Eccentricity of radiative discs in close binary-star systems

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ABSTRACT

Context. Discs in binaries have a complex behavior because of the perturbations of the companion star. Planetesimals growth and planet formation in binary-star systems both depend on the companion star parameters and on the properties of the circumstellar disc. An eccentric disc may significantly increase the impact velocity of planetesimals and therefore jeopardize the accumulation process.

Aims. We model the evolution of discs in close binaries including the effects of self-gravity and adopting different prescriptions to model the disc’s radiative properties. We focus on the dynamical properties and evolutionary tracks of the discs.

Methods. We use the hydrodynamical code FARGO and we include in the energy equation heating and cooling effects.

Results. Radiative discs have a lower disc eccentricity compared to locally isothermal discs with same temperature profile. Its averaged value is about 0.05, and it is almost independent of the eccentricity of the binary orbit, in contrast to locally isothermal disc models. As a consequence, we do not observe the formation of an internal elliptical low density region as in locally isothermal disc models. However, the disc eccentricity depends on the disc mass through the opacities. Akin to locally isothermal disc models, self-gravity forces the disc’s longitude of pericenter to librate about a fixed orientation with respect to the binary apsidal line ($\pi$).

Conclusions. The disc’s radiative properties play an important role in the evolution of discs in binaries. A radiative disc has an overall shape and internal structure that are significantly different compared to a locally isothermal disc with same temperature profile. This is an important finding both for describing the evolutionary track of the disc during its progressive mass loss, and for planet formation since the internal structure of the disc is relevant for planetesimals growth in binary systems. The non-symmetrical distribution of mass in these discs causes large eccentricities for planetesimals that may affect their growth.

Key words. Protoplanetary disks — Methods: numerical — Planets and satellites: formation

1. Introduction

Protoplanetary discs are known to exist in pre-main-sequence binary star systems through direct imaging (Koerner et al. 1993; Stapelfeldt et al. 1998; Rodriguez et al. 1998) and spectral energy distributions (Ghez et al. 1993; Prato et al. 2003; Monin et al. 2007). Petr-Gotzens et al. (2010) have recently claimed that as much as 80\% of all binary star systems in the ~1 Myr old Orion Nebula Cluster might have an active accretion disc. Trilling et al. (2007) showed that the incidence of debris discs in binary systems is not that different than that for single stars. These observations seem to suggest that the ground for planet formation in binary star systems is present even if, at subsequent stages, the gravitational perturbations by the companion star may negatively impact the growth process. Bonavita & Desidera (2007); Mugrauer & Neuhaüser (2009) have shown that the frequency of planets in binaries is not very different from that around single stars. However, this frequency critically depends on the binary separation and close binaries appear to be less favorable environments for planet formation. Only a few planets are presently known in tight systems (G186, HD41004 and $\gamma$ Cephei) and it is expected that when the binary separation is in the range 20-100 AU the gravitational influence of the companion star must have influenced the planet formation process, affecting either the disc evolution or the planetesimal accumulation process (Desidera & Barbieri 2007).

Of particular importance are the initial stages of planetesimal evolution when the mutual impact velocities must remain low to allow mass growth despite the perturbations by the companion star. Previous studies (e.g., Marzari & Scholl 2000; Thébault et al. 2006, 2008, 2009; Paardekooper et al. 2008; Xie & Zhou 2009; Paardekooper & Leinhardt 2010) have shown that the combination of gas drag force and secular perturbations by the secondary star has strong effects on planetesimal orbits, leading to pericenter alignment and to an equilibrium distribution for the eccentricity of small planetesimals. Since the magnitude of the gas drag force depends on the planetesimals size, the variation of eccentricity and pericenter longitude with particle size may well inhibit the formation of larger bodies by exciting large mutual impact velocities.

One question that needs to be addressed is to what extent the disc’s perturbation due to the companion star (e.g., Lubow 1991ab; Kley et al. 2008) affects the distributions of eccentricity and longitude of pericenter for planetesimals of different size. Models in which the planetesimals orbital evolution was computed along with the time evolution of the disc (Kley & Nelson 2008; Paardekooper et al. 2008) have shown that the disc eccentricity may strongly influence the dynamics of small planetesimals by introducing radial gas drag forces and non-axisymmetric components in the gravity field of the disc. This additional perturbing force may act either in favor or against planetesimal accretion by affecting the relative impact velocities between the
bodies. An in depth analysis is needed to explore the strength of these perturbations. This first requires investigating the impact of the companion star on the disc’s eccentricity. We focus on relatively close binary star systems with large mass ratios and potentially large eccentricities which, according to Duquennoy & Mayor (1991), populate the peak of the frequency distribution in our neighborhood. Modelling the response of a protoplanetary disc to the gravitational perturbations by a secondary (companion) star requires by necessity a numerical approach, since it is difficult to predict analytically the disc shape and evolution with time.

In a previous paper (Marzari et al. 2009, hereafter Paper I) we used the numerical code FARGO to model the time evolution of a two-dimensional (2D) circumstellar disc in close binary star systems, including the effects of disc self-gravity. We focused on massive discs, with an initial mass equal to $0.04M_\odot$, as well as a large binary’s mass ratio ($\mu = M_*/M_p = 0.4$). This value is statistically the most frequent among the binary systems observed so far (Duquennoy & Mayor 1991). We found that self-gravity significantly affects the increase in the disc eccentricity induced by the companion perturbations, and also influences the orientation of the disc relative to the binary reference frame by causing libration instead of circulation. We also sampled different values of the binary’s eccentricity, $e_b$, ranging from 0 to 0.6. The main findings of paper I were the following:

- self-gravity plays a significant role in shaping the disc. The dynamical eccentricity $e_d$ (defined in Sect. 2.3) of the disc typically ranges from $\sim 0.05$ to $0.15$, depending on the binary eccentricity, $e_b$. It is smaller than in models without self-gravity,
- $e_d$ is inversely proportional to $e_b$, with the case of a circular binary ($e_b = 0$) being the most perturbing configuration,
- the disc orientation $\omega_d$ (defined in Sect. 2.3) librates around $\pi$, while it was circulating in the absence of self gravity,
- an eccentric low-density region develops in the inner disc parts because of the large eccentricity and aligned pericenters of the gas streamlines there.

The results of paper I have been obtained assuming a locally isothermal equation of state for the gas, wherein the initial radial profile of the temperature remains constant in time, its value being set by the choice for the disc aspect ratio $h = H/r$, with $H$ the pressure scale height. This approximation is well suited in disc regions where radiation cooling is efficient and the gas is optically thin. However, in particular in the initial stages of their evolution, discs may be optically thick and a more detailed treatment of the energy balance is required. In addition, when it passes at its pericenter, the secondary star triggers spiral shocks that may generate local strong shock and compressional heating, which may violate the local isothermal approximation. The propagation of these shock waves may also be significantly altered in radiative discs. In this paper, we focus on how the disc eccentricity and orientation depend on the disc radiative properties. Our approach is the following. We first examine our previous results on locally isothermal discs depend on the choice for the (fixed) temperature profile of the disc. We then consider disc models with a radiative energy equation, for which we find that the averaged disc’s eccentricity in its inner parts is smaller compared to locally isothermal disc models with similar temperature profile. We finally discuss the impact of our results in terms of planetesimals dynamics.

2. Model description

2.1. Code

Two-dimensional hydrodynamical simulations were carried out with the ADSG version of the code FARGO. The code solves the hydrodynamical equations on a polar grid, and it uses an upwind transport scheme along with a harmonic, second-order slope limiter (van Leer 1977). The ADSG version of the FARGO code includes an adiabatic energy equation and a self-gravity module based on fast Fourier transforms (Baruteau & Masset 2008). Heating and cooling source terms have been implemented in the energy equation as described in Sect. 2.2. The specificity of the FARGO algorithm is to use a change of rotating frame on each ring of the grid, which increases the timestep significantly.

Results of simulations are expressed in the following code units: the mass unit is the mass of the primary star, $M_p$, which is taken equal to $1M_\odot$. The length unit is set to 1 AU, and the orbital period at 1 AU is $2\pi$ times the code’s time unit.

2.2. Physical model and numerical setup

We adopt a 2D disc model in which self-gravity and an energy equation are included (unless otherwise stated). The hydrodynamical equations are solved in a cylindrical coordinate system $(r, \phi)$ centered onto the primary star, with $r \in [0.5 \text{ AU} - 15 \text{ AU}]$ and $\phi \in [0, 2\pi]$. The grid used in our calculations has $N_r = 256$ radial zones and $N_{\phi} = 512$ azimuthal zones, and a logarithmic spacing is used along the radial direction. The frame rotates with the Keplerian angular velocity at the binary’s semi-major axis, and the indirect terms accounting for the acceleration of the primary due to the gravity of the secondary and of the disc are included.

**Binary parameters**— Throughout this study, we adopt as standard model a binary system where the secondary star has a mass $M_s = 0.4M_\odot$. The binary is held on a fixed eccentric orbit with semi-major axis $a_b = 30 \text{ AU}$ and eccentricity $e_b = 0.4$, corresponding to an orbital period $\approx 134 \text{ yr}$.

**Energy equation**— Since the purpose of this work is to examine the impact of an energy equation on the disc’s response to the periodic passages of a close companion, we carried simulations including either an energy equation, or a locally isothermal equation such that the initial temperature profile remains constant in time. In all cases, the disc verifies the ideal gas law,

$$ p = \kappa \Sigma T / \mu, \quad (1) $$

where $p$ and $T$ denote the vertically-integrated pressure and temperature, respectively, $\Sigma$ is the mass surface density, $\kappa$ is the ideal gas constant, and $\mu$ is the mean molecular weight, taken equal to 1.29. When included, the energy equation takes the form:

$$ \frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{v}) = -p\nabla \cdot \mathbf{v} + Q_{\text{visc}} + Q_{\text{cool}} + \lambda e \nabla^2 \log(p/\Sigma) \quad (2) $$

where $e = p/(\gamma - 1)$ is the thermal energy density, $\gamma$ is the adiabatic index, and $\mathbf{v}$ denotes the gas velocity. We take $\gamma = 1.4$ throughout this study. In Eq. 2, $Q_{\text{visc}}$ denotes the viscous heating. We use both a constant shear kinematic viscosity, $\nu = 10^{-5}$ in code units, and a von Neumann-Richtmyer artificial bulk viscosity, as described in Stone & Norman (1992), where the coefficient $C_2$ is taken equal to 1.4 ($C_2$) measures the number of

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1 See: [http://fargo.in2p3.fr](http://fargo.in2p3.fr)
zones over which the artificial viscosity spreads out shocks). The cooling source term in Eq. (2), $Q_{\text{cool}}$, is taken equal to $2\sigma_\text{SB}T_{\text{eff}}^4$, where $\sigma_\text{SB}$ is the Stefan-Boltzmann constant, and $T_{\text{eff}}$ is the effective temperature (Hubeny 1990).

$$T_{\text{eff}}^4 = T^4/\tau_{\text{eff}},$$

(3)

with effective optical depth

$$\tau_{\text{eff}} = \frac{3r}{8} + \frac{\sqrt{3}}{4} + \frac{1}{4r}.$$  

(4)

The vertical optical depth, $\tau$, is approximated as $\tau = \kappa \Sigma/2$, where for the Rosseland mean opacity, $\kappa$, the formulae in Bell & Lin (1994) are adopted. Following Paardekooper et al. (2011), we also model thermal diffusion as diffusion of the gas entropy, $s$, defined as $s = \mathcal{R}(y-1)^{-1}\log(p/\Sigma)$. This corresponds to the last term in the right-hand side of Eq. (2), where $\lambda$ is a constant thermal diffusion coefficient. Throughout this study, we adopt $\lambda = 10^{-6}$ in code units.

**Initial conditions**— The disc is initially axisymmetric and the angular frequency $\Omega(r)$ about the primary star is computed taking into account the radial acceleration due to the pressure gradient, the gravitational acceleration due to the primary star only and the self-gravity of the disk. The initial gas surface density, $\Sigma_0$, is set as $\Sigma_0(r) = \Sigma_0(1\text{ AU}) \times (r/1\text{ AU})^{-3/2}$ with $\Sigma_0(1\text{ AU}) = 2.5 \times 10^{-4}$ in code units. Assuming the mass of the primary star is $1M_\odot$, this corresponds to setting the disc surface density at $1\text{ AU}$ to $2.2 \times 10^3 \text{ g cm}^{-2}$. Beyond 11 AU, $\Sigma_0(r)$ is smoothly reduced to a floor value, $\Sigma_{\text{floor}} = 10^{-9} = 4 \times 10^{-6} \Sigma_0(1\text{ AU})$, using a Gaussian function with standard deviation equal to 0.4 AU. To prevent numerical instabilities caused by low density values or by steep density gradients near the grid’s outer edge, the gas density in each grid cell is reset to $\Sigma_{\text{floor}}$ whenever it becomes smaller than this floor value (Kley et al. 2008, Paper I). Similarly, we adopt a floor value for the thermal energy density, $\epsilon_{\text{floor}} = 10^{-18}$. Our choice for this parameter is conservative, and we checked that with a larger $\epsilon_{\text{floor}}$, the modelled disc behaved similarly.

The initial gas temperature, $T_0$, is taken proportional to $r^{-1}$: $T_0 = T_0(1\text{ AU}) \times (r/1\text{ AU})^{-1}$, where the value for $T_0(1\text{ AU})$, which is taken as a free parameter in our study, will be specified below. Writing the pressure scale height $H$ as $H = c_s \Omega_K^{-1}$, where $c_s$ denotes the sound speed and $\Omega_K$ the Keplerian angular frequency, the disc temperature can be conveniently related to the disc’s aspect ratio, $h = H/r$. In our code units, where $\mathcal{R}/\mu = 1$, this yields $T_0(1\text{ AU}) = 630 \text{ K} \times (h(1\text{ AU}))/0.05)^2$.

**Boundary conditions**— By default, an outflow zero-gradient boundary condition is adopted at both the grid’s inner and outer edges. The azimuthal velocity is set to its initial, axisymmetric value. No mass therefore flows back into the system, and the disk mass declines with time. The impact of the inner boundary condition on our results is examined in Sect. 4.3.

### 2.3. Notations

We will make use of the following quantities. We denote by $e_d$ and $e_{\Sigma d}$ the disc’s eccentricity and perihelion longitude, respectively. They are defined as in Kley et al. (2008), Pierens & Nelson (2007), Marzari et al. (2003):

$$e_d = M_d^{-1/2} \times \int e(r, \varphi) \Sigma(r, \varphi) r \, dr \, d\varphi$$

(5)

and

$$e_{\Sigma d} = M_d^{-1} \times \int e(r, \varphi) \Sigma(r, \varphi) r \, dr \, d\varphi$$

(6)

where $M_d$ denotes the disc’s mass, and $e$ and $\Sigma$ are the eccentricity and pericenter longitude of each grid cell, respectively, assuming that the local position and velocity vectors uniquely define a 2-body Keplerian orbit.

### 3. Locally isothermal disc models

Before examining the impact of an energy equation on the disc’s response to the tidal perturbations by the secondary star, we adopt in this section the simpler case for a locally isothermal equation of state, where the initial (axisymmetric) profile of the disc temperature remains fixed. This first step will help us analyze the more complex situation of a disc whose temperature evolves in time due to radiative cooling and various sources of heating, including that arising from the shock waves induced by the secondary.

#### 3.1. Disc’s eccentricity and surface density profiles

We carried out a series of simulations using a range of values for the disc’s aspect ratio at 1 AU, $h(1\text{ AU})$. This comes to varying the disc’s temperature at the same location. Other disc and binary parameters are as described in Sect. 2.2. We consider two different values for the secondary-to-primary mass ratio: $q = 0.4$ (our fiducial value), and $q = 0.1$. Results of simulations with $q = 0.4$ are shown in the upper panels in Fig. 1 and those with $q = 0.1$ in the lower panels. Azimuthally- and time-averaged profiles of the disc’s eccentricity and surface density are displayed in the left and right columns of Fig. 1 respectively. Profiles are displayed after ~ 60 orbits of the secondary, and time averaging is done over 5 orbits. By checking the time evolution of the disc’s eccentricity profile, we find that a steady state is reached after typically 20 binary revolutions with $q = 0.4$ for all values of $h$, and after 40 revolutions for $q = 0.1$. The value of $h(1\text{ AU})$ is indicated in each panel (and simply denoted by $h$).

We are primarily interested in the disc’s averaged eccentricity in its inner parts, below the truncation radius located at $r \sim 5 - 6$ AU for $q = 0.4$, where planet formation is more likely to occur. As shown in Marzari et al. (2009), the truncation radius of the disc closely matches the critical limit for orbital stability due to the secular perturbations of the companion star (Holman & Wiegert 1999). From Fig. 1 it is clear that the disc eccentricity increases from $r \sim 4$ AU downwards, peaks at $r \lesssim 1$ AU, then decreases towards the location of the grid’s inner edge, where the boundary condition imposes zero eccentricity. Interestingly, we see that the averaged peak eccentricity of the disc (reached at $r \lesssim 1$ AU) increases with $h$ up to $h = 0.05$ and decreases beyond this value. The same behavior is obtained with both values of $q$. This behavior may be interpreted as follows. The disc’s density perturbation due to the secondary decreases with increasing disc aspect ratio ($h$ or, equivalently, increasing sound speed). In the limit of large aspect ratios, the disc’s eccentricity thus decreases with increasing $h$. As $h$ decreases, the disc’s perturbed density increases, but shock waves become more tightly wound, and have to travel a longer distance before reaching the disc’s inner parts. Being then more prone to viscous damping, shock waves become less and less efficient at depositing angular momentum in the disc’s inner parts, where the eccentricity remains small.

This explains why when decreasing $h$,
the averaged eccentricity of the disc’s inner parts first reaches a maximum and then decreases.

We can see in Fig. 1 that the radial dependence of the density and eccentricity profiles reasonably match each other, as expected. The general trend is that the larger the disc’s eccentricity profile, the smaller the surface density profile. Note that this is more visible for $q = 0.4$, where the density’s perturbation by the secondary takes larger values than for $q = 0.1$. The significant decrease in the disc’s density profile in the disc inner parts (typically below $\sim 2$ AU) takes the form of an elliptic inner hole, which has been observed in a number of previous numerical studies (e.g., Kley et al. 2008, Paper I).

Our results concerning the dependence of the disc’s eccentricity and density profiles with $h$ differ from those of Kley et al. (2008), but this depends on intrinsic differences in the models. In particular, we consider more massive discs and we include the effects of self-gravity which proved to be efficient in affecting the disc evolution.

3.2. Fourier analysis of the density distribution

To provide some insight into the dependence of the disc’s eccentricity and density profiles with varying temperature, we examine in this paragraph the Fourier components of the disc’s surface density. Fig. 2 displays the instantaneous amplitude of the Fourier mode coefficients with azimuthal wavenumber $1 \leq m \leq 5$. Results are shown at 2550 yr, that is after $\approx 20$ orbits of the secondary, when the disc is truncated at about 7-8 AU. We compare the profiles obtained for previous series of locally isothermal disc models for $q = 0.4$, with $h = 0.02$ (left panel) and $h = 0.06$ (right panel). The secondary star is half-way between the pericenter and apocenter at this particular point in time.

From Fig. 2 it is clear that the amplitude of Fourier mode coefficients decreases with increasing $m$, and that the $m = 1$ mode prevails. The run with $h = 0.06$ displays larger mode amplitudes throughout the disc’s inner parts, which accounts for the larger disc eccentricity obtained in this case. Also, the large amplitude of the $m = 1$ mode below $r \approx 1$ for $h = 0.06$ is directly associated to the presence of an elliptic inner hole, whose presence has already been pointed out in the upper panels in Fig. 1.

4. Radiative discs models

In this section, we describe the results of our hydrodynamical simulations that include an energy equation. Our aim is to assess the impact of the energy equation on the disc’s averaged eccentricity.

4.1. Disc eccentricity

![Fig. 5. Time evolution of the averaged disc eccentricity $e_d$ (upper panel) and pericenter longitude $\pi_d$ (lower panel) for the locally isothermal and radiative runs of Sect. 4.1.](image)

As a first step, we compare a radiative and a locally isothermal model with same initial aspect ratio, $h = 0.05$. All other disc parameters are as described in Sect. 4. Fig. 4 shows contours of the disc’s surface density at 90 binary orbits obtained with two values of the binary’s eccentricity: $e_b = 0.4$ (upper panels) and $e_b = 0$ (lower panels). As already pointed out in Sect. 4, eccentric streamlines ($m = 1$ density mode) have different values of the pericenter depending on the radial distance, and, as a consequence, they combine into a pattern of spiral structure. However, the discs computed with the radiative model (left-handed plots in Fig. 4) appear smoother and more symmetric than the corresponding locally isothermal discs, and, in particular, they do not feature any elliptic hole near the inner edge, independently of $e_b$. The spiral density waves are less strong in the radiative case and this is possibly related to the absence of a low density region close to the star. The disc eccentricity $e_d$ and perihelion longitude
Fig. 1. Azimuthally- and time-averaged profiles of the disc’s eccentricity (left column) and surface density ($\Sigma$, right column) obtained with the series of locally isothermal disc models described in Sect. 3. In the density profile plots the initial, unperturbed profile is shown as reference. Results are shown at 60 orbits of the secondary, and time-averaging is done over 5 orbits. Several values of the disc’s aspect ratio at 1 AU are considered and two secondary-to-primary mass ratios: $q = 0.4$ (upper panels) and $q = 0.1$ (lower panels).

are shown as a function of time in Fig. 5 and they confirm that the radiative case has, on average, a lower eccentricity even if it takes more time to reach a steady state. The perihelion libration, observed also for the radiative case, strongly suggests that this behaviour is solely due to the disc self-gravity and that it does not depend on the energy equation. By inspecting the radial pericenter profile, even in the radiative case the azimuthally averaged pericenter of the gas streamlines changes with radial distance (as is illustrated in Fig. 2 for a locally isothermal model). This variation, in addition to causing spiral waves, leads to an asymmetric distribution of mass and then to a non-symmetric disc gravity field. This is critical for planetesimals embedded in the disc since the non-homogeneous disc forces non-radial components on the gravity field felt by planetesimals significantly perturbing their orbits. These perturbations are comparable in magnitude to the secular effects of the companion star but are irregular and may then cause larger changes in the planetesimals orbital elements. They are indeed an indirect effect of the companion gravity but for planetesimals they represent an independent source of perturbation.

To get further insight into the different densities and eccentricities with and without an energy equation, we carried out two additional locally isothermal disc models. In the first model, the initial temperature is set to the time-averaged temperature profile of the above radiative run. In the second model, the initial temperature is chosen to give the same sound speed profile as the time-averaged one in the radiative run. In Sect. 3.1, we pointed out that the disc eccentricity in locally isothermal models strongly depends on the aspect ratio $h$ and, as a consequence, on the temperature profile (see Fig. 1). In Fig. 6, bottom plot, we compare the temperature profile of the locally isothermal model with $h = 0.05$ to the time-averaged temperature profile of the radiative model. The temperature in the radiative run is significantly larger, implying that we should compare the radiative model to a locally isothermal model with $h \sim 0.07$. In the top panel of Fig. 6, we display the eccentricity and density profiles in all four models: (i) the radiative model, (ii) the locally isothermal model with same initial aspect ratio as in the radiative model, (iii) the locally isothermal model with same temperature profile as in the radiative case, and (iv) the locally isothermal model with same sound speed profile as in the radiative one. The disc eccentricity in models (iii) and (iv) is smaller than in model (ii), as expected from the results shown in Fig. 1 (top-left panel). Consequently, the disc surface density remains larger in models (iii) and (iv) compared to in model (ii). Still, models (iii) and (iv) do not match the low eccentricity of the radiative case and its smooth density distribution close to the star. The strength of the $m = 1$ Fourier mode in the radiative run is smaller in the
disc’s inner parts, and this difference depends on the form of the energy equation. In Fig. 7 we display density contours obtained with the radiative run (left panel), and with the locally isothermal model with same temperature profile (right panel). In the radiative model, the wave perturbations are less strong and the waves appear to be more damped. Being weaker in the inner disc parts in the radiative case, waves should be less efficient at depositing angular momentum there. This would explain why radiative discs are less eccentric in the regions close to the central star, and why the surface density is more homogeneous.

4.2 Radiative damping of waves

The main question arising from previous results is what causes a stronger damping of density waves in the radiative model than in the locally isothermal one, while the same (time-averaged) sound speed profile is adopted in both models. In Fig. 8 the radiative model shows indeed a significantly lower eccentricity profile. Assuming the disc eccentricity is related to the strength of the density waves induced by the binary gravitational perturbations, we have shown in Fig. 7 that spiral waves are more damped in the radiative case.

There are two potential sources of wave damping that may help understand why the disc eccentricity remains lower in the radiative case: shock damping (Goodman & Rafikov 2001) and radiative damping (Cassen & Woolum 1996). To explore the efficiency of the shock damping mechanism, we examined the vortensity distribution in the disc, since it experiences a jump at shocks, the magnitude of which depends on the strength of the shock. We did not observe significant differences in the disc vortensity distribution between the two models and thus we believe that shock damping does not significantly contribute to the smoother behaviour of the radiative disc.

The energy loss by radiation is an additional possible source of wave damping (Cassen & Woolum 1996). Wave propagation through adiabatic compressions and expansions may be damped by radiative losses which, in our model, are controlled by the cooling term $Q_{\text{rad}}$. To test this hypothesis, we restarted our standard radiative simulation ($e_b = 0.4$, $M_* = 0.4M_\odot$, and $a_b = 30$ AU) after 165 binary revolutions adopting different two cooling prescriptions. In a first run, we limit the cooling time throughout the disc to be no less than that at 6 AU from the star (that is, about 150 yr). To keep the temperature profile as close as possible to that of the standard radiative model, and thus to prevent discrepancies related to different temperature profiles, we limit the viscous heating timescale by a similar amount. In a second run, we increase the cooling rate throughout the entire disc by a factor of 10, and the viscous heating rate is increased accordingly. Both restart simulations were run for 50 additional binary orbits, over which the disc’s temperature profile does not evolve significantly, except within 1 AU from the central star.

Fig. 8 compares the disc time-averaged eccentricity and temperature profiles of the standard radiative model with those of the additional models with longer and shorter cooling times. The inner disc’s eccentricity is significantly increased with longer cooling timescale, exceeding ~ 0.1 almost uniformly from $R = 2$ AU to $R = 6$ AU. This value is in good agreement with that of the locally isothermal run with same sound speed profile (see Fig. 6). However, close to the inner edge the disc eccentricity is still small but this is possibly due to the fact that we cannot maintain constant the temperature profile within 1 AU of the central star in the model with reduced cooling. In the restart simulation with a cooling rate 10 times larger, the disc eccentricity is about half that of the standard radiative model, while the corresponding temperature profiles hardly differ.

The results shown in Fig. 8 suggest that radiative damping is responsible for the limited growth in the disc eccentricity compared to to similar locally isothermal disc models. This mechanism, like self-gravity, helps maintaining the disc eccentricity to a mild value.

4.3 Dependence on the boundary conditions

We examine in this paragraph the dependence of our results on the choice for the boundary condition at the grid’s inner edge. For this purpose, we compare the results of simulations using our fiducial boundary condition (zero-gradient outflow boundary condition, see Sect. 4.1) with those of two additional simulations:

- One using a viscous outflow boundary condition (Kley & Nelson 2008). It is very similar to our zero-
Fig. 4. Contours of the gas density after 90 binary revolutions. Results with an energy equation are shown in the left part of this figure, and those with a locally isothermal equation of state with fixed temperature profile are shown in the right part. The upper plots are for $e_b = 0.4$ and the lower plots for $e_b = 0.0$. The same initial aspect ratio ($h = 0.05$) is used in these simulations.

gradient outflow boundary condition, except that the radial velocity at the inner boundary is set to the local (azimuthally-averaged) viscous inflow velocity of a disc in equilibrium with locally uniform surface density profile ($-3\nu/2R_{\text{min}}$). The azimuthal velocity is also set to its initial axisymmetric value.

- Another simulation also using our standard outflow boundary condition, but where the azimuthal velocity at the inner boundary is extrapolated from that in the first active ring with a $r^{-1/2}$ law. In contrast to previous boundary conditions, the disc at the grid’s inner edge is no longer forced to remain circular.

The results of this comparison for locally isothermal runs with same temperature profile as in the radiative model are shown in Fig. 9. The profiles are in good agreement for all three different boundary conditions. Note that the surface density in the inner disc for the viscous boundary condition is larger than with the two other boundaries. This is expected, since the imposed viscous drift velocity is smaller that the radial velocity set by the propagation of the spiral waves induced by the secondary. A similar good agreement is obtained with a radiative model, as
Fig. 6. Time- and azimuthally- averaged disc eccentricity, density and temperature profiles for our radiative disc model and various locally isothermal disc models: (i) one with the same initial aspect ratio as in the radiative model ($h = 0.05$), (ii) one with the same temperature profile as in the radiative model, and (iii) another with same sound speed profile as in the radiative model.

Fig. 7. Contours of the disc surface density for the radiative model (left panel), and the locally isothermal model with same imposed temperature profile as in the radiative case (right panel). In the radiative case, spiral waves appear smoother and more damped.
4.4. Dependence on the binary eccentricity

In paper I, we showed that the disc eccentricity $e_d$ decreases with increasing binary eccentricity, the circular case ($e_b = 0$) being the most perturbing configuration. We interpreted this result as being due to the larger size of the disc for lower values of $e_b$, and to the consequent larger number of resonant perturbations which may affect it. The eccentricity of radiative discs, however, seems to be rather insensitive to $e_b$. The outcome of the simulations at different $e_b$ is shown in the left plot of Fig. 11 where we compare the values of $e_d$ obtained for locally isothermal and radiative discs. In contrast to locally isothermal discs, the averaged $e_d$ of radiative discs is almost constant around 0.05, and it does not show a significant dependence with $e_b$. However, the azimuthally-averaged profile of the disc’s eccentricity over the radiative disc does depend on $e_b$. In Fig. 12 the radial profile of the disc’s eccentricity is shown for different values of $e_b$, ranging from 0 to 0.6. We note that the eccentricity profiles significantly differ even if the position of the star with respect to the initial reference frame is the same. All radiative runs show an increasing eccentricity profile towards large radii, whereas locally isothermal runs feature a peak in the eccentricity in the inner disc parts for most values of $h$. It should be pointed out that the above comparison is done by adopting the same initial aspect ratio for radiative and locally isothermal disc models. A different approach would be to compare disc models with same temperature or sound speed profiles, as is done in Figs. 7 and 6. But, when comparing the temperature profiles of the radiative discs, we find that they correspond to locally isothermal discs with $h \sim 0.06 - 0.07$, which anyway feature a larger eccentricity in the disc inner parts.

In the right panel of Fig. 11 we also compare the values of the outer semi-major axis $a_d$ of the ellipse best fitting the outer edge of the disc (at a density level of $\Sigma = 10^{-6}$, code units). The radiative discs extend slightly farther out compared to the corresponding locally isothermal discs, except for our fiducial binary’s eccentricity ($e_b = 0.4$), where the disc’s size is approx-
immediately equal to its isothermal counterpart. The mass loss rate for radiative discs, for different values of $e_B$, is shown in Fig. 13. It is computed with a linear fit of the time evolution of the disc mass when a steady state is reached, so it is independent from the initial disc truncation process. It shows an almost linear dependence with $e_B$ and it is related to the strong perturbation effects on the disc as the secondary star passes at pericenter. The inspection of the amount of mass stripped vs. time reveals that almost all the mass loss occurs during and after the pericenter passage of the companion while a lower amount is constantly lost through the inner border due to the disc eccentricity and viscosity. The absolute value of the mass loss is large, and it predicts a reduction in the disc mass by a factor of two in about $3 \times 10^4$ yrs for our standard case ($e_B = 0.4$). However, this value depends on the disc mass, and a simulation with the same binary parameters but an initial disc mass 10 times smaller gives a mass loss rate $\approx 3.7 \times 10^{-8} M_\odot/yr$.

4.5. Dependence on the disc mass

In Paper I, we found that for locally isothermal discs, a decrease in the disc mass had no significant impact on the disc eccentricity. Below we show that radiative discs behave differently. In Fig. 14 we compare the disc eccentricity in the nominal case, where the initial density at 1 AU is that of the MMSN, to that of a disc initially 2 and 10 times less massive. The disc eccentricity $e_d$ in a steady state is much larger for the less massive discs. This is further illustrated by the contours of the disc density for $\Sigma_0 = 0.1\Sigma_{\text{MMSN}}$ in Fig. 15. The disc appears smaller and very eccentric, particularly in its outer regions.

It is difficult to interpret this outcome on the basis of the isothermal simulations. Less massive radiative discs, like that shown in Fig. 15, have lower temperature profiles. This is presumably due to a faster cooling rate. According to our model, a lower surface density of the disc implies a smaller optical thickness that leads to a shorter cooling timescale. As a consequence, our standard model with $\Sigma_0 = 1\Sigma_{\text{MMSN}}$ has a stationary temperature profile which is equivalent to that of a locally isothermal run with $h \sim 7 - 8\%$ while less massive discs have a lower temperature profile in a steady-state with a temperature typically $3 - 4$ times less high. This translates into equivalent locally isothermal models with $h$ down to $3 - 4\%$. By inspecting Fig. 11 (top left plot) we notice that in this range of aspect ratios, the disc’s eccentricity actually changes quickly with $h$. This might explain why less massive radiative discs have different disk eccentricity. Even self–gravity will play a minor role for less massive discs and in Paper I we showed that indeed self–gravity is effective in reducing the disc eccentricity. This, however, is not the full story and the different energy equation also plays a significant role. The disc eccentricity radial profile of radiative discs, also the less massive ones (see Fig. 14), does not peak close to the star like for the isothermal discs (Fig. 1). The value of $e_d$ for radiative discs grows for larger values of $R$ as predicted by the analytical theory of Paardekooper et al. (2008). This behaviour is further illustrated by examining the Fourier components of the normalized surface density. Fig. 16 compares the Fourier components for both our standard disc with $\Sigma_0 = \Sigma_{\text{MMSN}}$, and the disc model with $\Sigma_0 = 0.1\Sigma_{\text{MMSN}}$. The $m = 1$ and $m = 2$ components are much stronger for the less massive disc, and they account for the overall higher disc eccentricity. In the standard case, the high disc density is able to damp efficiently the two Fourier components of the binary perturbations as they move toward the disc inner parts. On the other hand, these components propagate further in for less massive discs, leading to a larger value for $e_d$. However, also in the less massive disc they do not reach the inner part of the disc, like in isothermal discs, preventing the formation of an eccentric low-density region close to the central star.

According to the results presented so far, isothermal and radiative discs behave differently. Massive isothermal discs in low eccentricity binaries are expected to be eccentric for reasonable values of $h$ while radiative discs always have low eccentricity. For isothermal discs there is a weak dependence of the disc eccentricity on the disc mass (see Paper I) while, for radiative discs, this dependence is strong with less massive discs being more eccentric. Hot isothermal discs develop an inner eccentric hole while radiative discs are smooth also at the inner edge.

5. Why is disc eccentricity so important? Planetesimals!

The shape and profile of the gas disc may have a crucial role in the early stages of planetary formation, when kilometer-sized planetesimals are colliding with each other. Even when neglecting gas disc gravity, several studies have shown that the coupling between secular perturbations and gas drag, which increases impact velocities between non-equal sized bodies and can lead to accretion-hostile environments (e.g. Thébault et al. 2004, 2008).
Fig. 8. Disc eccentricity and temperature profiles (azimuthally- and time-averaged) for our standard radiative model (labelled as $Q \times 1$), and for two restart simulations with different cooling rates. The disc eccentricity is higher in the restart run with smaller cooling rate ($10^{-3} \times Q$), while it is lower in the restart simulation with larger cooling rate ($10 \times Q$).

Fig. 12. Azimuthally-averaged eccentricity profiles for radiative discs with different binary eccentricities, displayed at 100 binary orbits. Instantaneous profiles are depicted to better highlight the dependence of $e_d$ with $e_b$.

Fig. 13. Mass loss rate of radiative discs (in $M_\odot/\text{yr}$) for different values of $e_b$ obtained through a linear fit of the time evolution of the disc mass after the initial fast truncation.

Fig. 14. Azimuthally- and time-averaged profiles of the disc’s eccentricity for three different initial surface densities: $\Sigma_0 = \Sigma_{\text{MMSN}}$ (our fiducial value), $\Sigma_0 = 0.5\Sigma_{\text{MMSN}}$, and $\Sigma_0 = 0.1\Sigma_{\text{MMSN}}$. 

2009), leads to further increasing the relative velocity between planetesimals if the gas disc gets eccentric [Paardekooper et al. 2008; Xie et al. 2010]. Disc gravity might further increase impact velocities by increasing the disc eccentricity and inducing additional dynamical perturbations on planetesimals because of non-isotropic distribution of the mass within the gas disc. The asymmetric distribution of mass within a massive disc can indeed significantly perturb the orbit of planetesimals, causing large eccentricities and unphased orbits, which may possibly halt the accretion process.

To test this hypothesis we integrated the trajectories of planetesimals orbiting within 6 AU from the primary star, and we computed their orbital evolution in 2D under the action of (i) stellar gravity, (ii) gas drag, and (iii) gas disc gravity. This procedure has been implemented in previous papers, but with different assumptions like isothermal disc models, no self-gravity and different binary parameters [Paardekooper et al. 2008; Kley & Nelson 2008]. We first present in Fig. 17 the results of a test run without gas drag, for which we see that the planetesimals eccentricity grows to large values regardless of their initial location in the disc. In addition, the drift towards the inner region of the disc, which is typical of planetesimals around single stars, may be halted and even reversed. This drag-free case could probably describe the evolution of large plan-
Mary. For the 1.5 AU case, the initial strong perturbations of the sized planetesimals in a MMSN disc, and we consider 2 initial

We explore 3 values for \(\Sigma_0\): equal to \(\Sigma_0 = 0.1\Sigma_{\text{MMSN}}\), \(\Sigma_0 = 0.3\Sigma_{\text{MMSN}}\), and \(\Sigma_0 = 1.0\Sigma_{\text{MMSN}}\). The steady state eccentricities are thus lower than in the 1.5 AU case, despite being in a region where secondary perturbations are stronger. This result is in sharp contrast with what was obtained by Paardekooper et al. (2008) for the gas drag-only case, where eccentricities steadily increase with increasing semi-major axis (see Fig. 10b of that paper). It clearly illustrates the fact that the gas disc gravity, which is stronger in the inner and denser part of the system, is the dominant mechanism controlling the planetesimals’ dynamical evolution. The residual short-term variations of the eccentricity, due to the companion’s perturbations, are in contrast much larger in the 3.5 AU case than in the 1.5 AU one. The pericenter alignment is maintained at this distance even if it is less collimated, as expected since the gas density is lower.

Assessing the consequences of these dynamical behaviors on the accretion process would require estimating the distribution of impact velocities, \(v_{\text{coll}}\), among the planetesimals population. It is here not possible to directly derive \(v_{\text{coll}}\) from the values of the eccentricity because of mutual orbital phasing. The simple \(v_{\text{coll}} \propto \langle e \rangle\) relation is in this case no longer valid and should be replaced by \(v_{\text{coll}} \propto \alpha_P \langle e \rangle\), where the factor \(\alpha_P < 1\) accounts for the phasing. Unfortunately, proper velocity estimates are difficult to derive with the limited number of planetesimals (50) considered here. Simulations with at least a few thousands test particles would be necessary (e.g. Thebault et al. 2006 Paardekooper et al. 2008 Xie & Zhou 2009), but such numbers are beyond the current computing capacities for a full model including the gas disc’s gravity. However, the preliminary results displayed in Figs. 17 and 18 seem to indicate that encounter velocities are probably further increased by the action of disc gravity, and this for 2 reasons: (i) Even if a significant orbital phasing is observed (right hand plots of Fig. 18), it is nevertheless not perfect, especially in the 3.5 AU case. Even in the 1.5 AU case it is size-dependent, which increases the factor \(\alpha_P\) in any realistic planetesimal population with a size distribution. (ii) The values of the steady-state eccentricities are higher than in the gas-drain only case, especially closer to the star where velocities are relatively low in the gas-drain only runs (compare for example the upper-left graph of Fig. 18 to Fig. 10 of Paardekooper et al. 2008). These steady-state eccentricities are in addition strongly size-dependent. These two effects separately increase each of the two components, \(\alpha_P\) and \(\langle e \rangle\), controlling the value of the encounter velocities. The extent of this velocity increase, and thus its concrete effect on the accretion process, cannot be quantitatively estimated here. It will be the purpose of a forthcoming study specifically addressing this issue. We are however confident that the general tendency is for disc gravity to act against planetesimal accretion.

6. Concluding remarks

We have shown that the evolution of a circumstellar disc in close binary-star systems strongly depends on the disc’s mass.

Fig. 15. Contours of the gas density after 150 binary revolutions for a radiative disc with \(\Sigma_0 = 0.1\Sigma_{\text{MMSN}}\).

Fig. 16. \(m = 1\) and \(m = 2\) Fourier components of the normalized surface density for a radiative disc with \(\Sigma_0 = \Sigma_{\text{MMSN}}\), and a radiative disc initially ten times less massive (\(\Sigma_0 = 0.1\Sigma_{\text{MMSN}}\)).

etesimals, 100 km or bigger, which are not significantly affected by gas drag. For the disc and star parameters, we consider our standard case.

We then present the results of a full simulation including gas drag, whose expression is given by the usual formulae \(F_d = K v_{\text{rel}} v_{\text{rel}}\), where \(v_{\text{rel}}\) is the relative velocity vector of the planetesimal with respect to the gas, and the drag parameter \(K\) is equal to \(\rho_g C_d / (8 \rho_0 s)\) (Kary et al. 1993), where \(s\) is the radius of a given planetesimal, \(\rho_0\) its mass density, \(\rho_g\) the gas density of the protoplanetary disc, and \(C_d\) a dimensionless drag coefficient related to the planetesimals shape (\(\sim 0.4\) for spherical bodies). We explore 3 values for \(K\), corresponding to 10, 20 and 50 km-sized planetesimals in a MMSN disc, and we consider 2 initial locations for the planetesimals: 1.5 AU and 3.5 AU from the primary. For the 1.5 AU case, the initial strong perturbations of the eccentric disc are partly damped by gas drag but the steady state eccentricities are much larger than the forced eccentricity of the companion star (see Fig. 18 upper box). Moreover, these steady state eccentricities do strongly vary with \(K\), i.e. with planetesimal sizes: they are almost twice as large for 50 km-sized objects as for 10 km-sized ones. As for the pericenter longitudes, they rapidly converge to steady state values that only marginally vary with planetesimal size. The evolution of the 3.5 AU case is different. The eccentricities decrease towards an equilibrium value predicted by the balancing between the forced component of the companion star, gas drag damping and disc gravity (see Fig. 18 lower plots) The steady state eccentricities are thus lower than in the 1.5 AU case, despite being in a region where secondary perturbations are stronger. This result is in sharp contrast with what was obtained by Paardekooper et al. (2008) for the gas drag-only case, where eccentricities steadily increase with increasing semi-major axis (see Fig. 10b of that paper). It clearly illustrates the fact that the gas disc gravity, which is stronger in the inner and denser part of the system, is the dominant mechanism controlling the planetesimals’ dynamical evolution. The residual short-term variations of the eccentricity, due to the companion’s perturbations, are in contrast much larger in the 3.5 AU case than in the 1.5 AU one. The pericenter alignment is maintained at this distance even if it is less collimated, as expected since the gas density is lower.

Assessing the consequences of these dynamical behaviors on the accretion process would require estimating the distribution of impact velocities, \(v_{\text{coll}}\), among the planetesimals population. It is here not possible to directly derive \(v_{\text{coll}}\) from the values of the eccentricity because of mutual orbital phasing. The simple \(v_{\text{coll}} \propto \langle e \rangle\) relation is in this case no longer valid and should be replaced by \(v_{\text{coll}} \propto \alpha_P \langle e \rangle\), where the factor \(\alpha_P < 1\) accounts for the phasing. Unfortunately, proper velocity estimates are difficult to derive with the limited number of planetesimals (50) considered here. Simulations with at least a few thousands test particles would be necessary (e.g. Thebault et al. 2006 Paardekooper et al. 2008 Xie & Zhou 2009), but such numbers are beyond the current computing capacities for a full model including the gas disc’s gravity. However, the preliminary results displayed in Figs. 17 and 18 seem to indicate that encounter velocities are probably further increased by the action of disc gravity, and this for 2 reasons: (i) Even if a significant orbital phasing is observed (right hand plots of Fig. 18), it is nevertheless not perfect, especially in the 3.5 AU case. Even in the 1.5 AU case it is size-dependent, which increases the factor \(\alpha_P\) in any realistic planetesimal population with a size distribution. (ii) The values of the steady-state eccentricities are higher than in the gas-drain only case, especially closer to the star where velocities are relatively low in the gas-drain only runs (compare for example the upper-left graph of Fig. 18 to Fig. 10 of Paardekooper et al. 2008). These steady-state eccentricities are in addition strongly size-dependent. These two effects separately increase each of the two components, \(\alpha_P\) and \(\langle e \rangle\), controlling the value of the encounter velocities. The extent of this velocity increase, and thus its concrete effect on the accretion process, cannot be quantitatively estimated here. It will be the purpose of a forthcoming study specifically addressing this issue. We are however confident that the general tendency is for disc gravity to act against planetesimal accretion.

6. Concluding remarks

We have shown that the evolution of a circumstellar disc in close binary-star systems strongly depends on the disc’s mass.
and thermodynamical properties. In locally isothermal disc models, the averaged eccentricity in the disc inner parts changes dramatically with varying the disc temperatures (or, equivalently, the disc aspect ratios \( h = H/r \), as illustrated in Fig. [1] In our model, the disc eccentricity typically peaks at \( \approx 0.4 \) for \( h \approx 0.05 \). Such large eccentricities result in the formation of an internal elliptic low-density region in the disc. Radiative discs, on the other hand, have a smoother density profile, and their eccentricity takes smaller values than in locally isothermal models with same temperature profile. Radiative damping of the waves induced by the secondary companion contributes to keep the disc eccentricity to a fairly small value, which in our model typically amounts to \( \sim 0.05 \) in the disc inner parts.

In both locally isothermal and radiative discs, self-gravity causes the libration of the disc orientation at an angle \( \pi \) with respect to the apsidal line of the binary orbit. However, the libration is not coherent within the disc, and the orientation of the gas streamlines changes with radial distance.

The averaged disc eccentricity in radiative discs is almost insensitive to the binary’s eccentricity, although it should slowly increase with time as the disc mass decreases due to its viscous evolution. A disc that is 10 times less massive than our nominal disc (that is, having \( \Sigma_0 = 0.1 \Sigma_{\text{MMSN}} \)) has a large eccentricity (about 0.3 for \( e_b = 0.4 \)). This behavior is not observed in locally isothermal discs.

Based on these different behaviors, we may envision an evolutionary track for discs in binaries. In the earlier stages, the disc is massive and probably optically thick so it is well described by radiative models. Its eccentricity should therefore remain small, around 0.05, and its radial density profile be smooth. Later, because of the viscous evolution, the disc progressively loses mass. This occurs at a fast rate for binaries with large values of \( e_b \) (see Fig. [1]). If the disc is still optically thick, and the radiative model is appropriate, its eccentricity is expected to grow because of the dependence of \( e_d \) with the disc mass (see Fig. [14]). If, finally, the disc becomes optically thin, a locally isothermal equation of state may then be more appropriate. In this case, the disc eccentricity will change and depend on \( e_b \) as shown in Marzari et al. (2009). At the same time, hotter discs will develop an internal...
elliptic hole, a significant decrease in the gas density at the inner edge of the disc.

The non-symmetric distribution of mass caused by the differential libration of the disc orientation and the disc overall eccentric shape causes significant perturbations to planetesimals. Their eccentricity is driven to values significantly larger than those caused only by the secular perturbations of the binary companion. Even when gas drag is included, the perturbations by the eccentric disc entail large planetesimals eccentricities, in particular in the inner zones of the disc. It is necessary to evaluate the impact of this eccentricity on the accumulation process of planetesimals.

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\[ \log_{10}(\Sigma) \]

Radial distance (AU)

Isothermal
Radiative