Gravitational instability in binary protoplanetary discs: new constraints on giant planet formation

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ABSTRACT

We use high-resolution three-dimensional smoothed particle hydrodynamic (SPH) simulations to study the evolution of self-gravitating binary protoplanetary discs. Heating by shocks and cooling is included. We consider different orbital separations and masses of the discs. Massive discs ($M \sim 0.1$ M$_\odot$) that fragment in isolation as a result of gravitational instability develop only transient overdensities in binary systems with a separation of about 60 au. This is true even when the cooling time is significantly shorter than the orbital time because efficient heating owing to strong tidally induced spiral shocks dominates. The resulting temperatures, above 200 K, would vaporize water ice in the outer disc, posing a problem even for the other model of giant planet formation, core accretion. Light discs ($M \sim 0.01$ M$_\odot$) do not fragment but remain cold because their low self-gravity inhibits strong shocks. Core accretion would not be hampered in them. At separations of about 120 au, tidally induced spiral shocks weaken significantly and fragmentation occurs similarly to isolated systems. If disc instability is the main formation mechanism for giant planets, ongoing surveys targeting binary systems should find considerably fewer planets in systems with separations below 100 au.

Key words: accretion, accretion discs – planets and satellites: formation – planetary systems: protoplanetary discs – stars: pre-main-sequence.

1 INTRODUCTION

The recent discovery of extrasolar planets (Mayor & Queloz 1995) has ignited renewed interest in models of giant planet formation. In the conventional model, core accretion (Lissauer 1993), it is difficult to grow planets of several Jupiter masses in less than a few million years, the typical disc lifetime estimated from observations (Haisch, Lada & Lada 2001). This problem is exacerbated by the fast inward migration rates produced by the disc–planet interaction as well as by the low accretion rates ensuing once a planet is big enough to open a gap (Nelson et al. 2000; Bate et al. 2003; Nelson & Benz 2003). Consequently, the disc instability model, in which giant planets arise in only a few disc orbital times (less than a thousand years) from the fragmentation of a massive, gravitationally unstable disc (Boss 1997, 2002; Pickett et al. 2000, 2003) has gained new attention (Mayer et al. 2002; Rice et al. 2003a,b).

The majority of solar-type stars in the Galaxy belong to double or multiple stellar systems (Duquennoy & Mayor 1991; Eggenberger, Udry & Mayor 2004). Binaries can be formed by the fragmentation of a single bar-unstable molecular cloud core into two distinct

objects (Boss 1986; Burkert, Bate & Bodenheimer 1997), from the collision of two dense cores in a giant molecular cloud (Whitworth et al. 1995) or owing to the capture of neighbouring stars in dense star-forming regions (Bate et al. 2002a). Fragmentation is usually considered the main channel of binary formation and can take place in any type of environment (Horton, Bate & Bonnell 2001). Two star–disc systems should form if the initial separation is larger than 10 au, while at smaller separations a circumbinary disc can arise (Bate 2000). Radial velocity surveys have shown that planets exist in some binary or multiple stellar systems where the stars have separations from 20 to several thousand au (Eggenberger et al. 2004). Although the samples are still small (20 out of the 120 known extrasolar planets are in binary systems), attempts have been made to compare properties of planets in single and multiple stellar systems (Patience et al. 2002; Udry et al. 2004). The first adaptive optics surveys designed to quantify the relative frequency of planets in single and multiple systems are just starting (Udry et al. 2004). These surveys could offer a new way to test theories of giant planet formation, provided that different models yield different predictions as for the effect of a stellar companion.

So far, two works have studied giant planet formation in binary systems. Both focused on the disc instability model and reached opposite conclusions. Nelson (2000, hereafter N00) performed

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two-dimensional SPH simulations of protoplanetary discs that did not form protoplanets in isolation due to quite long cooling times, and found fragmentation to be even more unlikely in the presence of another disc with identical mass at a mean separation less than 100 au. In fact, the discs were achieving a high stability owing to internal disc heating. Boss (1998, 2003) performed three-dimensional (3D) grid calculations of a disc interacting with a stellar companion closer than 100 au and found that giant planet formation by disc instability can be enhanced by the tidal perturbation.

In this paper we revisit giant plant formation in a binary system using high-resolution 3D SPH simulations. In Mayer et al. (2002, 2004b, hereafter MA04), we have shown that high resolution is required to follow the fragmentation of a massive protoplanetary disc into gravitationally bound clumps. Fragmentation requires the disc to cool on a time-scale comparable to or shorter than the disc orbital time (Mayer et al. 2004a; Rice et al. 2003a,b). Here we consider binary systems of protoplanetary discs which mostly fragment in isolation (Mayer et al. 2004a) and investigate whether the tides raised by the companion enhance or suppress fragmentation.

2 MODELS AND SIMULATIONS

The initial conditions comprise two protoplanetary discs, usually of equal mass, orbiting around each other and a central star. We restrict our investigation to coplanar discs corotating with their orbital motion as expected from fragmentation of a cloud core (Bate 2000). Table 1 lists the most important parameters of the simulations. The orbital separation of the discs is in the range 60–120 au (eccentricity $e = 0.14$), corresponding to some of the smallest separations among binary systems with detected giant planets (Eggenberger et al. 2004). Each of them is represented by 2×10^5 equal mass SPH particles with a fixed gravitational softening of 0.06 au, while the central star has a softening of 2 au (see MA04). We used discs that were slowly grown up to the desired mass in order to achieve a quiet start and remove spurious amplification of initial seed perturbations due to sharp edges. This is important to avoid overestimating the effects of gravitational instability, especially in the most massive, strongly self-gravitating among our discs. The starting model

extends roughly from 4 to 20 au, its density distribution being exponentially truncated at these characteristic inner and outer radii. As the disc grows, some redistribution of the mass occurs and its edges are smoothed out. The description of this type of set-up as well as of the temperature and surface density profiles of the discs can be found in MA04. Discs initially extend out to a radius somewhat larger than the tidal radius imposed by their binary orbit and therefore will shrink in size as they cross pericentre. In Section 4 we discuss how sensitive our results are to such initial readjustment of the disc structure as well as motivating our choice for the initial set-up.

Models from as light as the minimum mass solar nebula (0.012 $M_{\odot}$) to as massive as the heaviest among T Tauri discs (0.1 $M_{\odot}$; see D'Alessio, Calvet & Hartmann 2001) are considered. A gaseous Keplerian disc is stable against local axisymmetric perturbations if $Q > 1$, $Q = \Omega c_s / \pi G \Sigma$, where Ω is the angular frequency, c_s is the sound speed, G is the gravitational constant and Σ is the surface density of the disc. The shape of the profile of the Toomre Q parameter is the same in all discs, while its normalization depends on the mass of the disc. Initially the minimum Q parameter, $Q_{\min} \sim 1.4$ or higher (see Table 1), is at the disc edge, where the temperature falls to 65 K.

The radiative cooling time is proportional to the local orbital time, as in Rice et al. (2003a). Cooling is switched off inside 5 au in order to maintain temperatures high enough to be comparable to those in protosolar nebula models (e.g. Boss 1998), and in regions reaching a density above 10^{-10} g cm^{-3} to account for the local high opacity; indeed, according to the simulations of Boss (2002) with flux-limited diffusion the temperature of the gas evolves nearly adiabatically above such densities. We consider cooling times going from 0.3 to 1.5 the local orbital time. The jury is still out on whether the cooling times adopted here are credible or excessively short, but recent calculations by Boss (2002) and Johnson & Gammie (2003), which use different approximate treatments of radiative transfer, do find cooling times of this magnitude through a combination of radiative losses and convection (but see Mejia et al. 2003; Mejia 2004). Our aim here is just to compare the outcomes of isolated and binary systems for the same choice of the cooling time.

Table 1. Parameters of the simulations. Column 1, name of run; column 2, disc mass (A) ($M_{\odot}$); column 3, disc mass (B) ($M_{\odot}$); column 4, star mass (A) ($M_{\odot}$); column 5, star mass (B) ($M_{\odot}$); column 6, semimajor axis of the orbit (au); column 7, initial minimum Toomre Q parameter; column 8, cooling time (in units of the orbital time); column 9, γ; column 10, whether the discs in a binary fragment or not ('Tr' denotes transient clumps); column 11, whether the isolated discs fragment or not ('Tr' denotes transient clumps).

| Model	M_{dA}	M_{dB}	M_{*A}	$M_{*,B}$	a	$Q_{\min}$	t_{cool}	γ	Clumps (bin)	Clumps (is)
RB1a	0.1	0.1	1	1	58	1.4	0.3	1.4	No	Yes
RB1b	0.1	0.1	1	1	58	1.4	0.5	1,4	No	Yes
RB1c	0.1	0.1	1	1	58	1.4	1	1.4	No	Yes
RB1d	0.1	0.1	1	1	58	1.4	1.5	1.4	No	Yes
RB1e	0.1	0.1	1	1	58	1.4	0.3	1.66	No	Yes
RB1f	0.1	0.1	1	1	58	1.4	1	1.66	No	Yes
RB2a	0.05	0.05	1	1	58	2.8	0.5	1.4	Tr	No
RB2b	0.05	0.05	1	1	58	2.8	0.3	1.4	Yes	No
RB3a	0.08	0.08	1	1	58	1.75	0.5	1.4	No	Yes
RB3b	0.08	0.08	1	1	58	1.75	0.3	1.4	Yes	Yes
RB4a	0.012	0.012	1	1	58	11	0.3	1.4	No	No
RB4b	0.012	0.012	1	1	58	11	1.5	1.4	No	No
RBm2	0.1	0.05	1	0.5	58	1.4 (2)	0.3	1.4	Tr	Yes
RBwa	0.1	0.1	1	1	116	1.4	0.3	1.4	Yes	Yes
RBwb	0.1	0.1	1	1	116	1.4	0.5	1.4	Yes	Yes
RBwc	0.1	0.1	1	1	116	1.4	1	1.4	Tr	Yes
RBwd	0.1	0.1	1	1	116	1.4	0.5	1.66	Tr	Yes

Heating by compressions and shocks is included in the simulations. We adopt $\gamma = 7/5$, appropriate for molecular hydrogen, or $\gamma = 5/3$. Shocks are modelled using the standard Monaghan viscosity with $\alpha = 1$ and $\beta = 2$ plus the Balsara correction term to suppress shear viscosity (see Wadsley et al. 2003). The analysis of the runs with isolated discs is carried out elsewhere (Mayer et al. 2004a; Mayer et al., in preparation). Here we only report on whether the isolated discs fragment or not (see Table 1).

3 RESULTS

We begin by describing the outcome of the runs with the smallest orbital separations, corresponding to $a = 58$ au (see Table 1). Fig. 1 shows the evolution of the discs in one such simulation. Disc models are typically followed for two orbits. A binary orbit corresponds to about 288 yr, or, equivalently, 10 disc orbital times at 10 au from the disc centre. Two calculations were extended further for two more orbits. Discs start at apocentre and develop a strong two-armed spiral pattern after crossing pericentre. The last stable streamline for each discs is at about 14 au from the centre; therefore, gas outside this radius will be transferred from disc to disc or will be ejected and become unbound if it acquires enough energy. At the same time, mass is driven inwards by the strong non-axisymmetric torques acting inside the discs as self-gravity amplifies the tidal perturbation. Over two orbits, each disc loses around 10 per cent of its mass while its mass distribution becomes more concentrated. In models that do not fragment (see Table 1) transient, moderately strong high-order spiral arms continue to develop at subsequent pericentric passages, but Q_{min} always remains above the threshold for stability (see Fig. 2). In the few models that fragment, Q_{min} drops below 1 (see Fig. 2) already halfway along the first orbit and clumps appear on the disc side which is further from the other disc, along a strong unwinding
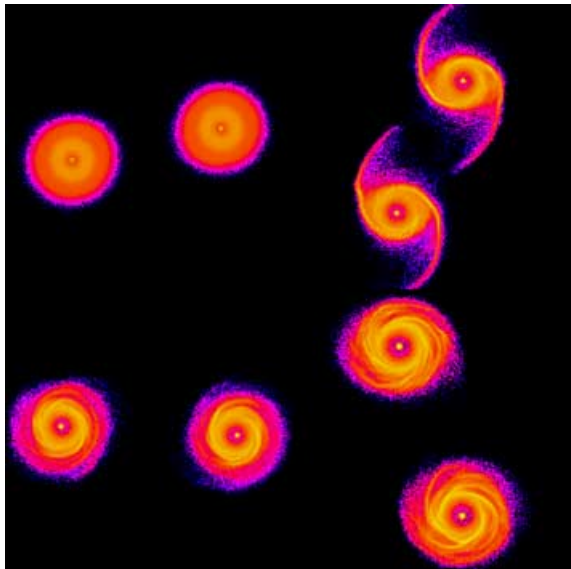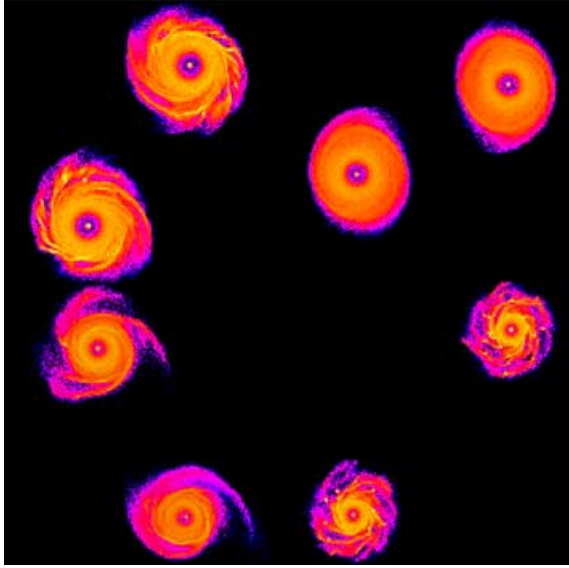

Figure 1. Colour-coded projected gas density in the plane of the binary orbit (brighter colours correspond to higher densities) for run RB1a. Densities between 10^{-15} and 10^{-8} g cm^{-3} are shown. Boxes are about 100 au on a side. From top-left to bottom-right, snapshots at 16 yr (shortly after the beginning), 150 yr (after first pericentre passage), 300 yr and 450 yr (close to the second pericentre passage) are shown. See text for details. Note the overdensities along the spiral arms at 150 yr; they are rapidly quenched by the high pressure along the arms.
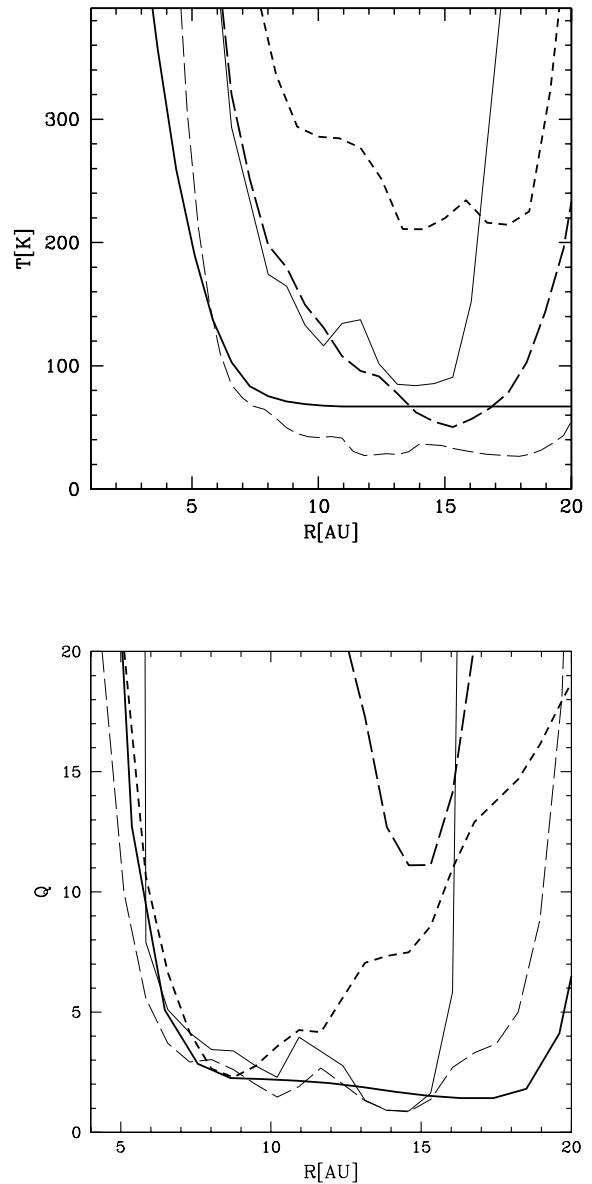
Figure 2. Azimuthally averaged mid-plane temperature (top) and Q (bottom) profiles at the time of maximum amplitude of the overdensities (at between 120 and 200 yr depending on the model). Discs with outer temperatures above 100 K are too hot to fragment, as shown by the high values of Q. We show the initial conditions (thick solid line, Q profile normalized as in the RB1 runs), RB1a (thick short-dashed line), isolated disc run with model used in RB1a (thin long-dashed line), RBwb (thin solid line) and RB4b (thick long-dashed line).

trailing spiral arm. On the other side of the disc, the developing overdensities are destroyed as tides tear them apart.
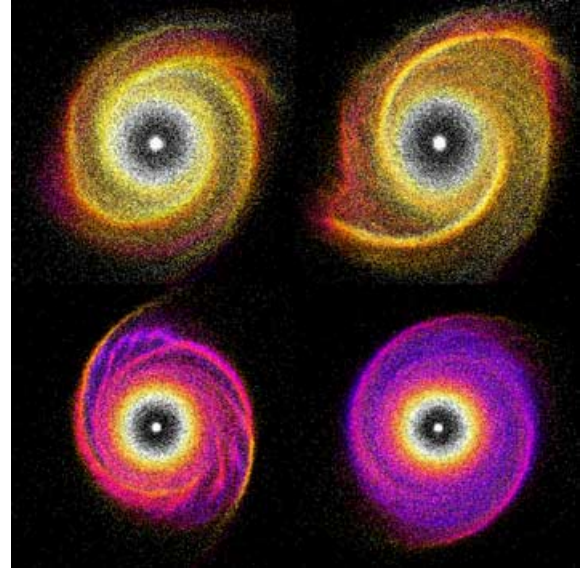
We can identify three regimes as for the disc response to the tidal perturbation, with disc mass being the key parameter. Our lightest discs (RB4 runs in Table 1), always stable in isolation, develop a clear two-armed spiral pattern but their self-gravity is too low to amplify the mode and sustain the instability (Fig. 3). This spiral mode simply evolves periodically with the orbit, strengthening at pericentre and weakening at apocentre. In discs at the high-mass end (RB1 runs), a much stronger spiral pattern develops after the first pericentre passage (see Fig. 1) associated with intense compressional heating. These spiral shocks (see Fig. 4) lead to an increase of the

Figure 3. Colour-coded projected gas density in the plane of the binary orbit (see Fig. 1). We show selected snapshots from runs employing discs with different masses. From top-left to bottom-right, run RB2b, run RB4b, run RBm2 and run RBwb are shown at 200, 200, 140 and 160 yr, respectively (we have chosen time frames corresponding to the maximum growth of the overdense regions). Boxes are 100 au (top), 130 au (bottom-left) and 200 au (bottom-right). The clumps seen in run RBm2 are transient, while many of those in the runs RB2b and RBwb survive and contract to densities 10^4 times higher.

Figure 4. Colour-coded temperature map of one of the two discs in four different runs near the second pericentre passage. Brighter colours are for higher temperatures, and the scale is logarithmic and extends from 20 to 400 K. From top-left to bottom-right, runs RB1c, Rb1a, RB2a and Rb4a are shown. Boxes are 20 au on a side. The highest temperatures always occur along spiral shocks and such temperatures are clearly lower for runs using binary systems of lower-mass discs. It is also evident that shorter cooling times (upper-right panel versus upper-left panel) allow the spiral modes to grow stronger.

temperature of the outer disc by nearly a factor of 3. As a result, Q rises rapidly above 2 (e.g. run RB1a in Fig. 2) and fragmentation is inhibited despite the fact that these discs fragment in isolation across the whole range of cooling times considered here (see Mayer et al. 2004a). Fig. 2 shows the azimuthally averaged temperature profiles of the discs. The spiral arms fade away considerably during the second orbit (see Fig. 1) because of disc heating, especially for longer cooling times. The suppression of fragmentation by tidally induced disc heating was also advocated by N00; although in such a paper the details of the heating mechanisms are not indicated, the largest temperatures in those simulations are also found along spiral shocks. In the intermediate mass regime, $M_d = 0.05$, $0.08\,M_\odot$, self-gravity is non-negligible and spiral instabilities are visibly amplified, but shock heating is mild enough for non-axisymmetric features to last longer and build up more pronounced overdensities (Fig. 3). These discs can fragment for the shortest, probably unrealistic, cooling times despite the fact that they can avoid fragmentation in isolation. Interestingly, Boss (1998) also found enhanced fragmentation in locally isothermal simulations of tidally perturbed discs with $M_d = 0.05\,M_\odot$. However, in isothermal simulations one expects fragmentation to always be enhanced in a binary system because in the absence of any heating mechanism acting in the disc any perturbation should simply grow stronger and faster due to the tidal disturbance.

The temperature along spiral shocks is higher than the mean temperature of the disc at the same distance from the centre, while the opposite holds for gas between the spirals. Fig. 4 shows temperature maps of one of the discs in four different simulations near pericentre passage. It is clear that while quite a sharp temperature gradient is seen in all simulations close to the spiral shocks, it is only in the most massive discs that the temperature rises well above 300 K along the arms. For fragmentation to occur (i.e. for Q to approach 1) at such

high temperatures, the required surface density would be an order of magnitude higher than that measured along the arms. We also find that the outcome depends slightly on the how stiff is the equation of state for the same initial conditions and cooling times. In fact, runs employing $\gamma = 5/3$ fragment less easily than runs using $\gamma = 7/5$ (see Table 1, compare runs RBwb and RBwd). This can be traced back to the fact that stronger compressional heating occurs with a stiffer equation of state, or, in other words, the 'net' thermal energy losses are smaller.

We can ask how realistic are the temperatures seen in our simulations. The high temperatures developing in the outer parts of the most massive disc models are comparable to those in the simulations of N00. This is just incidental because cooling times in those discs were different from those adopted in this paper. In N00, discs cool via thermal blackbody emission at the photosphere. A rough estimate of the radiative cooling time in the discs simulated in N00 can be obtained by dividing the total thermal energy in a vertical column of the disc by the rate at which energy is lost from the surface of the column by means of blackbody radiation, $t_{cool} = \Sigma U / (\sigma T_e^4)$, where Σ is the mass surface density, U is the specific internal energy and σ is the Stefan–Boltzmann constant. Calculating this time-scale at 10 au from the centre for the N00 discs after the first pericentric passage (at this distance the Toomre parameter reaches a minimum, $Q \sim 4$, and we have $T \sim 100$ K and $\Sigma \sim 500$ g cm^{-2}) we obtain $t_{cool} \sim 70$ yr, which corresponds to nearly $2T_{orb}$ at such radius. For the state before pericentric passage, instead, the cooling time is much longer, $t_{cool} \sim 4 \times 10^4$ yr (mostly because the disc is an order of magnitude colder). Such cooling times are always longer than those needed to obtain fragmentation in a binary system according to our results.

Ultimately the net energy losses near the disc mid-plane are those that really matter in comparing the evolution of different disc

simulations. Such 'net' cooling is the ratio between heating by compression plus artificial viscosity, and radiative cooling, and is thus a complicated function of both space and time. It is unfortunately not straightforward to obtain this from either N00 or our runs. The self-gravity of the discs in N00, and therefore the amount of heat generated by means of spiral shocks, should be comparable to those in our intermediate mass discs (runs RB2a and RB2b), both having $M_d = 0.05 \, M_\odot$. We showed that these can fragment, but only for $t_{cool} = 0.3 T_{orb}$. However, we also note that Q rises from 1.5 to 3–4 in one orbit in N00. This variation in Q is comparable to what we see in our simulation on the first orbit for the massive discs (e.g. RB1a), which suffer much stronger shock heating, whereas our intermediate mass discs show a less pronounced increase in Q, which rises only from 1.8 to 2.5. Such a difference is likely due to the fact that cooling times are shorter in our simulations relative to N00, so that a more massive disc is needed to generate enough heating through spiral shocks and increase Q, as in N00.

N00 calculated the corresponding radiation flux at far-infrared and radio wavelengths (from 870 μm to 1.3 cm), assuming that the disc emits like a blackbody at the photospheric temperature, and found it to be slightly lower than that of a prototype young binary protostellar disc system, L1551 IRS 5 (Bachiller, Tafalla & Cernichiaro 1994). Therefore, the temperatures seen in our simulations are probably a conservative estimate of those occurring in real binary systems.

Temperature in excess of 200 K, such as those obtained here (Fig. 2) for the most massive disc models, would be enough to vaporize water ice. The latter should contribute almost half of the mass of solid material in a protoplanetary disc (Pollack et al. 1994), and are therefore a fundamental building block of large solid grains and, ultimately, of planetesimals. A reduced growth of rocky planetary embryos could result, and therefore giant planet formation by core accretion could also be less likely in such binary systems relative to isolated systems. Light or intermediate mass discs, instead, maintain outer disc temperatures lower than 100 K between 10 and 20 au (Fig. 2) posing no problem for core accretion. N00 first realized the implications that disc heating in binaries has on core accretion but simply concluded that the growth of planetesimals would be inhibited because he had not explored a range of disc masses.

We also simulated the interaction between two disc+star systems with masses differing by a factor of 2 (run Rbm2; see Fig. 3), this being a quite common configuration among binaries. The most massive disc in the system ($0.1 \, M_\odot$), which never fragmented when interacting with an equally massive disc (e.g. runs RB1a, RB1b and RB1c), now produces two clumps of roughly one Jupiter mass. Yet these clumps are quickly dissolved as the pressure still overcomes self-gravity. The lighter disc soon develops high-order spiral modes. Although the temperature remains quite low (Q drops close to unity locally), nascent overdensities are sheared away before they can fragment owing to the strong tidal field of the more massive companion. We emphasize that a $0.1\text{-}M_\odot$, disc does not produce permanent clumps either in a binary with an equal mass disc (RB1a) or in a binary with a disc 50 per cent lighter (RBm2). Conversely, in run RB3b, a slightly lighter disc (see Table 1) does give rise to long-lived clumps while interacting with a system of identical mass (all these runs employ the same cooling times). This suggests there is some critical value of the disc self-gravity above which tidally induced spiral shocks become too strong and wipe out any overdensity owing to the heat they generate.

Among the few known binary systems with planets, the majority have stars with a projected separation above 100 au. In runs RBw(a,b,c) we evolved the massive disc models on orbits with a larger semimajor axis, $a = 116$ au. In all these runs, we witnessed fragmentation (Fig. 3), although in the run having the longest cooling time (RBwc), clumps did not survive for more than $\sim$ three disc orbital times. We conclude that at these larger orbital separations disc instability proceeds similarly to the case of isolated discs because tidal forces are considerably weaker. Moreover, the temperatures at such separations are low enough (Fig. 2) to guarantee the survival of ice grains.

4 SUMMARY AND DISCUSSION

We have shown that fragmentation by disc instability is suppressed in binary systems harbouring massive protoplanetary discs with orbital separations around 60 au. This occurs because shock heating overwhelms cooling and damps any overdensity, even for cooling times shorter than the orbital time; because models including radiative transfer (e.g. Boss 2002) predict cooling times at the high end of those considered here for high mass discs, our result has to be general. Shock heating occurs in the spiral arms, which reach a much greater amplitude relative to spiral arms in isolated discs because of the tidal forcing. Such shocks are particularly strong in the most massive discs because their higher self-gravity amplifies the spiral arms more effectively.

The role of shock heating in disc instability is widely recognized as crucial (Pickett et al. 2000, 2003). In systems with a separation of 120 au, disc temperatures remain quite low and fragmentation proceeds more similarly to the isolated discs. The high temperatures (>200 K) developing in massive binary disc systems with separations less than 60 au make it hard to form giant planets even by disc core accretion. Intermediate-mass systems are those in which both mechanisms are possible if cooling is very efficient whereas in binary discs with small masses, comparable to that of the minimum mass solar nebula model, core accretion is the only viable mechanism. Models of the core accretion mechanism used to require a disc three to four times more massive than the minimum solar nebula in order to form Jupiter in less than 10 million years (Lissauer 1993). However, more recent models that account for orbital migration of rocky cores find formation time-scales of a few million years even in a minimum mass solar nebula because the cores feed more efficiently with planetesimals as they migrate in the disc (Rice & Armitage 2003; Alibert, Mordasini & Benz 2004). If core accretion can take place in light discs, then giant planets could form regardless of the presence or distance of a companion. This suggests that binarity can be used to probe planet formation models. If the new surveys aimed at quantifying the relative number of giant planets in single and binary systems find no trend with binary separation, disc instability cannot be the main formation mechanism. The opposite might be true if such a trend emerges.
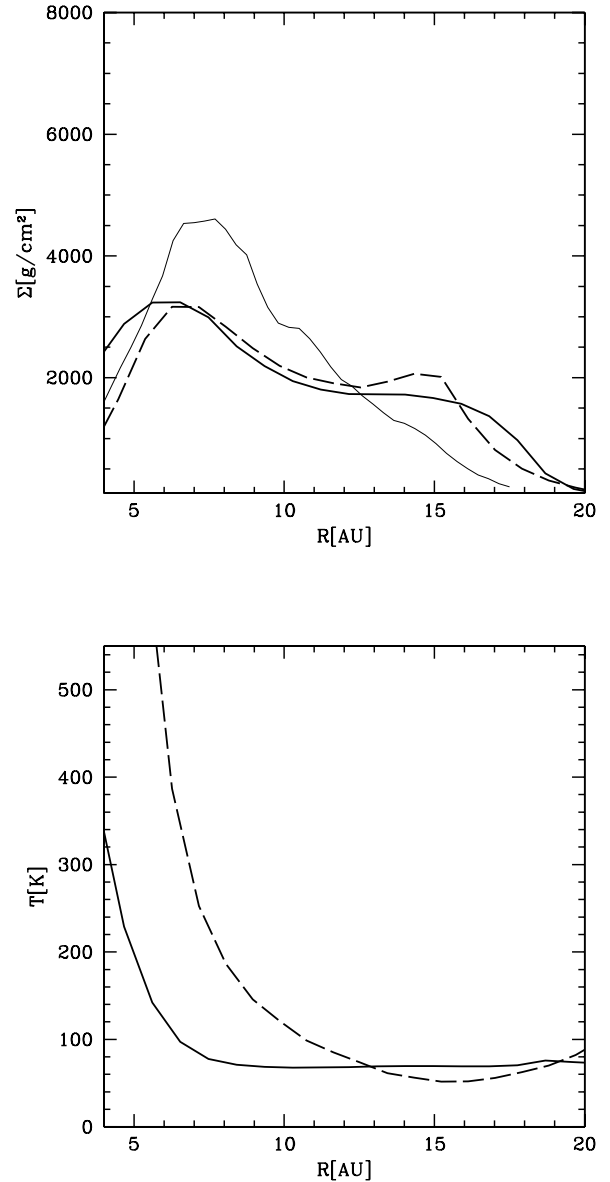
One concern is that we might be overestimating the effect of the tidal field because the disc models are first initialized in isolation and then suddenly placed on orbits whose small pericentre forces a rapid reduction of their truncation radius as well as causing mass transfer that might heat the other disc at its edge. Motivated by this, we repeated run RB1a without self-gravity for the first two orbits, and then switched self-gravity on during the third orbit. This way, the disc profile has time to adjust. The spiral arms tidally induced on the third orbit are indeed slightly weaker than those in the standard run, transient localized overdensities are apparent that were not present before, but no gravitationally bound clumps occur, and the outer disc temperature after one orbit ($\lesssim 300$ K) is comparable to that in the original run (see Fig. 5). The final surface density profiles of the discs in the two runs are also quite similar. Mass redistribution
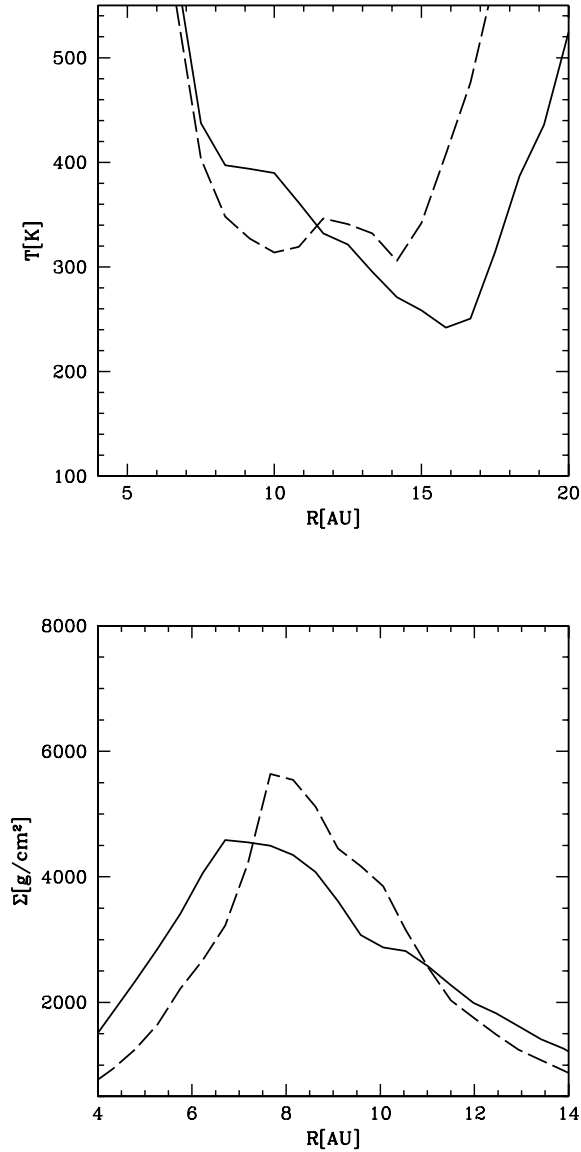
Figure 5. Azimuthally averaged mid-plane temperature (top) and surface density (bottom) profiles for run RB1a (solid line) and for a run in which the same disc model (with the same cooling time) was evolved without self-gravity for the first binary orbit (dashed line). The profiles are computed after two orbits in both cases.

Figure 6. Azimuthally averaged mid-plane temperature (bottom) and surface density (top) profiles of a disc with mass $M_d = 0.01$ at $t = 0$ (solid line) and for its evolved state after being run without self-gravity for two orbits around an equally massive companion (dashed line). See Section 4 for the description of such a test run. The cooling time is chosen as in run RB1a. In the bottom panel, the surface density profile of run RB1a, already shown in Fig. 4, is repeated (thin solid line). We recall that this run employed the same binary disc system of the test run but of course included self-gravity. Clearly the effect of self-gravity on the evolution of the disc profile is more important than that simply due to the torques from the companion.

due to gravitational torques leads to a profile which cannot be described by a single power law, has a remarkable density peak close to 7–8 au and is steeper than r^{-2} outside such a radius. This kind of restructuring is indeed recurrent in all of our runs.

The question arises of how much of such restructuring is due to self-gravity and how much to tidal torques induced by the companion. Fig. 6 shows the evolution of the disc surface density profile of the model used in the test run both with and without self-gravity. Clearly some mass transport has occurred even without self-gravity. Such mass transport is the result of tidal torques induced by the gravitational interaction with the companion. These tidal torques produce a two-armed spiral mode in the otherwise passive disc. The disc becomes truncated to a smaller radius and more mass piles up in the inner few astronomical units as the arms redistribute angular momentum. The mass inflow produces compressional heating, raising the temperature of the disc inside 10 au. Exchange of mass between

the two discs occurs but their mass varies by only ∼10 per cent, as we have already mentioned. Despite the fact that the tidal interaction modifies the disc structure irrespective of disc self-gravity, Fig. 6 shows that such changes are really moderate compared to those occurring when self-gravity is included. We note that when self-gravity is included the density peak that develops is almost a factor of 2–3 higher than the maximum density in similar disc models evolved in isolation (MA04). This statement applies to all of our runs. The larger density may explain why models with masses lower than 0.1 $M_{\odot}$ become more prone to fragmentation when

perturbed by a binary companion; evidently, in these lighter discs the heating from shocks is not enough to compensate for such a large density increase. Because discs are truncated within 15 au, when clumps form they do so within such a radius, typically between 8 and 12 au. The locations where they form correspond to the location of the density maximum and are slightly closer to the star compared to those of clumps in the isolated discs studied by MA04. In fact, in isolation gravitationally unstable discs typically develop a density maximum between 12 and 15 au, and this is where Q drops below 1 and fragmentation occurs (MA04). We can conclude that in all our simulations the restructuring of the disc results from a combination of tidal torques and intrinsic self-gravity. Because in the early stages protoplanetary discs should be massive enough to be self-gravitating (Yorke & Bodenheimer 1999), it seems that this profound restructuring driven by the two simultaneous effects will likely occur in binary systems.

We did not start from discs truncated at a radius corresponding to the last stable streamline imposed by the tidal field of the companion, but we let the truncation arise spontaneously during the simulation. This choice is motivated by simulations of core collapse into a binary or multiple system. Simulations that follow the fragmentation of turbulent molecular clouds show that star–disc systems arise from localized collapse of several neighbouring cores (Bate et al. 2002b). The collapse of the individual cores occurs on a time-scale much smaller than the average collapse time-scale of the larger star-forming region and the resulting systems undergo several tidal interactions with bound or unbound companions since their birth. In other words, discs will not have time to slowly adjust to such an extremely dynamic environment by the time they become gravitationally unstable. A short collapse time of cores is suggested also by observations. Two examples are the observations that prestellar cores have large enhancements in column densities and that molecular abundances in them are consistent with a rapid collapse (Aikawa 2004). SPH simulations of the collapse of an individual core, currently being carried out by the authors using a variable mass resolution to achieve unprecedented detail (Mayer et al., in preparation), also show the formation of binary star–disc systems which undergo a strong tidal interaction since their birth. These systems result from the violent fragmentation of a bar-unstable prestellar core. Mass transfer and strong tidally induced spiral structure are observed for several orbital times. Therefore, strongly tidally interacting discs whose structure, as in our simulations, is modified by the tidal torques simultaneously with the development of gravitational instability, are consistent with the results of simulations of protoplanetary disc formation. Moreover, we recall that massive discs, larger than the minimum protosolar nebula (0.01–0.02 $M_\odot$), are required for gravitational instability to develop at all, and such high masses were typical of the early, probably most dynamic stages of the evolution of the star–disc system, when the mass of the disc was comparable or just below the mass of the central star. Therefore, we believe our set-up is appropriate to study giant planet formation by disc instability. Of course, one may wonder if there is any meaning in choosing one particular initial temperature or density profile of the discs within the dynamic scenario that we are advocating. The answer to this question is unfortunately beyond the scopes of this paper and will be sought in our new simulations in which both the formation and the evolution of the discs are modelled.

The low orbital eccentricity in our runs implies that the tidal perturbation is nearly continuous in amplitude. This could favour high temperatures because each disc suffers nearly constant compressional heating. Although N00 did not find any remarkable difference in systems with orbital eccentricities varying by a factor of

3, impulsive tidal perturbations, caused for example by a close fly-by of a star or brown dwarf, which would be common in highly dynamical star formation scenarios (e.g. Bate, Bonnell & Bromm 2002a,b), could produce a different outcome. A strong short-lived shock would occur in this case but, over time, compressional heating would be much lower. We will investigate such situations in a forthcoming paper. We will also consider a larger variety of initial orbital configurations, for example non-coplanar discs possibly resulting from a capture event. A study of the geometry and relative orbits of debris discs around young binaries will be necessary to find out to what extent the simple orbital configurations used in this paper are really representative.

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