), in good agreement with theoretic

cal expectations. The maximum densities attained are $\approx 2 \times 10^{-15}$ and $5 \times 10^{-15} \text{ g cm}^{-3}$ for the shocked O6 and O8 winds, respectively. These maximum values are all attained near the stagnation point.

The ratio of post-shock densities across the CD is found to vary with downstream distance. The factor of 2.5 difference at the stagnation point increases to a factor of 7–10 in the arm where the O8 gas forms the trailing edge, but becomes a factor of 3 or so in favour of the O6 wind (i.e. the shocked O6 material is denser than the shocked O8 material) in the opposite arm. The temperature

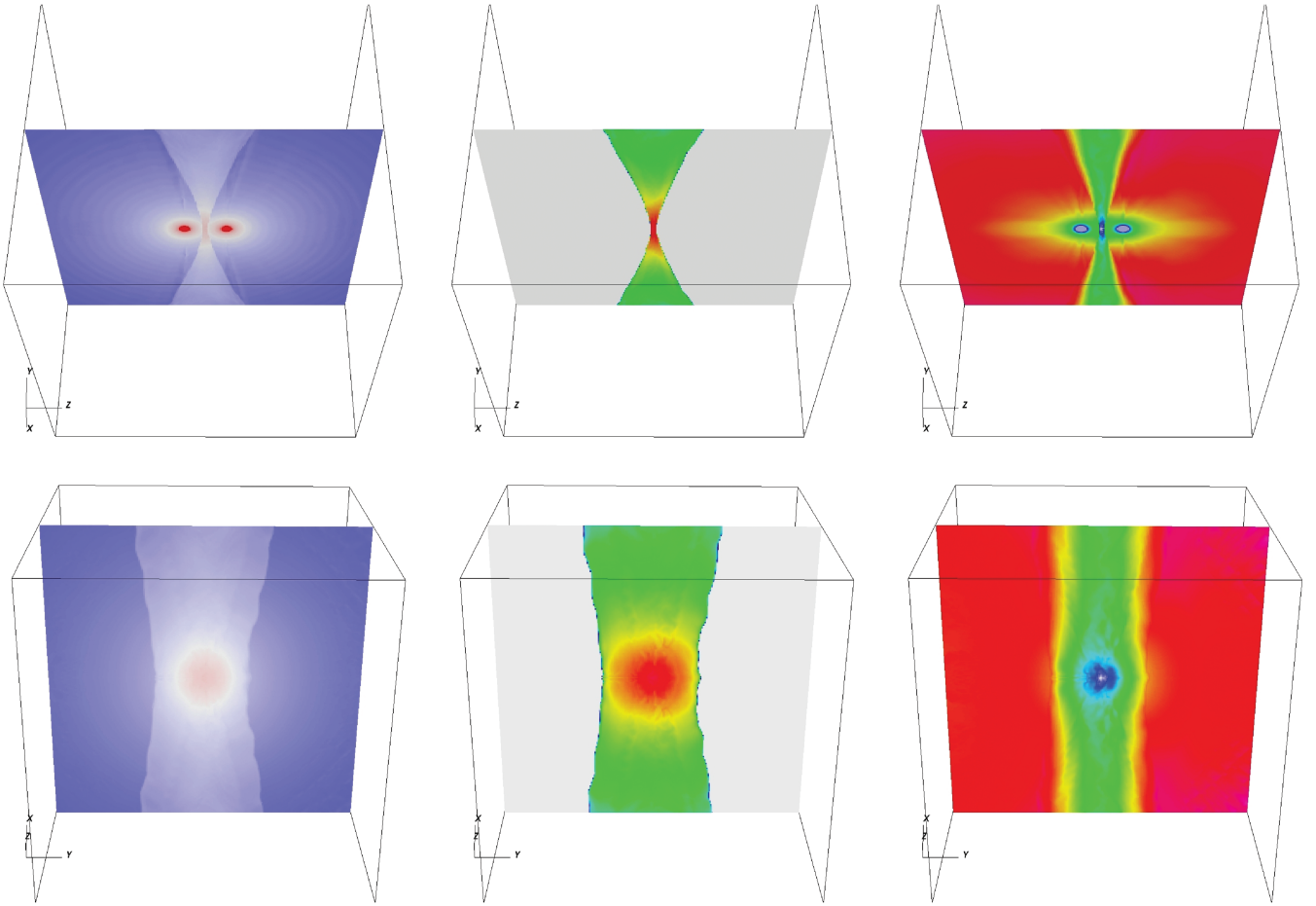


Figure 9. Density (left), temperature (middle), and speed (right) slices of model cwb2 in the plane orthogonal to the orbital plane containing the stars (top), and in the plane orthogonal to this and the orbital plane (bottom). The colour scales are the same as in Fig. 5.

difference across the CD increases in the WCR arm where the O6 material is at the trailing edge, whereas it inverts (i.e. the shocked O8 material becomes hotter, through less rapid cooling, than the O6 material) in the opposite arm.

The post-shock electron and ion temperatures rapidly attain equilibrium in all parts of the flow, in common with the previous models. The significantly higher density and lower temperature of the shocked O8 wind at the stagnation point leads to more rapid ionization equilibrium compared to the shocked O6 wind. At the WCR apex, the ionization age of the shocked O8 wind is typically $4.5 \times 10^{12} \text{ cm}^{-3} \text{ s}$, while nearer to the CD it increases to $\approx 3.5 \times 10^{13} \text{ cm}^{-3} \text{ s}$. The ionization age of gas near the CD further increases downstream, as already noted for the other models.

Fig. 7(e) shows the mass–density distribution of hot gas ($T > 10^5 \text{ K}$) in model cwb3 within a spherical volume centred on the system centre of mass and extending to a radius of $285 R_{\odot}$ (again excluding material within $14 R_{\odot}$ of the centres of the stars). The distribution is similar to that from model cwb2 over an identical volume, though the total mass is somewhat less owing to the smaller mass-loss rate of the secondary star in model cwb5. However, it is interesting to find that the mass at higher densities is dominated by material from the O8 wind, and vice versa. This is because the shocked O8 wind is denser at the WCR apex than the O6 wind (due to the latter’s greater pre-shock speed), and remains denser as it

flows out of the system due to the curvature/confinement of the O8 gas as the WCR bends behind the O8 star.

The mass–speed distribution is shown in Fig. 7(f). Compared to the distribution obtained from model cwb2, the cwb3 distribution extends to a slower maximum speed. This is due to the lower terminal velocity of the O8 wind, and the reduction in the combined radiative driving force due to the reduced luminosity of the O8 star. Model cwb3 has more mass at speeds $< 1400 \text{ km s}^{-1}$ – this is dominated by material from the O8 star, and indicates the slower acceleration of its wind, and subsequently the lower speed of its post-shock gas. Conversely, material from the O6 star dominates the hot gas moving at speeds above 1600 km s^{-1} . These differences may have implications for the emission-line profiles from the WCR of such systems.

Fig. 7(g) shows the mass–temperature distribution. Compared to model cwb2, the distribution from model cwb3 contains less mass overall (as already noted), but also has gas at a higher maximum temperature, since the O6 wind has more room to accelerate along the line-of-centres before being shocked. Model cwb3 also contains much more mass at $T < 2 \times 10^6 \text{ K}$ because of the slower acceleration and speed of the O8 wind.

The volume–temperature distribution of hot gas ($T > 10^5 \text{ K}$) is shown in Fig. 7(h). Compared to model cwb2 we find that the volume of hot gas above $4 \times 10^7 \text{ K}$ is greater in model cwb3, due

to the faster pre-shock speed of the O6 wind. The volume of hot gas is slightly less between 4×10^6 and 4×10^7 K, is comparable at $\approx 3 \times 10^6$ K, and is greater for $T < 1.4 \times 10^6$ K. Shocked O6 gas dominates the volume of hot plasma at $T > 2 \times 10^6$ K, below which the O8 wind dominates.

The emission measure ($n_e^2 V$) of the hot gas, divided into temperature bins of width 0.1 in log, peaks at $9.2 \times 10^{54} \text{ cm}^{-3}$ at $T \approx 1.75 \times 10^7$ K (this is not shown in Fig. 7). The shocked O8 wind is almost completely dominant, with the emission measure from O6 wind material peaking at $2.4 \times 10^{54} \text{ cm}^{-3}$ at the slightly hotter temperature of $T \approx 2.25 \times 10^7$ K. Thus the shocked O8 wind should dominate, for example, the thermal radio and X-ray emission generated in the WCR – in fact, we find that the O8 wind dominates the intrinsic X-ray emission below 4.5 keV (Pittard, in preparation). The total emission measure is $7.1 \times 10^{55} \text{ cm}^{-3}$, with the shocked O8 wind contributing 70 per cent of this value. Since the shocked O8 material in the leading arm of the WCR is compressed into about half of the volume of the shocked O6 material in this arm (note the high-density contrast in Fig. 1c), it is interesting to examine the contributions of each wind to the emission measure from each arm of the WCR. We find that the shocked O8 material dominates the emission measure in the leading arm ($2.8 \times 10^{55} \text{ cm}^{-3}$ versus $0.8 \times 10^{55} \text{ cm}^{-3}$ for the shocked O6 wind). In the trailing arm the ratio of the emission measures between the winds is much closer to unity ($2.0 \times 10^{55} \text{ cm}^{-3}$ for the shocked O8 wind, versus $1.4 \times 10^{55} \text{ cm}^{-3}$ for the shocked O6 wind), though the O8 material again dominates the emission.

3.4 Model cwb4

As one might expect given the large differences between models cwb1 and cwb2, the structure and properties of the WCR in model cwb4 undergo rich and dramatic changes as a result of the varying separation between the stars as they progress in their respective orbits. Fig. 10 shows the evolution of the mass density in the plane of the orbit. At periastron the WCR is highly radiative and subject to strong dynamical instabilities. The cooled post-shock gas is sheet-like, as in model cwb1, and maintains a cohesive structure. As the stars separate and the cooling of the post-shock gas becomes less severe, this sheet fragments and discombobulates into smaller, individual clumps. By apastron, the WCR is largely adiabatic. At both periastron, when the stars are separated by the same distance as in model cwb1, and at apastron, when the stars are separated by the same distance as in model cwb2, the wind–wind interaction somewhat resembles the WCR in these other models (cf. also Fig. 15). For instance, the velocity profiles between the stars along the line-of-centres from model cwb4 at periastron and apastron are in good agreement with those from models cwb1 and cwb2, respectively.

Nevertheless, there are some interesting differences. For instance, some dense clumps of cool gas exist within the WCR even at apastron, in contrast to the entirely hot state of the WCR in model cwb2. These clumps were formed during the previous periastron passage. Because of their high density and inertia relative to the surrounding hot, more rarefied, plasma, it can take some considerable time for the faster flowing hot plasma to push the clumps out of the system. Clearly, this time-scale is of the order of half the orbital period of the stars in model cwb4. The slow acceleration of the clumps out of the system also results in some of the clumps crossing the global shocks bounding the WCR and moving into the fierce high-speed environment of the unshocked winds (this is clearly seen at phases

0.4 – 0.6 in Fig. 10). This process occurs because the hot plasma in the WCR responds quite quickly to the movement of the stars (and thus rotates with the stars), whereas the direction vectors of the dense clumps respond much less rapidly and the clumps tend to maintain straighter paths. For this reason, the clumps exit only out of the trailing shocks of each arm of the WCR, and not out of the leading shock. Once formed, the clumps are gradually destroyed by thermal evaporation and ablation, with larger and denser clumps surviving longer.

The presence of clumps in or around an otherwise adiabatic WCR may affect some observational signatures. For instance, gas mixed from the clumps into the surrounding flow ‘mass-loads’ it, making it denser. The effect of the clump on the temperature of the surrounding flow is more complex. A bow shock forms upstream when the surrounding flow is supersonic with respect to the clump, heating the surrounding flow. This is seen, for example, when the clumps move out of the WCR and into the unshocked winds. Bow shocks also form upstream of clumps *within* the WCR when the clumps are far enough downstream that the hotter flow past them is supersonic – this is the case for the lowermost clump above the WCR apex in the apastron panel of Fig. 10. Friction between the clump and a surrounding subsonic flow also heats the flow. Further downstream, the addition of mass into a flow generally leads to lower temperatures once the injected mass is fully mixed into the flow (e.g. Pittard et al. 2003a), though this will require reconnection of field lines in a magnetic environment. The presence of clumps outside the main WCR may also lead to more of the winds’ kinetic power being processed through shocks than would otherwise be the case, and may affect the variation of, for example, the X-ray emission with phase. Finally, the boundary layer between clumps and the surrounding diffuse flow contains intermediate densities, temperatures and velocities, all of which affect the resulting emission (Hartquist & Dyson 1993). Line emission is expected to be particularly sensitive to the conditions in this region, and such regions may help to explain discrepancies in current models (e.g. Henley et al. 2008) where mixing of cold material into a hotter medium is neglected.

Another difference with our previous models is that cold dense gas does not exist far downstream of the apex of the WCR when the stars are at periastron, whereas it does in model cwb1 (compare the top-left panels in Figs 10 and 11 with Figs 1a and 4a, and remember that the stellar separations are identical). This is simply because the downstream gas in model cwb4 at this phase reflects the less radiative environment which existed within the WCR when the stars were more widely separated.

Not surprisingly, there is a large variation in the aberration and curvature of the WCR in model cwb4 with orbital phase. The aberration angle reaches a maximum at periastron due to increased stellar velocities and reduced pre-shock wind speeds. At periastron, $v_{\text{orb}} = 334 \text{ km s}^{-1}$, while $v_w \approx 710 \text{ km s}^{-1}$, giving an expected aberration angle of $\approx 25^\circ$, in good agreement with the measured angle of $\approx 21^\circ$. At apastron, v_{orb} drops to 156 km s^{-1} , while v_w increases to $\approx 1665 \text{ km s}^{-1}$, giving an expected aberration angle of $\approx 5^\circ$, again in good agreement with the measured angle of $\approx 4^\circ$. Note that the orbital speeds at periastron and apastron are different to the speeds in models cwb1 and cwb2, so the aberration and curvature of the WCR differs compared to the circular orbit models (see also Table 4).

Fig. 11 shows the temperature in the orbital plane of model cwb4. The hottest gas occurs at apastron ($T_{\text{max}} \approx 5 \times 10^7 \text{ K}$), and its temperature is similar to the hottest gas in model cwb2. While

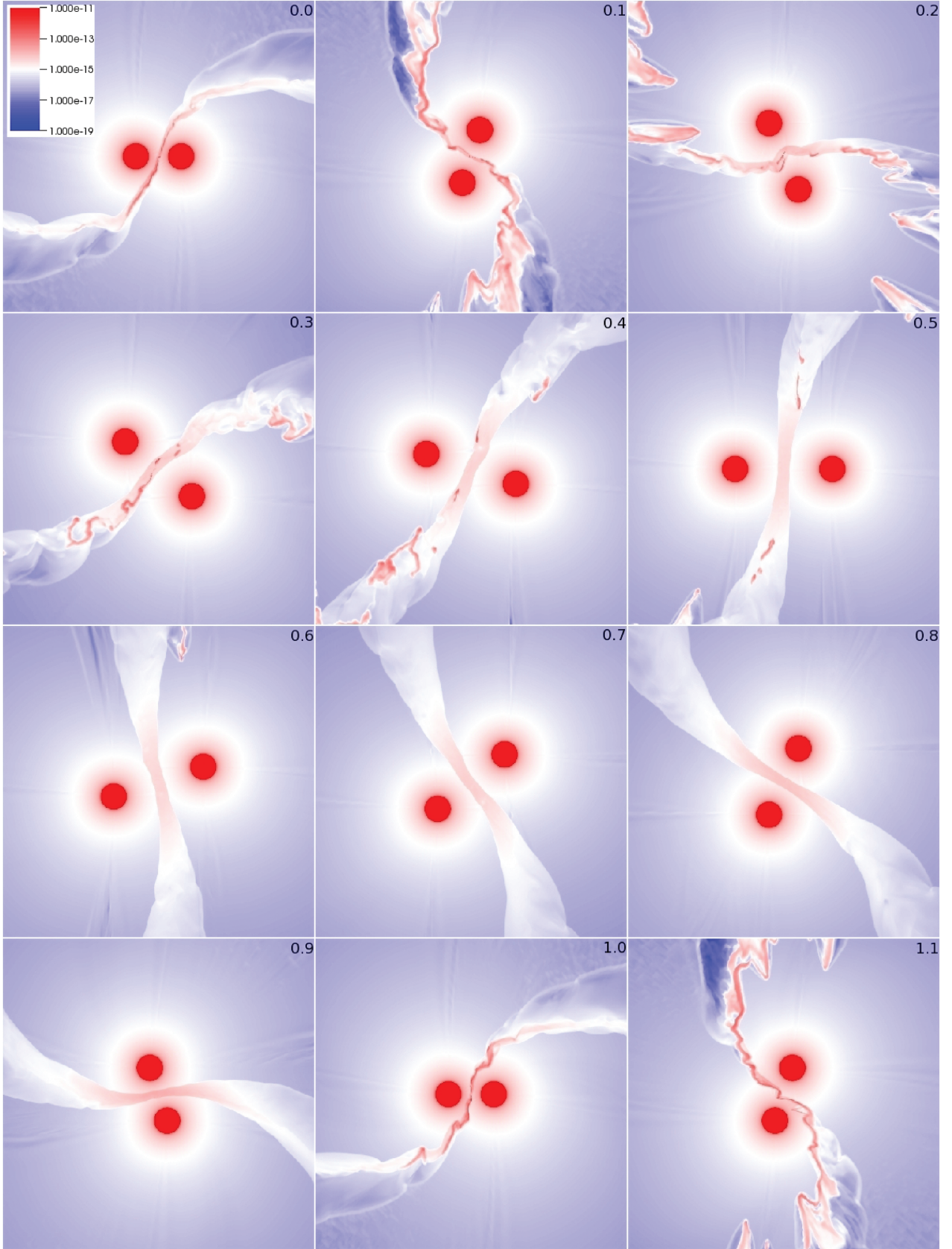


Figure 10. Density snapshots of model cwb4 at specific phases in the orbit, which progresses from left to right, and from top to bottom. The top-left panel shows the model at periastron, and subsequent panels increase the orbital phase in steps of 0.1. The right-most panel of the second row from the top shows the stars at apastron, with periastron again occurring in the middle panel of the bottom row. The colour scale is logarithmic, spanning 10^{-19} g cm $^{-3}$ (blue) to 10^{-11} g cm $^{-3}$ (red). The panels have sides of length $240 R_{\odot}$.

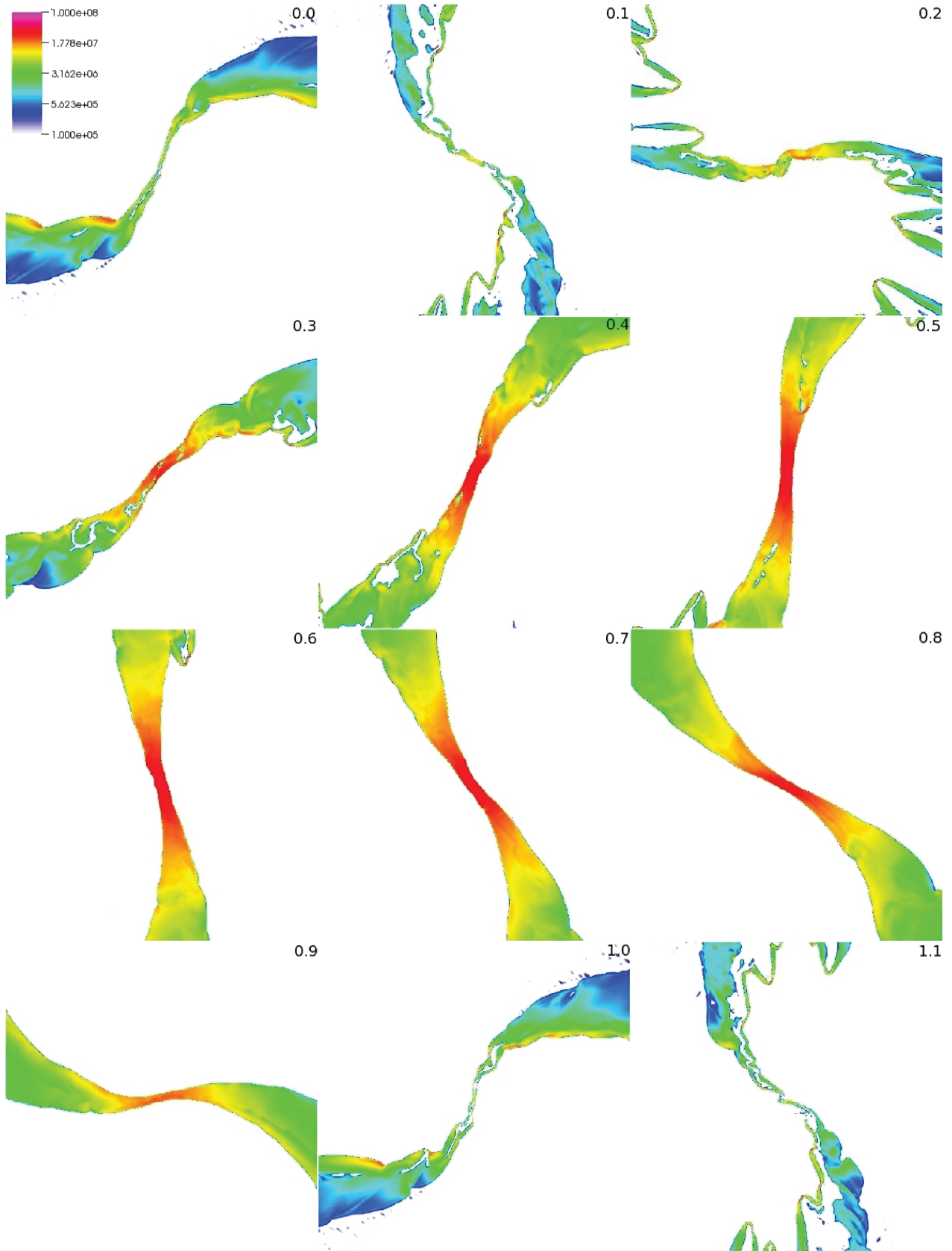


Figure 11. As Fig. 10 but showing temperature snapshots. The colour scale is logarithmic, spanning $\leq 10^5$ K (white) to $\geq 10^8$ K (pink).

the maximum gas temperature attains a minimum around periastron ($T_{\max} \approx 2 \times 10^7$ K), this value is found in localized bow shocks enveloping dense clumps in the downstream flow and is sensitive to rapid changes in the local dynamics. It also relates to a very small fraction of the total mass within the WCR, and hence is not representative of the typical temperatures which are much lower (cf. Fig. 15e). Fig. 11 also reveals that at periastron the trailing edge of each arm of the WCR is hotter than the leading edge. This is because of the severe curvature of the WCR due to orbital motion, which results in the shock at the trailing edge staying more normal to the pre-shock wind vector. This effect is not seen at apastron when the effects of orbital motion are less intense (see Fig. 11). However, model cwb2 suggests that gas at the trailing edge of each arm of the WCR will become hotter than gas at the leading edge at distances further downstream than can be probed in model cwb4 (model cwb2 has a larger grid – see Table 3).

Fig. 12 shows various slices through the 3D hydrodynamical grid when the stars are at periastron, again to allow appreciation of the 3D structure of the winds and their collision. The slices in the right-most panels pass through the stagnation point at an angle aligned with the shock surfaces between the stars, and so sample a relatively large distance through the WCR despite its small width. This figure illustrates again that cold dense gas exists near the apex of the WCR at periastron, but not further downstream at this phase.

Fig. 13 displays a 3D temperature surface from model cwb4 at apastron. The sheet-like structures of the global shocks bounding the WCR are clearly visible. However, this figure also highlights that while cold gas has been largely cleared out of the central regions of the WCR, some still remain further downstream. The large bow shock projected towards the bottom-right of the plot envelopes the dense blob of gas seen outside of the WCR towards the bottom-left of the $\phi = 0.5$ panel in Fig. 10. Fig. 14 shows temperature surfaces viewed from above the orbital plane at phase $\phi = 0.4$. Fig. 14(a) traces gas at a temperature of 2×10^5 K, which highlights the global shocks bounding the WCR and the interface between cold, dense clumps embedded within the hotter, more rarefied plasma of the

WCR. Figs 14(b) and (c) show surfaces of progressively higher temperatures. As the temperature of these surfaces increases the intermediate-temperature material ablated from the cold clumps is revealed. Comparison between Figs 13 and 14(c) highlights the gradual removal of cold dense clumps from the WCR as the orbit progresses away from the previous periastron passage.

Fig. 15(a) shows the mass within $120 R_{\odot}$ of the system centre of mass (excluding the stars) as a function of density from model cwb4 at periastron, and from model cwb1. The distributions are reasonably similar, with the main differences being a relative excess of mass at high ($\rho > 5 \times 10^{-14} \text{ g cm}^{-3}$) and intermediate ($\rho \sim 10^{-15} \text{ g cm}^{-3}$) densities, and a lack of low-density material ($\rho < 3 \times 10^{-16} \text{ g cm}^{-3}$) in model cwb4. The first of these is explained by the recent history of the interaction in model cwb4 – i.e. that there is hotter gas in the downstream regions of the WCR because this gas was shocked and advected out of the central regions of the system before cooling became as strong as it is now that the stars are at periastron. The last is explained by a reduction in the degree of ‘shadowing’, since prior to periastron the rate at which the stars sweep out angle is much smaller than the rate in model cwb1.

A comparison between the mass versus density histograms of models cwb2 and cwb4 at apastron (Fig. 15b) again reveals similar distributions, with the most notable difference being a relative excess of mass at $\rho > 5 \times 10^{-15} \text{ g cm}^{-3}$ in model cwb4. This now reflects the presence of cold dense clumps in the WCR from the previous periastron passage. A comparison of the mass of hot ($T > 10^5$ K) gas reveals a similar excess at higher densities, due to the intermediate temperatures of gas ablated off the cold dense clumps.

The mass versus speed histogram of models cwb1 and cwb4 at periastron is shown in Fig. 15(c). The material in model cwb4 does not quite reach the maximum speeds seen in model cwb1, most likely because the combined radiative driving force, which is greater the closer the stars are to each other, would have been weaker in model cwb4 prior to periastron. Model cwb4 also displays an excess of mass relative to model cwb1 at speeds $< 1400 \text{ km s}^{-1}$.

Table 4. Some key parameters of each model. In model cwb3, two values are given for many of the parameters – the first corresponds to the primary (O6V) star/wind, and the second to the secondary (O8V) star/wind. For model cwb4, values at periastron and apastron are noted. v_{orb} is the orbital speed of the stars and v_w is the pre-shock wind speed along the line-of-centres, both in km s^{-1} . v_w/v_s is the ratio of the pre-shock wind speed along the line-of-centres to the wind speed at the same radial distance from a single-star solution. Smaller values indicate more effective radiative inhibition. The ratio v_{orb}/v_w affects the aberration angle, θ_{ab} , of the WCR. The values quoted for θ_{ab} are measured directly from the simulations (not calculated from the simple formula in Section 2.3), and noted in degrees. The degree of downstream curvature of the WCR in the orbital plane is specified by α_{cor} , where the curvature is assumed to trace an Archimedean spiral which in polar coordinates is described by $r = \alpha_{\text{cor}} \theta$. The value of α_{cor} corresponds to the downstream distance (in units of d_{sep}) along the WCR for each radian of arc it sweeps out in the orbital plane. Smaller values indicate tighter curvature. The leading and trailing arms of the WCR in model cwb3 display differing degrees of curvature, so the value quoted for this model is a rough average. For model cwb4, the quoted values roughly represent the ‘instantaneous’ curvature at periastron and apastron. χ is the ratio of the post-shock cooling to flow time-scales, and is calculated using the pre-shock wind speed, v_w , as measured from the simulations. $\chi \lesssim 1$ indicates that the shocked gas rapidly cools, while $\chi \gtrsim 1$ indicates that the plasma in the WCR remains hot as it flows out of the system.

Model	v_{orb}	v_w	v_w/v_s	v_{orb}/v_w	θ_{ab}	α_{cor}	χ
cwb1	290	730	0.58	0.40	17	3.5	0.34
cwb2	225	1630	0.90	0.14	3-4	6.5	19
cwb3	152,208	1800,1270	0.90,0.88	0.08,0.16	2	4.5	28,14
cwb4	334-156	710-1665	0.57-0.91	0.47-0.09	21-4	3-10	0.34-19

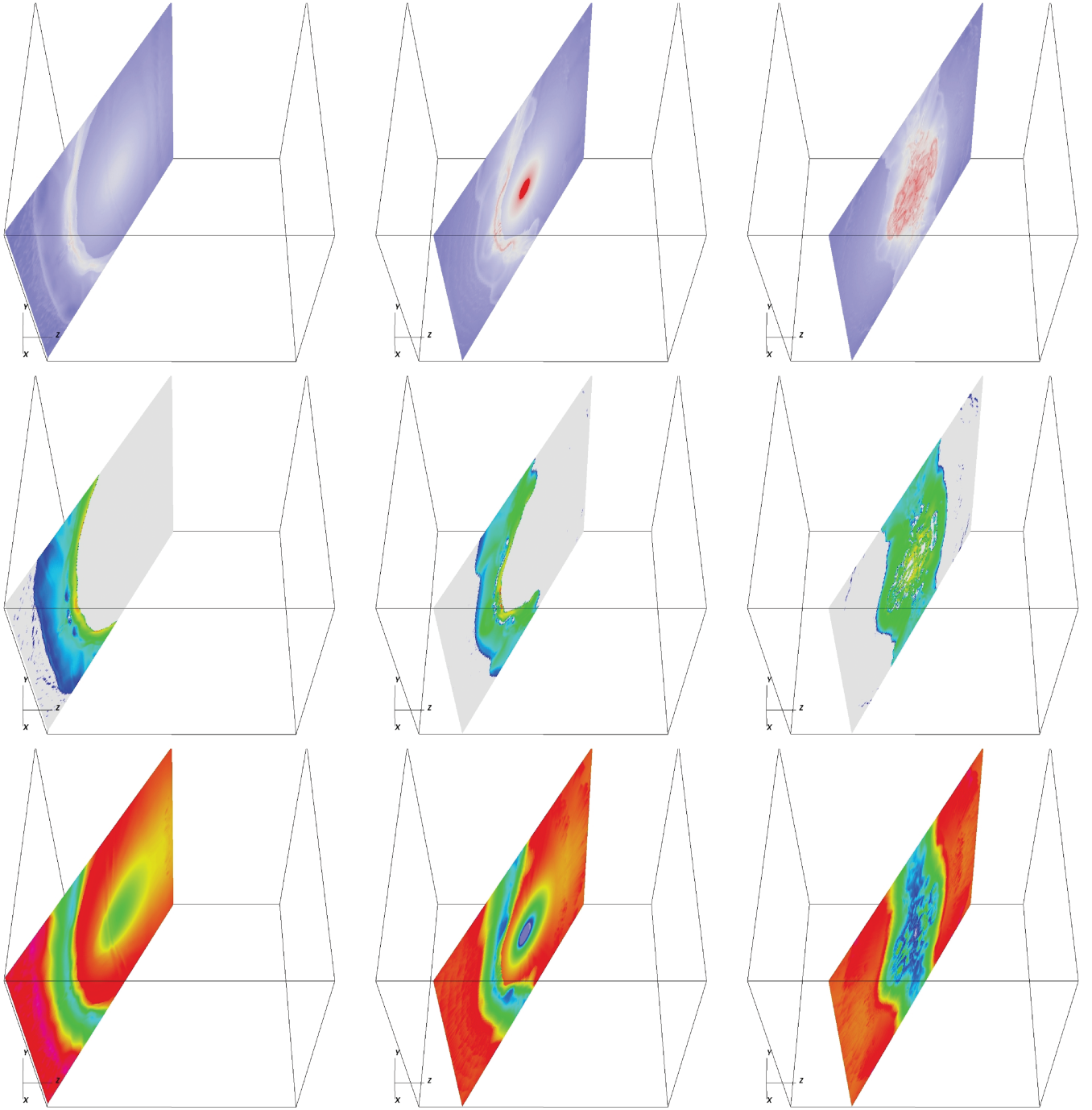


Figure 12. Density (top), temperature (middle) and speed (bottom) slices of model cwb4 parallel to the surface of the WCR near its apex at periastron. The left-hand panels pass through the WCR downstream of its apex, the middle panels pass through the centre of one of the stars and the right-hand panels pass through the stagnation point and apex of the WCR. The colour scales are the same as in Fig. 5.

Fig. 15(d) compares the distributions between models cwb2 and cwb4 at apastron. They are remarkably similar, except again model cwb4 displays a relative mass excess at speeds $< 1400 \text{ km s}^{-1}$, which is likely due to the presence of cold clumps. The distributions of hot ($T > 10^5 \text{ K}$) gas are also remarkably similar.

Fig. 15(e) shows mass versus temperature histograms from models cwb1 and cwb4 at periastron. Model cwb4 has more than twice as much mass at temperatures above 10^6 K , but less mass at lower

temperatures, due to the reduced cooling in the post-shock history of the downstream gas in model cwb4. At apastron, model cwb4 has slightly less mass at $T > 8 \times 10^6 \text{ K}$ compared to model cwb2 (Fig. 15f), but significantly more mass between temperatures of $4\text{--}8 \times 10^6 \text{ K}$.

The volume versus temperature histograms from models cwb1 and cwb4 at periastron are shown in Fig. 15(g). There is a significantly greater volume of gas at $T \sim 10^6 \text{ K}$ in model cwb4. This

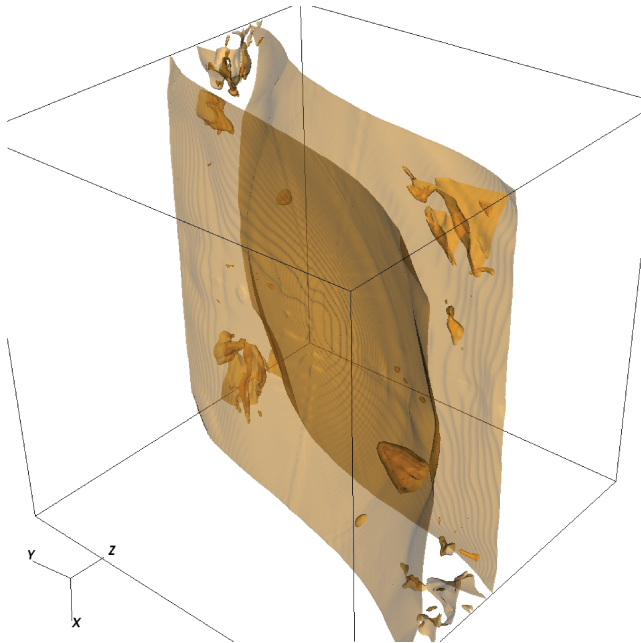


Figure 13. 3D temperature surface from model cwb4 at apastron. The surface traces gas at a temperature of 3×10^6 K.

excess combines with a reduction in the relative volume of gas at intermediate temperatures ($1.5 \times 10^4 < T < 6 \times 10^5$ K). These differences reflect the hotter thermal history of the shocked gas in model cwb4 prior to periastron. At apastron in model cwb4, the volume of hot gas at temperatures above 8×10^6 K is 25–60 per cent smaller than in model cwb2. Model cwb4 generally also has smaller volumes of gas at intermediate temperatures ($1.5 \times 10^4 < T < 4 \times 10^6$ K) – this is likely a numerical effect due to the higher resolution in model cwb4 compared to model cwb2, which leads to a narrower layer of intermediate temperature cells at the unresolved shocks. Model cwb4 has almost an order of magnitude greater volume of gas at $5\text{--}6 \times 10^6$ K than model cwb2. Such tem-

peratures are encountered in the mixing regions downstream of the clumps in model cwb4 (cf. Fig. 14).

4 SUMMARY AND CONCLUSIONS

The model results described above reveal a wealth of interesting dynamical effects which occur in short period, O+O binaries, including radiative inhibition, rapid post-shock cooling and powerful instabilities, all of which had been expected. However, there have also been some surprising findings, such as the ability of cold dense clumps to exist for substantial periods of time in the WCR when current post-shock conditions are largely adiabatic. Another surprise is that the slow exit velocity of these clumps out of the system allows some of them to exit the WCR through its trailing shock. More generally, the presence of clumps increases the complexity of the WCR, affecting the density, temperature and velocity of the shocked plasma, and allowing additional material to be processed through normal shocks. As a result, the emission from the WCR may be affected in a non-trivial manner.

In future work, we will study the multiwavelength emission from these models, and will repeat our study for WR+O systems where we expect radiative braking to have a significant effect on the dynamics, and the observed emission to show greater orbital modulation due to the larger differences in the attenuation through the stellar winds. Braking should also be important in O+O systems where there is a larger ratio of wind opacities than explored here. We will also turn our attention to modelling specific systems, with the aims of determining key system parameters and understanding the natures of the diverse range of wind–wind interactions which occur.

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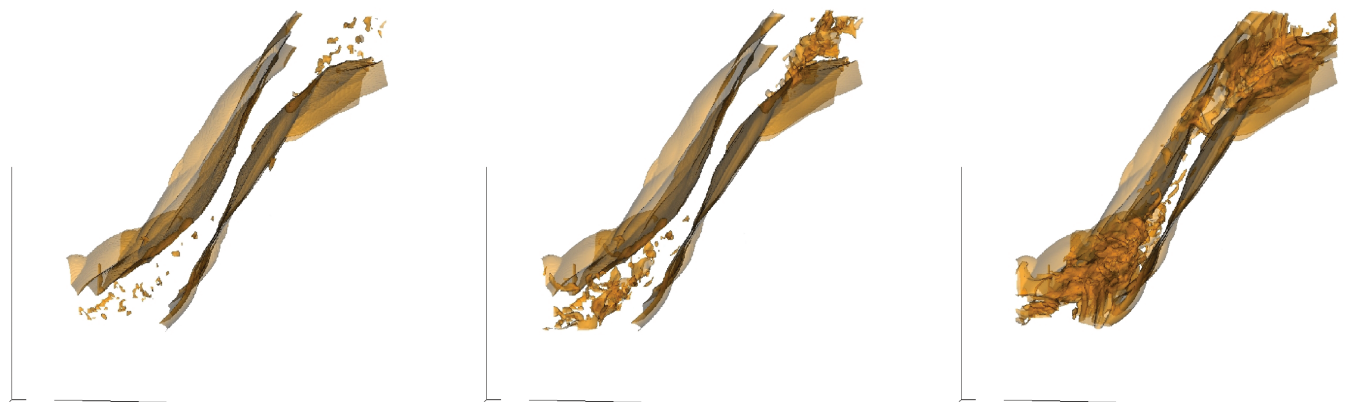


Figure 14. 3D temperature surface from model cwb4 at $\phi = 0.4$. The surface traces gas at a temperature of 2×10^5 K (left), 10^6 K (middle) and 3×10^6 K (right).

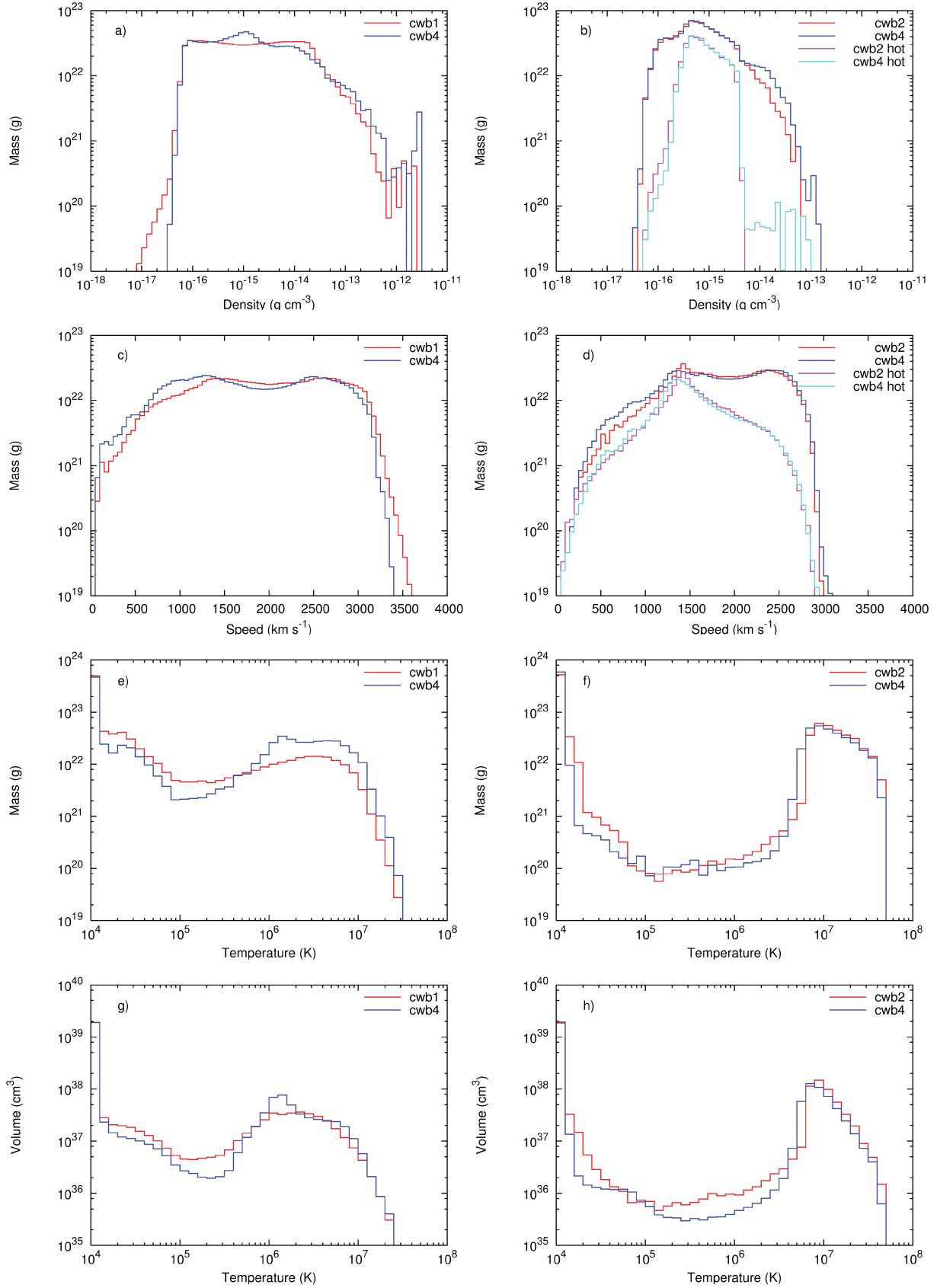


Figure 15. Histograms of various quantities in model cwb4, compared to models cwb1 and cwb2. The left-hand column shows data from models cwb1 and cwb4 with the later at periastron, while the right-hand column compares model cwb2 with cwb4 at apastron. All histograms examine the material within a radius of $120 R_{\odot}$ of the system centre of mass, and exterior to 1.2 stellar radii around the stars.

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