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The impact of radiation and wind momenta on mass transfer in massive close binary systems

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Abstract. We investigate to what extent the radiation and stellar wind momenta in a massive close binary system can remove part of the matter flowing from one towards the other star during a mass transfer phase. We perform radiation-hydrodynamics simulations in the co-rotating frame of a binary system made-up of two main sequence stars of 27 $M_{\odot}$ and 26 $M_{\odot}$ in a 4 day orbit. We study the interaction of the winds of both stars, and of their photons, with the accretion stream originating from the Roche-lobe filling component. For our simulation, we adopt a mass transfer rate of 5×10^{-6} $M_{\odot}$ yr^{-1}, a mid-point in the range of values during massive binary star evolution. Our simulations show that even for such moderate mass transfer rates, the wind and radiative momenta do not alter the dynamics of the accretion stream which is observed to follow essentially ballistic trajectories. Such a conclusion is reinforced for higher mass transfer rates because of the increased stream density and the correspondingly reduced radiation force. We anticipate that the radiation and wind momenta will affect the accretion stream only when its density is comparable to the wind's, a situation wherein the mass transfer rate is vanishingly small and irrelevant for binary star evolution. Alternatively, such reduced accretion stream density could be obtained from spatial dilution in wider systems, potentially leading to non-conservative mass transfer.

Key words. stars: early-type – stars: winds, outflows – stars: binaries: general – hydrodynamics

1. Introduction

Massive close binary stars may produce the most powerful explosions in the universe, the cosmic gamma ray bursts (GRBs), which can trace star formation to very high redshifts (Lloyd-Ronning et al. 2002). While the merger model for GRBs is clearly based on massive binaries (Fryer et al. 1999), even the collapsar model (MacFadyen & Woosley 1999) may require accretion of angular momentum in the GRB progenitor (Langer et al. 2002), as current single star models appear to have too little angular momentum (Heger et al. 2000, 2002). Further evolved observed massive binary counterparts include massive X-ray binaries – where in particular the black hole systems may again be linked to GRBs (Brown et al. 2000) –, supernovae of Type Ib and Ic (Podsiadlowski et al. 1992), Wolf-Rayet binaries (Schulte-Ladbeck 1989) and massive Algol systems (Penny et al. 2002).

To understand all these exciting objects, we need to understand the evolution of massive close binaries. However, the reliability of massive binary evolution models is hampered by a major uncertainty: What fraction of the mass transfered during a Roche-lobe overflow phase can be accreted by the secondary star?

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From observations of post-mass transfer systems, there seems to be evidence for both extremes. The two O stars in the binary V 729 Cyg have a mass ratio of 3.5 but the same spectral type and visual flux (Bohannan & Conti 1976). An initial mass ratio close to 1 is required to ensure the possibility of accretion (see below). However, since during the mass transfer phase a primary star would lose just about half of its mass, a mass ratio of at most 2 could be produced were the secondary not allowed to accrete. Another system showing strong evidence for accretion is the massive X-ray binary Wray 977; it would require that stars of $M \gtrsim 40$ $M_{\odot}$ form neutron stars to explain this system without accretion (Wellstein & Langer 1999).

Several Galactic short period WNE+O binaries, on the other hand, cannot be understood had the O star accreted substantial amounts from the WNE progenitor (cf. Petrovic & Langer 2002). While those might have formed through common envelope evolution – for which no accretion is expected – the key X-ray binary 4U 1700-37 has such a short period that a major accretion phase can be excluded. However, as common envelope evolution would lead to a compact object much more massive than 2.4 $M_{\odot}$, a short initial period is most likely here (Clark et al. 2002).

From the theoretical viewpoint, accretion in massive close binaries appears difficult. Indeed, the accreted material carries a large amount of angular momentum, potentially spinning the surface of the secondary star up to critical rotation, thereby halting the accretion process (Packet 1981; Wellstein 2001;

Langer et al. 2002). In particular for the case of massive binaries, where accretion appears possible from the stellar structure point of view – short period systems consisting of two main sequence stars with nearly equal masses – this process faces another threat.

Short period systems, because of their reduced orbital separation, undergo mass transfer during the core hydrogen burning evolution of the primary (so called Case A mass transfer). As the masses of both stars are similar, so are their thermal time scales, which means that the secondary does not swell due to mass overflow on the thermal time scale of the primary, thus avoiding a contact situation (Wellstein & Langer 1999; Wellstein et al. 2001). As both stars have a similar size, the accreting star fills a significant fraction of its critical volume, leaving no space for an accretion disk, i.e. the overflowing matter may impact directly onto the accreting star, thereby minimising the angular momentum gain of the secondary (Wellstein 2001; Langer et al. 2002).

However, the price to pay for these advantages for accretion is a threat to it: a mass ratio close to one in a massive Case A binary means that the secondary is a massive and luminous main sequence star, i.e., it has an intense radiation field and a powerful stellar wind. Evolutionary studies of massive binary star systems so far have not investigated the impact of such wind and radiation momenta on the dynamics of accretion streams, but instead *adopted*, with a variable level of justification, how conservative mass transfer ought to be. This covers investigations that simply assume the amount of mass loss from the system (Huang & Taam 1990; Kondo 1974; Vanbeveren 1996) and those that account for a modulation depending on luminosity, evolutionary stage etc. (Podsiadlowsky et al. 1992; Doom & de Greve 1983; de Loore & de Greve 1992; de Loore & Vanbeveren 1994). Some detailed calculations of mass transfer and accretion do exist but were limited to objects with no stellar wind and weak radiation fields (Blondin et al. 1995; Boroson et al. 2001). Here, we wish to study the mass transfer properties in massive binary systems, avoiding former educated guesses by addressing with a physical rather than phenomenological model the dynamical properties of the accretion stream in the presence of stellar winds and intense radiation fields expected in such environments.

We present radiation-hydrodynamic simulations in Sect. 2, discussing the choice of geometrical set-up, boundary conditions and the radiation force implemented. In Sect. 3, we show the results of such a model for different scenarios of wind-momentum balance between the two components. We also discuss the outcome for different accretion stream densities and cross-sections. From our simulations, we conclude in Sect. 4 that radiation and wind momenta play an insignificant role in the mass budget during the mass transfer evolution of our example system.

2. Description of the radiation-hydrodynamics model

The radiation-hydrodynamics simulations presented in this paper were performed with ZEUS-2D (Stone & Norman 1992), a finite difference, Eulerian code whose original magnetism and radiation modules were switched–off during the calculations. Hence, we only make use of the hydrodynamical structure of the code, implementing our own radiation module independently (see below). The advection scheme used is the first order Van Leer method. We introduce some artificial viscosity to smooth out strong shocks, improving the stability of the code without affecting the main features of the simulations. The simulated fluid is assumed isothermal, so that the sound speed is everywhere equal to a unique value corresponding to a temperature of 30 000 K.

In the present work, we have slightly modified the code to work in the equatorial plane of the system, in spherical polar rather than cylindrical coordinates. Since we wish to study the trajectory of the accretion stream leaving the primary photosphere *via* the first Lagrangian point L1, the secondary is placed at the origin of the coordinate system. We calculate the fluid properties from the secondary photosphere out to a distance which corresponds to the orbital separation. In the azimuthal direction, we cover the full 2π angle as seen from the secondary star center. However, the simulated domain is truncated along the line of centers and near the primary. The surface of the latter cannot be described by a simple change of one of the coordinates, but rather follows a curve relating the coordinates (r, ϕ). Its photosphere, which acts as a boundary, has a sawtooth shape, making its treatment very delicate, as encountered by Owocki et al. (1994) and Petrenz & Puls (2000) in simulations of winds from rotating hot stars. The steep acceleration of hot star winds as predicted by radiatively-driven wind theory requires a thorough treatment of the small subsonic region confined to the photosphere, specifically because it is in this region that the mass loss rate is set (Castor et al. 1975). To keep the computation time of our simulations to a reasonable value, we decided to fix the density and the velocity at the surface of the primary, allowing the use of a lower grid resolution. The mass loss rate of the primary is then set by the user rather than being a solution of the calculation. In the case of 1D simulations of hot star winds, this would be highly unorthodox, but in our present study, the primary has a very ellipsoidal surface, possesses a zero gravity point and is likely to be gravity darkened. In other words, we believe that the proper treatment of such a hot star surface and wind is beyond the scope of this paper – in fact such an exercise defies even the current best models of hot star winds – so that our choice is not such a bad compromise (see Friend & Castor 1982; Owocki et al. 1996).

Hot stars drive outflows from the photosphere out to infinity by imparting a radiative acceleration on the atmospheric material that supersedes the local gravitational acceleration. In the phenomenon of mass transfer, it is the *thermal pressure* within the outer layers of the stellar envelope that lead to an outflow in the region where the gravitational step is minimum, i.e. the vicinity of the first Lagrangian point. Thus, the dense photospheric material expands and accelerates through the L1 region and "falls" into the gravitational potential well of the secondary star. The velocity of the accretion stream through the L1 point is at most the sound speed, i.e. of the order of a few tens of km s^{-1} for hot stars, and its geometrical cross section is of the order of a few degrees (Lubow & Shu 1975; Ritter 1988). Typical photospheric densities of hot stars are 10^{-10} g cm^{-3}, which would then correspond to a mass transfer rate of the order of few times 10^{-6} $M_\odot$ yr^{-1}. Such a value will be adopted in most of the simulations discussed in Sect. 3. However, there is evidence from binary star evolutionary calculations that mass transfer occurs routinely with a much larger magnitude of the order of 10^{-3} $M_\odot$ yr^{-1}. Physically, this can occur through an increase in density or cross section of the accretion stream, alternatives we investigate with our radiation-hydrodynamics model and discuss in Sects. 3.2 and 3.3.

For our simulations, we assume both mass transfer and stellar wind mass loss rates of the primary and secondary stars. To simulate the wind from the secondary, we choose a surface density such that the sound-speed inflow of material at the boundary corresponds to the mass loss rate as calculated with identical stellar and opacity parameters but with a high spatial resolution (done separately in a 1D simulation), and using reference parameters from Kudritzki et al. (1989). Each of our simulations is first performed until a stationary solution is found for both winds. Once this steady-state is reached, we turn on the mass transfer. This takes the form of a sound-speed inflow of mass from the primary surface at the L1 location, with specified density and cross-section. These parameters are chosen so that they cover the range of mass transfer rates predicted by stellar evolutionary calculations. Note that the problem we are trying to tackle here shares very little common ground with previous radiation-hydro simulations of mass transfer by Roche-lobe overflow, which focused on the case of white dwarfs, neutron stars, Algol systems, where the magnitude of the mass transfer is always feeble, i.e. $\sim 10^{-7}$ $M_\odot$ yr^{-1} (Blondin et al. 1995; Boroson et al. 2001).

For the outer boundary, we clearly have an outflow if we treat exclusively the stellar winds. It was not clear whether such boundary type was appropriate for the simulations including mass transfer. However in all simulations performed, we find that any material reaching the outer edge of the grid possesses a velocity in excess of the escape value, ensuring that the choice of outflow for the outer boundary is adequate. Note that the staircase inflow boundary describing the surface of the primary is not perfectly handled (see Fig. 1) and leads to a spurious flow phenomenon in a few confined directions. This does not affect the gross fluid properties derived here.

We also have to treat the eventuality of the accretion stream impacting the secondary surface. The physics of the shock interface is very complex and cannot be modeled with the desired accuracy, especially with the low resolution of our simulations. We could have adopted different conditions that cover the extreme dynamical scenarios: material is allowed to freely penetrate the secondary surface, to do so at most with the sound speed or not at all (reflecting boundary). However, for simplicity, if material impacts the secondary star surface, the boundary type switches to reflecting.

For the calculation of the radiation force, we use two approaches. Either we calculate the radiation force from a point star with a constant correction factor for the finite disk size, or we integrate the radiation force over the two stellar disks. We have found that the two methods lead to similar properties, for two reasons. First, we find that the radiation force on the accretion stream itself is only moderate (Sect. 3). Moreover, the binary system we study is so compact that the wind-wind-interaction region overlaps with the acceleration regions of both winds, i.e. there is no wind stagnation for which multi-ray calculation of the radiation force led to the discovery of the radiative braking phenomenon (Gayley et al. 1997). Hence, a single ray calculation of the radiation acceleration is performed according to

$$g^{L}_{\rm rad}(r,\phi) = CF * \frac{k\sigma_{\rm e} L_\star}{4\pi c r^2}\left[\frac{1}{\sigma_{\rm e}\rho(r,\phi) v_{\rm th}}\left(\boldsymbol{n}\cdot\nabla(\boldsymbol{n}\cdot\boldsymbol{v})\right)\right]^{\alpha},$$

where $\boldsymbol{n}$ is the unit vector centered either at the primary or the secondary origin and pointing towards the equatorial grid point (r,ϕ). The parameter CF represents the finite disk correction, taken to be $1/(1+\alpha)$ for the two stars for simplicity. k and α are parameters describing the line opacity distribution, $\sigma_{\rm e}$ the electron scattering cross section (cm^2/g), $v_{\rm th}$ the thermal velocity of metal ions, c the speed of light and $\rho(r,\phi)$ ($\boldsymbol{v}(r,\phi)$) the density (velocity) at (r,ϕ) and in cgs units.

We also include the contribution from the centrifugal and Coriolis forces in the momentum equation. At the start of the computation, we calculate the centrifugal potential for all grid points, together with its gradient in the azimuthal and radial directions. It is then incorporated into the momentum equation in the same way as the pressure gradient. The Coriolis force is calculated using the coordinates of the center of mass and the gas parcel velocities with respect to it in a standard way.

3. Results

In this section, we discuss the results of our calculations. We investigate in particular the properties of the accretion stream in a number of simulations with different stellar wind mass loss and mass transfer rates (cf. Table. 2).

3.1. Varying radiation and wind momenta

The central question of our investigation is whether radiation and wind momenta can significantly affect the dynamics of the accretion stream generated by the Roche-lobe filling component. Therefore, we have performed various simulations adopting different primary star luminosities and mass loss rates, hence modifying the strength of the radiation field and the density of the wind emanating from it. This way, we investigate three scenarios: 1) the primary wind winning over the secondary's; 2) a wind balance between the two stars leading to the formation of a wind-wind collision zone; and 3) a situation where the secondary wind wins over the primary wind. For each of these three cases, we investigate what happens to the accretion stream using a moderate mass transfer rate (5×10^{-6} $M_\odot$ yr^{-1}). The results are shown in Fig. 1.

In case 1) $\dot{M}_1$ is enhanced by a factor 100 and the luminosity of the primary by a factor of ten compared to the more realistic default values presented in Table 1. We observe in Fig. 1 that in this situation, the wind of the secondary star is completely overwhelmed. We find that the motion of the accretion stream is not impeded, nor is it modified in any significant way from a standard ballistic trajectory. For the fluid densities concerned here, the stream momentum is orders of

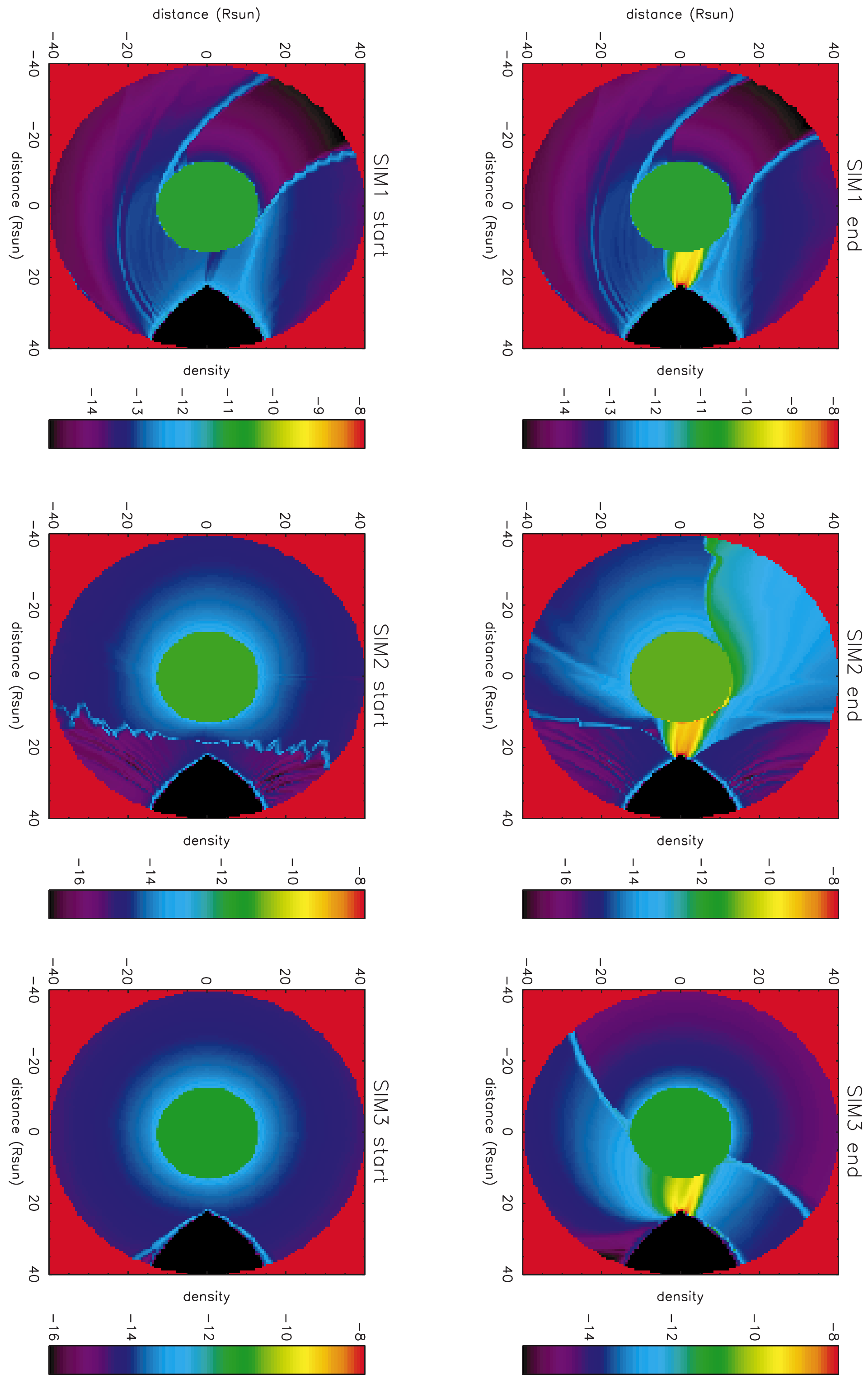

Fig. 1. (Left column) Sequence of gray scale images showing the logarithm of the density of the fluids surrounding the two stars (steady state is reached). The details for each simulation from 1 to 3 are given in Table 2. (Right column) Same as above after mass transfer has been switched on for about 100 ksec (the images do not correspond to a steady state, which will not necessarily be reached before some fraction of the system evolutionary time scale). The secondary star surface does not permit inflow in the simulations shown here.

magnitude above that of the winds, which explains the disregard of the accretion stream with respect to the "ambient" medium. In this close binary system, this leads to a fully conservative mass transfer.

Case 2) corresponds to the situation where the wind momenta of both stars are equal ($\dot{M}_1 = \dot{M}_2$ and similar luminosity for both stars), giving rise to a wind-wind collision between the two binary components. It has been argued in the past that the

Table 1. Standard parameters of our simulations. Table 2 gives updates to those parameters that are modified for the calculations presented in Sect. 3.

	$M_\star$ ($M_\odot$ yr)	$L_\star$	$R_\star$	$\dot{M}$
Primary	27 $M_\odot$	1.8×10^5 $L_\odot$	15 $R_\odot$	10^{-8} $M_\odot$ yr^{-1}
Secondary	26 $M_\odot$	1.5×10^5 $L_\odot$	11.8 $R_\odot$	10^{-8} $M_\odot$ yr^{-1}
	Orbital separation	Period	ρ_{L1}	ϕ_{L1}
System	40 $R_\odot$	4 d	10^{-8} g cm^{-3}	3 deg

Table 2. List of performed simulations and the respective values used for the key parameters. Sim 1-3 focus on the impact of varying wind properties (through wind and radiation momenta). Sim 4 treats the case of a bigger stream cross section and Sim 5-7 address the situation for an enhanced stream density. These changes are implemented by changing ϕ_{L1}, the half angular width of the stream as seen from the primary center, or the density at L_1. Scaling ρ_{L1} (ϕ_{L1}) by x scales the mass transfer by $x(x^2)$.

	$\dot{M}_1$ $M_\odot$ yr^{-1}	ρ_{L1} g cm^{-3}	ϕ_{L1} deg	$\dot{M}_{\rm transfer}$ $M_\odot$ yr^{-1}
1	1×10^{-6}	1×10^{-8}	3.	5×10^{-6}
2	1×10^{-8}	1×10^{-8}	3.	5×10^{-6}
3	5×10^{-9}	1×10^{-8}	3.	5×10^{-6}
4	1×10^{-8}	1×10^{-8}	10.	5×10^{-5}
5	1×10^{-8}	1×10^{-8}	3.	5×10^{-6}
6	1×10^{-8}	1×10^{-7}	3.	5×10^{-5}
7	1×10^{-8}	1×10^{-6}	3.	5×10^{-4}

collision interface, because it lies between L_1 and the secondary surface, could interfere and maybe prevent mass transfer from occurring. In our simulation, it is clear that the accretion stream is not at all affected by this colliding zone. The same argument as in case 1) applies, where essentially the density contrast favors the stream over the two winds and the colliding interface. An analogy that may help is to view such density contrasts as much bigger than that between air and water (at room temperature). So, case 2) robustly leads to conservative mass transfer.

In case 3), we make the wind of the primary artificially small by reducing $\dot{M}_1$ to half the secondary's value. This situation would apparently be unfavourable to the primary's mass transfer, but again, for similar arguments as used in case 2) and 1), the wind from the secondary is no match for the dense accretion stream.

This leads us to conclude that the radiation and wind momenta are totally irrelevant for the general dynamics of the accretion stream, even in the situation where the mass transfer rate is moderate (5×10^{-6} $M_\odot$ yr^{-1}). Hence, in such close binary systems, our simulations strongly advocate conservative mass transfer.

3.2. Varying the mass transfer rate

As discussed in Sect. 2, the mass transfer rate can vary enormously during the evolution of a massive binary system. We investigate in this section the various ways such a mass transfer rate could be enhanced, namely by means of an increased density or geometrical cross section. We devote less attention to the case of lower rates than adopted in the previous section because they are doomed to play a weaker role, the accretion through direct impact of the companion *wind* potentially becoming an efficient alternative.

3.2.1. Varying the stream cross section

As discussed in the introduction to this section, a change in stream cross-section can amplify the amount of transfered mass by at most a factor of a few. We have run a number of simulations increasing the value of this cross section up to 20 deg (Sim 4). While this seems a lot, one needs to remember that given the low density in the outer envelope of the star, at the onset of mass transfer, the corresponding rate of mass loss through L1 will likely be small. We anticipate that the stellar envelope will continue growing beyond the Roche surface, until the dense layers located deeper in the envelope near the L1 region lead to a strong increase in mass transfer and the stabalisation of the envelope. During this transition, the stream could indeed be much broader than the values suggested in Ritter (1988). Our simulations demonstrate that this case is a hybrid. A large fraction of the accretion stream impacts the secondary surface, while the rest creates a colliding interface with the secondary's outflow. This fraction of interacting material is however small and therefore leads only to a minor departure from conservative mass transfer.

3.2.2. Varying the stream density

We have performed simulations for L1 densities a factor ten and a hundred higher than in Sect. 3.1 (Sim 5, 6 and 7). The momentum contrasts between the stream and the winds are even larger than in Sect. 3.1, and we find that the simulations, as expected, re-enforce the conclusion already made before. Namely, for the high mass transfer rates ($\sim 10^{-3}$ $M_\odot$ yr^{-1}) at which most of the mass from the primary is lost during Case A mass transfer, the winds and radiation from either component have no effect on the accretion stream.

4. Discussion and conclusion

We have investigated the importance of radiation and wind momenta on the dynamical behaviour of accretion streams produced by overflow of the Roche-lobe filling component in a binary system. We performed radiation-hydrodynamic simulations of a typical young, close (4 day period) and massive binary system, calculating explicitly the radiation force and wind properties for each component. We discussed situations for the different mass transfer rates encountered in evolutionary calculations for massive binary systems (Wellstein 2001), as well as the occurrence of different wind momentum balance.

The central result of our calculation is that the dynamics of mass transfer in massive close binary stars is not affected in any noticeable way by the radiation and wind momenta from each luminous component. These latter mechanisms cannot therefore be at the origin of the non-conservative mass transfer required to explain the observed mass ratios of many Wolf-Rayet binaries.

The reader may find surprising that the radiation force does not modify the dynamical behaviour of an accretion stream. Although the radiation force efficiency is complex because it depends on the local velocity gradient and therefore on the dynamics itself, its dependence on the inverse of the density is really what makes it so ineffective here. The source of confusion on the importance of the radiation force in massive close binary systems could possibly arise from the failure to realise that important mass transfer rates for the evolution of those systems are of the order of $10^{-3}\ M_{\odot}\ \mathrm{yr}^{-1}$, corresponding to density regimes orders of magnitude beyond those of hot star winds where the radiation acceleration is admittedly crucial. One must also bear in mind that this mass transfer occurs through a restricted region of space whilst stellar winds occur in principle from all stellar surface locations. Thus, for a mass transfer and wind mass loss of identical magnitude correspond a stream density a factor $1/\sin^2(\Phi_{L1}/2)$ greater than the wind's, simply from geometrical arguments.

Finally, we anticipate that in wider binary systems, the dilution of the accretion stream through spatial expansion could lead to a progressive "switch-on" of the importance of radiation and wind momenta, when and if the stream density becomes comparable to the standard wind density of the accreting star (as derived in single-star radiation-hydrodynamics simulations). This would offer an explanation for non-conservative mass transfer in wide massive binary systems.

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