On the evolution of giant protoplanets forming in circumbinary discs

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ABSTRACT

We present the results of hydrodynamic simulations of Jovian mass protoplanets that form in circumbinary discs. The simulations follow the orbital evolution of the binary plus protoplanet system acting under their mutual gravitational forces, and forces exerted by the viscous circumbinary disc. The evolution involves the clearing of the inner circumbinary disc initially, so that the binary plus protoplanet system orbits within a low density cavity. Continued interaction between disc and protoplanet causes inward migration of the planet towards the inner binary. Subsequent evolution can take three distinct paths: (*i*) The protoplanet enters the 4:1 mean motion resonance with the binary, but is gravitationally scattered through a close encounter with the secondary star; (*ii*) The protoplanet enters the 4:1 mean motion resonance, the resonance breaks, and the planet remains in a stable orbit just outside the resonance; (*iii*) When the binary has initial eccentricity $e_{bin} \geq 0.2$, the disc becomes eccentric, leading to a stalling of the planet migration, and the formation of a stable circumbinary planet.

These results have implications for a number of issues in the study of extrasolar planets. The ejection of protoplanets in close binary systems provides a source of 'free–floating planets', which have been discovered recently. The formation of a large, tidally truncated cavity may provide an observational signature of circumbinary planets during formation. The existence of protoplanets orbiting stably just outside a mean motion resonance (4:1) in the simulations indicate that such sites may harbour planets in binary star systems, and these could potentially be observed. Finally, the formation of stable circumbinary planets in eccentric binary systems indicates that circumbinary planets may not be uncommon.

Key words: accretion, accretion disks – stars: binaries: close – stars: planetary systems: formation – stars: planetary systems: protoplanetary discs

1 INTRODUCTION

Since the discovery of the first extrasolar giant planet around 51 Peg (Mayor & Queloz 1995; Marcy et al. 1996), over one hundred planetary detections have been announced (see for example the websites: *www.obspm.fr/encycl/encycl.html* and *exoplanets.org*). Their masses range between $0.14 \leq m_p \leq 17$ Jupiter masses, and the semimajor axes are in the range $0.038 \leq a_p \leq 5.9$ AU (Marcy, Cochran, & Mayor 1999; Vogt et al. 2002; Santos et al. 2003) . The majority of the planets orbit around single solar–type stars, but there have been also been detections in binary systems [e.g. γ Cephei (Cochran et al. 2002; Hatzes et al. 2003), 16 Cygni B (Cochran et al. 1997)].

Most solar–type stars in the field appear to be members of binary systems (Duquennoy & Mayor 1991). The period distribution of binaries in the solar neighbourhood follows a near–Gaussian profile, peaking at a period $P \sim 100$ yr, but with a significant number of systems having periods going down to a few days. It seems probable that planets could be found orbiting stably in a number of these systems. For the longer period systems they may be orbiting around one member of the binary. In the shorter period cases they could orbit stably around both stars (i.e. circumbinary planets).

The majority of field stars appear to be in binary or multiple systems, and the same applies to T Tauri stars (Ghez, Neugebauer & Matthews 1993; Leinert et al. 1993; Mathieu et al. 2000), whose discs are thought to be the sites of planet formation. The majority of T Tauri stars in binary systems have sufficiently large separations that it is expected that each component will have its own circumstellar disc. For shorter period systems, however, one expects the existence of a circumbinary disc, a number of which have been observed (e.g. DQ Tau, AK Sco, UZ Tau, GW Ori, GG Tau).

The confirmed existence of planets in binary systems, combined with the fact that binary systems appear to be common, and to be present during the T Tauri phase of protostellar evolution, means that it is of great interest to explore how stellar multiplicity affects planet formation, and post-formation planetary orbital evolution, including formation in circumbinary discs. Previous work examined the stability of planetary orbits in binary systems using N–body simulations (Dvorak 1986; Holman & Wiegert 1999). This work showed that there is a critical ratio of planetary to binary semimajor axis for stability, depending on the binary mass ratio, q_{bin}, and eccentricity e_{bin}. A recent paper (Quintana et al. 2002) explored the late stages of terrestrial planet formation in the α Centauri system. This work concluded that the binary companion can help speed up planetary accumumlation by stirring up the planetary embryos, thus increasing the collision rate.

Recent work by Kley & Burkert (2000) examined the effect that an external binary companion can have on the migration and mass accretion of a giant protoplanet forming in a circumstellar disc. They found that for sufficiently close companions, both the mass accretion rate and the orbital migration rate could be increased above that expected for protoplanets forming around single stars.

In this work we explore the evolution of Jovian mass protoplanets forming in *circumbinary* discs using hydrodynamic simulations of a binary star plus protoplanet system interacting with a viscous protostellar disc. The models apply primarily to binaries with orbital periods of ~ 1 yr, and semimajor axes of ~ 1 AU that have protoplanets forming at a radius of a few AU in the circumbinary disc, although the results can be scaled to apply to different parameters. Previous work has shown that a giant protoplanet embedded in a disc around a single star undergoes inward migration driven by the viscous evolution of the disc (Lin & Papaloizou 1986; Nelson et al. 2000), and this provides an explanation for the existence of the so–called 'hot–Jupiters'. Here we are interested in how this process is affected if the central star is replaced by a close binary system. In particular we wish to explore the orbital stability of protoplanets that migrate towards the central binary. The situation here is similar to that found in two–planet systems. Disc induced differential migration can induce resonant locking in two–planet systems (Snellgrove, Papaloizou, & Nelson 2001), and this model has been used to explain the resonant system GJ876 (Marcy et al. 2001). It seems likely that if a protoplanet forms in a circumbinary disc, then it will also migrate towards the binary, passing through a series of mean motion resonances in the process. One issue that we explore in this paper is whether a planet can become stably locked into resonance with a central binary, with the disc acting as a source of dissipation. The issue of whether or not such a system can remain stable depends in part on the rate of eccentricity damping provided by the disc.

The results of the simulations provide an interesting picture of giant planet formation in circumbinary discs. Early evolution involves the tidal clearing of a large cavity within which the binary and protoplanet system orbit. This may provide an observational signature of giant planet formation in circumbinary discs, since the cleared cavity is significantly larger than the gap that would be formed by the action of the binary system alone. Gap formation by binary systems alone has been examined by Artymowicz & Lubow (1994) and Günther & Kley (2002). The large cavity obtained when a protoplanet is included in the model may provide an explanation for the large cavity inferred to exist in the circumbinary disc that orbits the young spectroscopic binary GW Ori (Mathieu et al. 1995). For low eccentricity binary systems ($e_{bin} < 0.2$), we find that continued evolution involves the protoplanet migrating in towards the central binary system, and being temporarily captured into the 4:1 mean motion resonance with the binary. The protoplanet may then either be scattered by the binary, probably leading to eventual ejection from the system, or may be able to orbit stably just outside of the resonance if the resonance breaks. Planets that are scattered out of the system will become 'free–floating planets', as observed by Lucas et al. (2001) and Zapatero–Osorio et al.(2000). For a central binary with a larger initial eccentricity $e_{bin} \geq 0.2$, it was found that the circumbinary disc becomes eccentric, which causes the migration of the protoplanet to stall completely. Such systems are likely to result in the formation of stable circumbinary planets, since they are unable to migrate close to the central binary.

This paper is organised as follows. In section 2 we describe the numerical setup and the assumptions implicit within our model. In section 3 we present the results of the simulations. Finally, we discuss the results and draw conclusions in section 4.

2 NUMERICAL SETUP

We consider the interaction between a coplanar binary and protoplanet system and a two–dimensional, gaseous, viscous, circumbinary disc within which it is supposed the giant protoplanet formed. We do not consider the early evolution of the protoplanet in this work or address the formation process itself, but make the assumption that a Jovian mass protoplanet is able to form and examine the dynamical consequences of this. We work in a frame of reference based on the centre of mass of the binary star and planet system. The equations of motion are similar to those described in (Nelson et al. 2000).

Each of the stellar components and the protoplanet experience the gravitational force of the other two, as well as that due to the disc. The disc is evolved using the hydrodynamics code NIRVANA (Ziegler & Yorke 1997). The planet and binary orbits are evolved using a fifth–order Runge–Kutta scheme (Press et al. 1992). The force of the planet on the disc, and of the disc on the planet, is softened using a gravitational softening parameter $b = 0.5a_p(H/r)$, where a_p is the semimajor axis of the planet, and H/r is the disc aspect ratio. The calculation of the force of the disc acting on the protoplanet does not include the effect of material within the Hill sphere of the protoplanet. We consider the material bound to the protoplanet to be part of the planet itself, and accordingly do not include its effect on the orbital evolution. We assume that the mass of the protoplanet is fixed, and so do not allow accretion of matter from the disc onto the protoplanet. While this may not be an entirely realistic assumption, it nonetheless reduces the number of parameters to consider. The additional effects of mass accretion onto the protoplanet will be considered in a future paper.

We adopt a disc model in which the effective aspect ra-

Run label	m_p (M_J)	q_{bin}	e_{bin}	$m_d(r_p)/M_J$	$N_r \times N_\phi$	Result
A1	1	0.1	0.1	4	160×320	Mode 2
A2	1	0.1	0.1	4	320×640	Mode 2
B1	3	0.1	0.1	4	160×320	Mode 1
B2	3	0.1	0.1	4	320×640	Mode 1
C1	1	0.1	0.1	12	160×320	Mode 2
C2	1	0.1	0.1	12	320×640	Mode 2
D1	3	0.1	0.1	12	160×320	Mode 1
D2	3	0.1	0.1	12	320×640	Mode 1
E1	1	0.1	0.05	4	160×320	Mode 1
E2	1	0.1	0.05	4	320×640	Mode 1
F1	1	0.1	0.05	12	160×320	Mode 1
G1	1	0.25	0.1	4	160×320	Mode 1
G2	1	0.25	0.1	4	320×640	Mode 1
H1	1	0.25	0.1	12	160×320	Mode 1
H2	1	0.25	0.1	12	320×640	Mode 1
I1	3	0.25	0.1	12	160×320	Mode 1
I2	3	0.25	0.1	12	320×640	Mode 1
J1	1	0.1	0.2	4	160×320	Mode 3
K1	1	0.1	0.3	4	160×320	Mode 3

Table 1. Column 1 gives the run label, column 2 the planet mass (Jupiter masses), column 3 the binary mass ratio, column 4 the binary eccentricity, column 5 the disc mass interior to the initial planet location r_p for a full disc without the initial cavity imposed (in Jupiter masses). Column 6 gives the number of grid cells in the r and ϕ direction, column 7 describes the mode of evolution which is defined in the text.

tio $H/r = 0.05$, and the Shakura–Sunyaev viscosity parameter $\alpha = 5 \times 10^{-3}$ (Shakura & Sunyaev 1973). This choice of disc parameters provides a mass accretion rate through the disc that is comparable to that inferred for T Tauri stars from observations (e.g. Hartmann et al. 1998). The surface density Σ is initialised to have an inner cavity within which the planet and binary orbit:

$$\begin{aligned}\Sigma(r) &= 0.01\Sigma_0 && \text{if } \mathrm{r} < \mathrm{r_p} \\ &= \Sigma_0 r^{-1/2} exp[(r - r_g)/\Delta] && \text{if } \mathrm{r_p} \leq \mathrm{r} \leq \mathrm{r_g} \\ &= \Sigma_0 r^{-1/2} && \text{if } \mathrm{r} > \mathrm{r_g} \end{aligned} \quad (1)$$

where r_p is the initial planet orbital radius, r_g is the radius where the gap joins the main disc, and Δ is chosen to ensure that the gap profile smoothly joins the main disc and the inner cavity. Simulations initiated with no inner cavity (which are not described here in detail) show that one is formed by the action of the binary system and planet clearing gaps in their local neighbourhood. As the planet migrates in towards the central binary these gaps join to form a single cavity. The disc mass is normalised through the choice of Σ_0 such that a standard disc model with $\Sigma(r) = \Sigma_0 r^{-1/2}$ throughout would contain about 4 Jupiter masses interior to the initial planet radius r_p (assumed in physical units to be 5 AU). Thus the disc mass interior to the initial planet radius would be about twice that of a minimum mass solar nebula model. Calculations were also run with disc masses a factor of three higher.

The total mass of the binary plus protoplanet system is assumed to be 1 $M_\odot$. Dimensionless units are used such that the total mass of the binary system plus planet $M_{tot} = 1$ and the gravitational constant $G = 1$. The initial binary semimajor axis is $a_{bin} = 0.4$ in all simulations, and the initial planet semimajor axis $a_p = 1.4$. The simulations are initiated with the binary system having an initial eccentricity, e_{bin}, and the protoplanet is initially in circular orbit. The unit of time quoted in the discussion of the simulation results below is the orbital period at $R = 1$.

The parameters chosen for each of the runs are shown in table 1. The protoplanet mass, in Jupiter masses, is denoted by m_p. The disc mass interior to the protoplanet's initial location, for a disc without an inner cavity impsoed, is denoted by m_d, and is expressed in Jupiter masses. The initial binary eccentricity is denoted by e_{bin} and the binary mass ratio $q_{bin} = m_{2*}/m_{1*}$, where m_{1*} and m_{2*} are the primary and secondary star masses, respectively. Many of the simulations were run at two different numerical resolutions to test for numerical convergence. The number of grid cells used was either (N_r,N_ϕ)=(160, 320) or (N_r,N_ϕ)=(320, 640), where (r,ϕ) are polar coordinates. In the following discussion we use a_p to denote the semimajor axis of the protoplanet and e_p to denote its eccentricity. We note that the orbital elements of the protoplanet are calculated with respect to the centre of mass of the binary system.

3 NUMERICAL RESULTS

The results of the simulations are shown in table 1. They can be divided into three categories, which are described below, and are most strongly correlated with changes in the binary mass ratio, q_{bin}, and binary eccentricity e_{bin}. Changes to the disc mass and/or protoplanet mass appear to be less important. In some runs the planet enters the 4:1 mean motion resonance with the binary. The associated resonant angles in the coplanar case are defined by:

$$\psi_1 = 4\lambda_s - \lambda_p - 3\omega_s \qquad \psi_2 = 4\lambda_s - \lambda_p - 3\omega_p \quad (2)$$
$$\psi_3 = 4\lambda_s - \lambda_p - 2\omega_s - \omega_p \qquad \psi_4 = 4\lambda_s - \lambda_p - 2\omega_p - \omega_s$$

where λ_s, λ_p are the mean longitudes of the secondary star and protoplanet, respectively, and ω_s, ω_p are the longitudes of pericentre of the secondary and protoplanet, respectively.

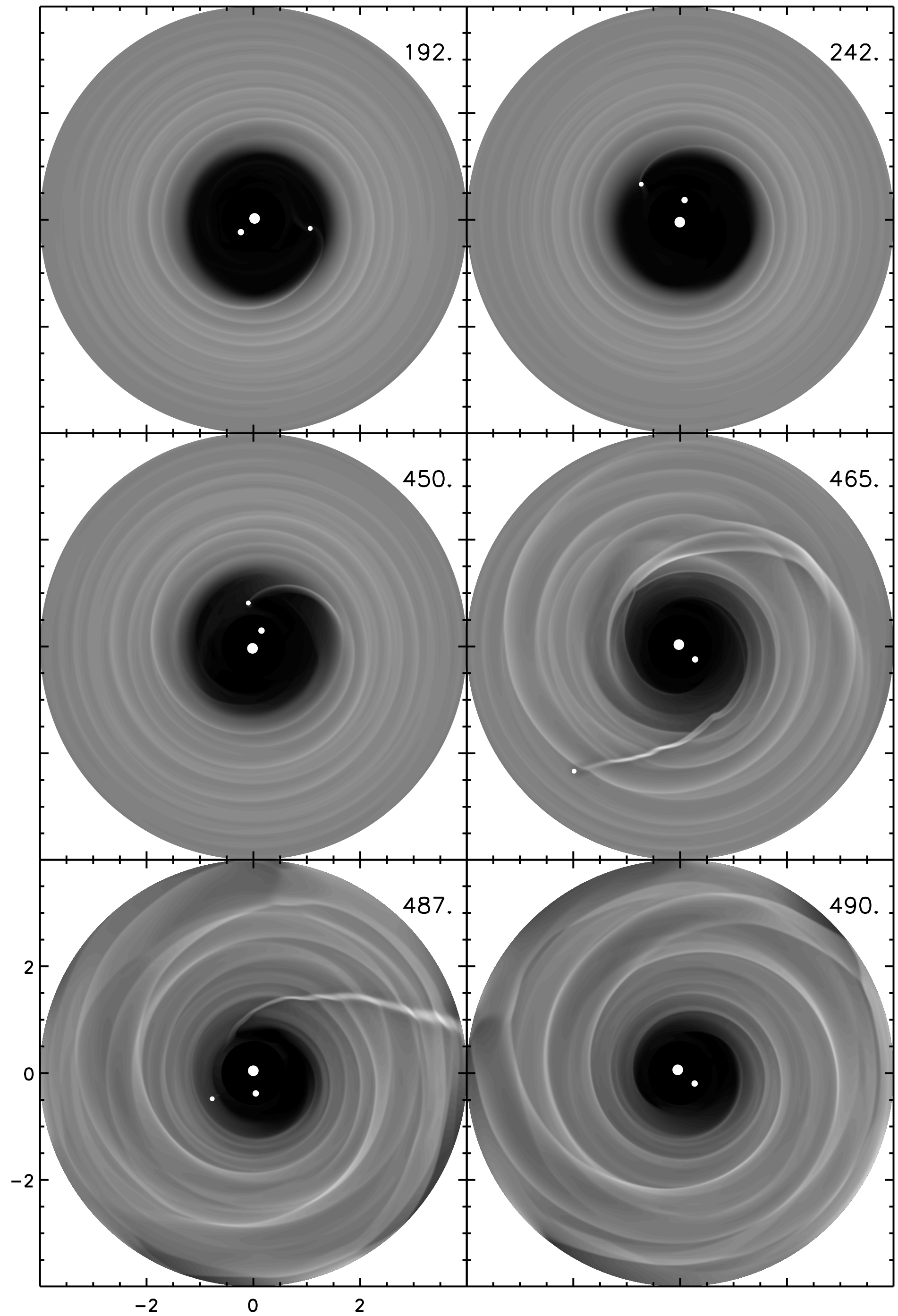

Figure 1. This figure shows the evolution of disc and planet plus binary system for run D2. Times are shown at top right hand corners in orbital periods at $R = 1$. The evolution is described in the text.

When in resonance ψ_3 or ψ_4 should librate, or all the angles should librate, since ψ_1 and ψ_2 may be written as linear combinations of ψ_3 and ψ_4.

In principle the protoplanet is able to enter higher order resonances than 4:1, such as 5:1 or 6:1, since its initial location lies beyond these resonance locations. However, none of the simulations presented here resulted in such a capture. We have performed some test calculations to understand why the 4:1 resonance is favoured. These calculations involved simulating the orbital evolution of binary plus protoplanet systems using an N–body code, but with simple prescriptions being used to provide migration torques and

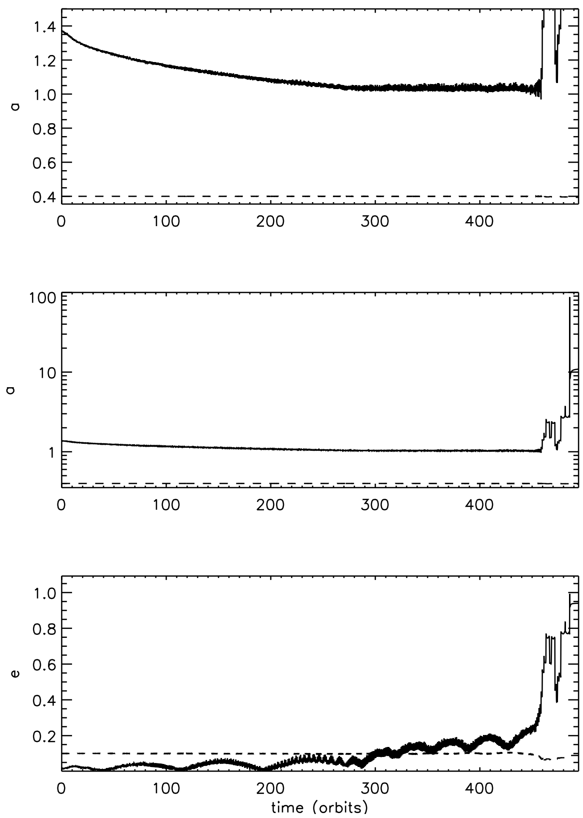

Figure 2. This figure shows the evolution of the semimajor axes and eccentricities of the planet (solid line) and binary system (dashed line) for run D2.

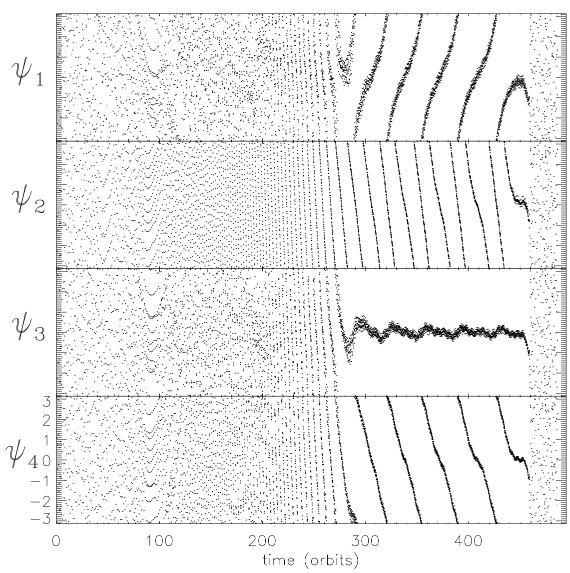

Figure 3. This figure shows the evolution of the resonant angles (ψ_i, $i = 1 ... 4$) for run D2. Note the low amplitude libration of ψ_3 for $t > 300$, indicating that planet is strongly locked in resonance.

eccentricity damping for the protoplanet [see Nelson & Papaloizou (2002) for a fuller description of the method]. These calculations indicate that for migration rates expected for a Jovian mass protoplanet interacting with a viscous disc (i.e. migration times of $\sim 10^4$ orbits), capture into 4:1 is favoured if $e_{bin} \simeq 0.1$. Increasing the migration time by an order of magnitude, and/or increasing e_{bin} to 0.2 or 0.3 can result in capture into either 5:1 or 6:1. This larger migration time does not apply to the full hydrodynamic simulations, however, and in addition we find that migration of the protoplanet stalls when $e_{bin} = 0.2$ or 0.3 when a full hydrodynamic simulation is performed (see section 3.3). Significantly faster migration is required for the protoplanet to pass through the 4:1 resonance.

Below we give a brief description of the three different modes of evolution obtained in the full hydrodynamic simulations.

Mode 1: The protoplanet migrates inwards and is eventually scattered through a close encounter with the central binary.

Mode 2: The protoplanet migrates inwards but stalls near the 4:1 mean motion resonance for the duration of the simulation. The planet remains stable.

Mode 3: For more eccentric binary systems the circumbinary disc becomes eccentric. The interaction between protoplanet and eccentric disc stalls the inward migration, and the protoplanet remains orbitally stable.

Examples of each of these modes of evolution are described in detail below. Note that similar simulations run at different numerical resolution resulted in the same qualitative results, as shown in table 1, indicating that numerical convergence of the results has been reached.

3.1 Mode 1 – Planetary Scattering

Table 1 shows that a number of simulations resulted in a close encounter between the protoplanet and binary system, leading to gravitational scattering of the protoplanet to larger radii, or into an unbound state. These runs are labelled as 'Mode 1'. Typically the initial scattering causes the eccentricity of the planet to grow to values $e_p \simeq 0.9$, and the semimajor axis to increase to $a_p \simeq 6 - 8$. In runs that were continued for significant times after this initial scattering, ejection of the planet could occur after subsequent close encounters. We note, however, that the small disc sizes considered in these models preclude us from calculating the post-scattering evolution accurately, since the planet trajectories take them beyond the outer boundary of the disc, usually located at $R_{out} = 4$. The eventual ejection of the planets may be a function of this if continued disc–planet interaction after scattering causes eccentricity damping and outward migration. Subsequent close encounters may then be prevented. We note further, however, that full 3–D simulations may result in the protoplanet receiving a significant component of motion in the z direction during the initial close encounter with the binary. This would substantially reduce the subsequent tidal interaction with the disc, potentially allowing for further close encounters leading to ejection. 3–D simulations of this kind will be the subject of future work.

3.1.1 Low Binary Mass Ratios

In all models with $q_{bin} = 0.1$ and $e_{bin} \leq 0.1$ that resulted in the protoplanet being scattered, the evolution proceeded as follows. The protoplanet migrates in towards the central binary due to interaction with the circumbinary disc, and temporarily enters the 4:1 mean motion resonance with the binary. The resonant angle ψ_3 defined in equation 3 librates with low amplitude, indicating that the protoplanet is strongly locked into the resonance. The resonance drives the eccentricity of the protoplanet upwards, until the protoplanet has a close encounter with the secondary star during or close to periapse, and is scattered out of the resonance into a high eccentricity orbit with significantly larger semimajor axis. We note that being in resonance normally helps maintain the stability of two objects orbiting about a central mass. However, when one of the objects is a star, the large perturbations experienced by the planet can cause the resonance to break when the eccentricities are significant. Once out of resonance, the chances of a close encounter and subsequent scattering are greatly increased.

We use the results of model D2 to illustrate the main points discussed above. Figure 1 shows the evolution of the disc and protoplanet plus binary system in this model. The early evolution, as the protoplanet migrates towards the central binary, is shown in the first two panels. The third panel corresponds to a time when the protoplanet is in the 4:1 resonance, shortly before being scattered. The fourth panel shows the system just after the initial scattering encounter between protoplanet and secondary star, with the planet now being immersed in the main body of the circumbinary disc. The fifth panel shows the planet approaching the central binary during a subsequent pericentre passage, and the sixth panel shows a time when the protoplanet orbit takes it out beyond the main body of the disc modeled here. For those simulations that resulted in the planet being completely ejected, a circumbinary disc remains that eventually returns to a state similar to that which would have existed had no planet ever been present.

The orbital evolution of the planet and binary for model D2 is shown in figure 2. The upper panel shows the semimajor axis on a log–linear plot, displaying the full range of variation of a_p, and the middle panel shows the semimajor axes on a linear-linear plot versus time. The lowest panel shows the evolution of the eccentricities versus time. The time evolution of the resonant angles ψ_1, ψ_2, ψ_3, and ψ_4 defined in equation 3 is shown in figure 3. The protoplanet migrates inwards and enters the 4:1 resonance at $t \sim 300$, corresponding to the time when the protoplanet eccentricity e_p starts to grow steadily (figure 2). Figures 2 and 3 show that the resonance breaks at $t \sim 460$, and that e_p at this stage has been increased to $e_p \simeq 0.3$. This large value of e_p leads to a close encounter with the secondary star at periapse which initial excites e_p up to $e_p \simeq 0.8$. Subsequent close encounters modify the values of a_p and e_p, and the final state at the end of the simulation has $a_p \simeq 10$ and $e_p \simeq 0.95$. It is likely that a longer integration of this system would result in the planet being ejected from the system, leading to the formation of a 'free-floating planet'. The ejection of the protoplanet was observed in other simulations such as B1, B2, and D1.

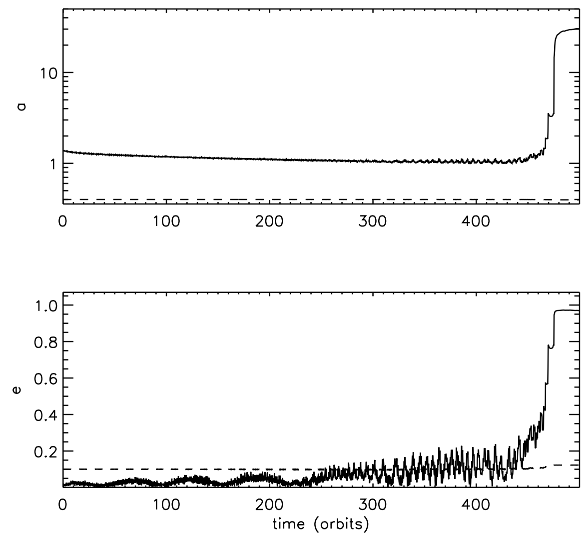

Figure 4. This figure shows the evolution of the semimajor axes and eccentricities for the protoplanet (solid line) and binary system (dashed line) in run I1.

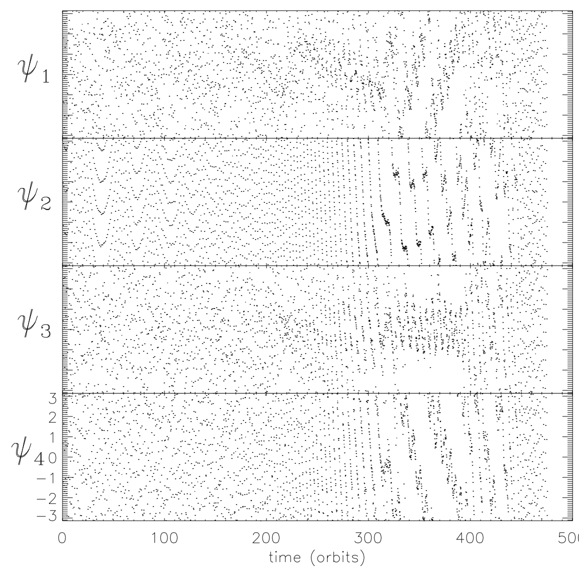

Figure 5. This figure shows the evolution of the resonant angles (ψ_i, $i = 1...4$) for run I1. Note the high amplitude libration of ψ_3 for $t > 300$, showing that the protoplanet is weakly locked in resonance.

3.1.2 Higher Binary Mass Ratios

For calculations with $q_{bin} = 0.25$, the evolution differed from that just described in all but one case (model I2), although scattering of the protoplanet still occurred. The planet enters the 4:1 mean motion resonance, and large amplitude librations of the resonant angle ψ_3 occur, accompanied by large oscillations of e_p, indicative of weak resonant locking. The resonance becomes undefined and breaks when $e_p = 0$ during one of these high amplitude librations, and the subsequent interaction between protoplanet and binary causes a close encounter and scattering of the protoplanet. This is facilitated by the larger value of q_{bin}, since similar runs involving weak resonant locking with $q_{bin} = 0.1$ do not lead to scattering of the planet (see section 3.2 below). The scattering is also facilitated by the fact that the protoplanet eccentricity rapidly increases back up to $e_p \sim 0.2$ after the resonance breaks, ensuring a closer approach to the secondary star at periapse.

Results for model I1 are shown in figures 4 and 5. Figure 4 shows the evolution of the semimajor axes and eccentricities. Figure 5 shows the time evolution of the resonant angles. Comparing figure 4 and figure 2 we can see that the eccentricity in model I1 does not increase to such large values before the resonance breaks. Instead the resonance appears to break because e_p goes to zero momentarily at $t \simeq 390$ (this is also the time at which the resonant angle ψ_3 ceases librating in figure 5). After resonance breaking, the protoplanet eccentricity e_p increases to $e_p \geq 0.2$, and the protoplanet–binary interaction is strong enough to perturb the protoplanet into an orbit that leads to a close encounter with the secondary star. Comparing figures 5 and 3, we see that the resonant angles undergo libration with much greater amplitude in this case, indicating that the resonant locking is weaker in run I1 than in run D2.

We note that run I2 provided a slightly different mode of evolution that is closer to that described in section 3.1.1, although $q_{bin} = 0.25$ for this model. Here the protoplanet becomes locked in the 4:1 resonance, and the strength of the resonant locking is intermediate between that observed in run D2 and run I1. The resonant angle ψ_3 undergoes libration with a significant amplitude but the oscillations in e_p do not lead to the protoplanet eccentricity going to zero. The resonance breaks because resonant eccentricity pumping drives the eccentricity to $e_p \simeq 0.3$. The perturbation experienced at periapse is strong enough to break the resonance and to cause the protoplanet to be scattered. It is clear that a full range of behaviour between strong resonance locking and weak resonance locking can occur. Prediciting the mode of evolution of each run is not possible since the details of the behaviour in the resonance depend on the details of the orbital phase of the protoplanet and binary system upon capture into resonance, as well as the details of the disc interaction.

3.2 Mode 2 – Near–resonant Protoplanet

A mode of evolution was found in some of the simulations with $q_{bin} = 0.1$ and $e_{bin} = 0.1$ leading to the protoplanet orbiting stably just outside of the 4:1 resonance. These cases are labelled as 'Mode 2' in table 1. Here, the protoplanet migrates inwards and becomes weakly locked into the 4:1 resonance, with the resonant angle ψ_3 librating with large amplitude. The evolution in the resonance is similar to that described for run I1 in section 3.1.2. The resonance becomes undefined and breaks when e_p goes to zero momentarily during the high amplitude oscillations of e_p that accompany the high amplitude librations of ψ_3 when the resonance is weak. However, because q_{bin} is smaller, the protoplanet is not perturbed into an orbit that leads to a close encounter with the binary. Instead it undergoes a period of outward migration through interaction with the disc by virtue of the eccentricity having reattained values of $e_p \simeq 0.17$ once the resonance

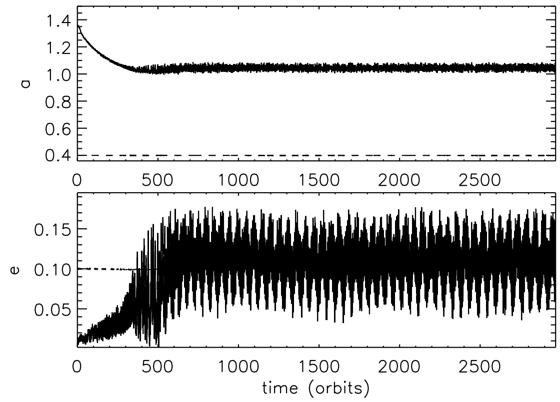

Figure 6. This figure shows the evolution of the semimajor axes and eccentricities of the planet (solid line) and binary system (dashed line) for run C1.

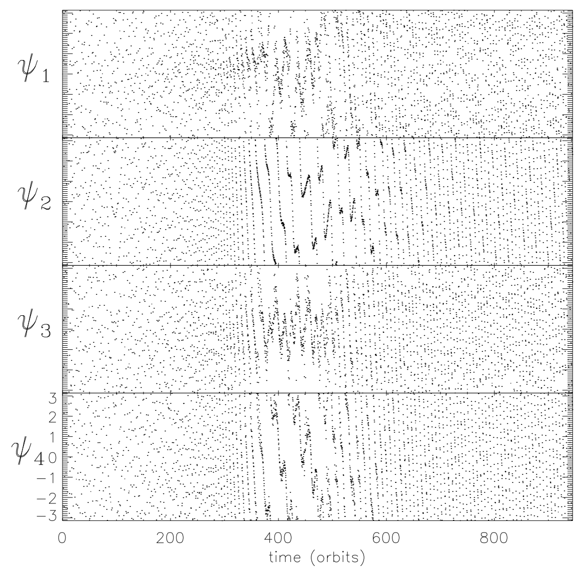

Figure 7. This figure shows the evolution of the resonant angles (ψ_i, $i = 1...4$) for run C1. Note the high amplitude libration of ψ_3 for $t > 300$, showing that the planet is weakly locked in resonance.

is broken. Calculations by Nelson (2003) have shown that gap–forming protoplanets orbiting in tidally truncated discs undergo outward migration if they are given eccentricities of this magnitude impulsively, due to the sign of the torque exerted by the disc reversing for large eccentricities. Analysis of the forces exerted on the protoplanet by the disc, in conjuction with equations (2.143) and (2.147) for the evolution of a_p and e_p in Murray & Dermot (1999), show that the disc causes the semimajor axis of the protoplanet to increase just after the resonance breaks. The outward migration moves the planet to a safer distance away from the binary, helping to avoid instability.

Interestingly, the protoplanet in models with $q_{bin} = 0.25$ that undergo resonance breaking when $e_p \to 0$ also experi-

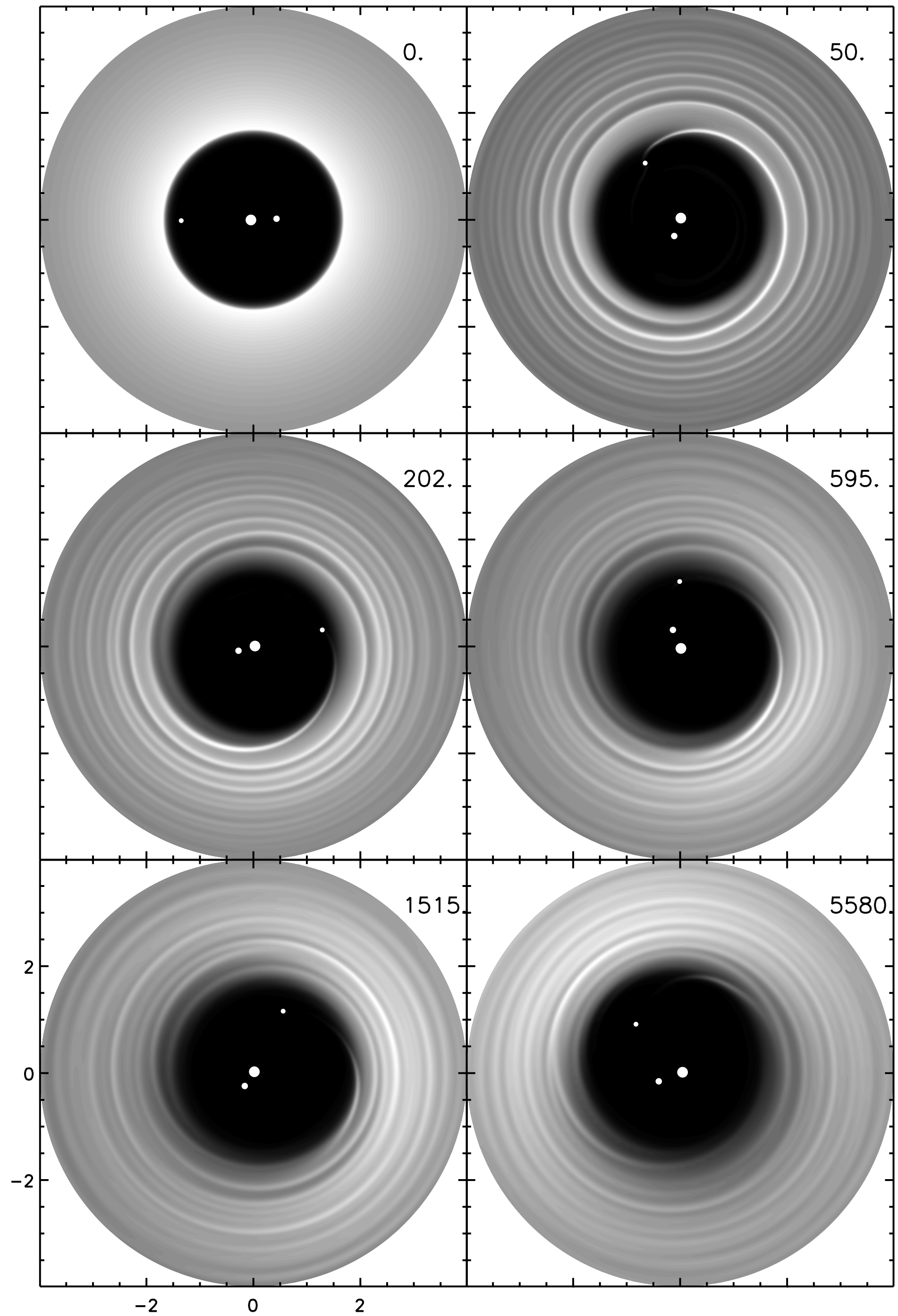

Figure 8. This figure shows the evolution of the disc and planet plus binary system for run J1. Note the formation of the eccentric disc.

ence outward migration forces from the disc when $e_p \simeq 0.2$ after the resonance breaks. However, the interaction between protoplanet and binary is stronger because of the larger value of q_{bin}, resulting in the protoplanet being scattered before it can migrate outwards.

Once the protoplanet has migrated to just beyond the 4:1 resonance the outward migration halts, since its eccentricity reduces slightly, and the planet remains there for the duration of the simulation. The system achieves a balance between eccentricity damping by the disc and eccentricity excitation by the binary, maintaining a mean value of $e_p \simeq 0.12$. The torque exerted by the disc on the protoplanet is significantly weakened by virtue of the finite eccentricity

(Nelson 2003), preventing the planet from migrating back towards the binary.

We use calculation C2 to illustrate the points discussed above. The orbital evolution of the system is shown in figure 6. The upper panel shows the semimajor axes. The protoplanet initially migrates in towards the binary, and halts as it reaches $a_p \simeq 1$. The protoplanet enters the 4:1 resonance and the resonant angle ψ_3 undergoes large amplitude librations (as shown in figure 7), similar to those observed for run I1 in figure 5 and in contrast to those observed in figure 3 for run D2. e_p also undergoes large amplitude oscillations, with the planet eccentricity reaching $e_p = 0$ just prior to the breaking of the resonance at $t \simeq 500$. Once the planet leaves the resonance, e_p increases to $e_p \simeq 0.17$, and the semimajor axis a_p increases. The protoplanet remains outside the 4:1 resonance for the duration of the simulation, (i.e. for nearly 3000 planetary orbits) since the migration is essentially stalled, with the eccentricity oscillating between values of $0.05 \le e_p \le 0.18$. Continuation of this run in the absence of the disc indicates that the planet remains stable for over 6×10^6 orbits. This is in good agreement with the stability criteria obtained by Holman & Wiegert (1999) since the protoplanet lies just outside of the zone of instability found by their study.

3.3 Mode 3 – Eccentric Discs

A mode of evolution was found in which the planetary migration was halted before the protoplanet could approach the central binary and reach the 4:1 resonance. This only occurred when the central binary had an initial eccentricity of $e_{bin} \ge 0.2$. The migration stalls because the circumbinary disc becomes eccentric. We label runs of this type as 'Mode 3' in table 1. Interaction between the protoplanet and the eccentric disc leads to a dramatic reduction or even reversal of the time–averaged torque driving the migration. This is because the disc–planet interaction becomes dominated by the $m = 1$ surface density perturbation in the disc rather than by the usual interaction at Lindblad resonances in the disc. Simulations of this type can be run for many thousands of planetary orbits without any significant net inward migration occurring. Such systems are likely to be stable long after the circumbinary disc has dispersed, since the planets remain in the region of stability defined by the work of Holman & Wiegert (1999), and are probably the best candidates for finding stable circumbinary extrasolar planets. Interestingly, spectroscopic binary systems with significant eccentricity are significantly more numerous than those with lower eccentricities (e.g. Duquennoy & Mayor 1991; Mathieu et al. 2000), suggesting that circumbinary planets may be common if planets are able to form in circumbinary discs.

Model J1 is used to illustrate the evolution of the 'Mode 3' class of models. The evolution of the disc, binary, and protoplanet are shown in figure 8. Early on the system looks similar to the one shown in figure 1. However, the circumbinary disc eventually becomes eccentric. The orbital evolution of the protoplanet and binary is shown in figure 9. The upper panel shows the semimajor axes, and the lower panel the eccentricities. Initially the protoplanet undergoes inward migration. After a time of $t \simeq 400$ the migration reverses. This is the time required for the eccentric disc mode to be fully established. Over longer time scales the protoplanet

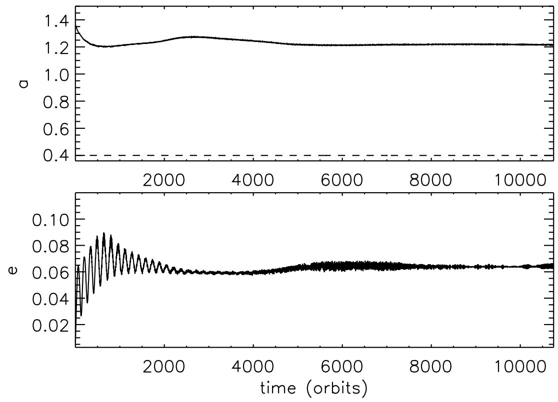

Figure 9. This figure shows the evolution of the semimajor axes and eccentricities of the planet (solid line) and binary system (dashed line) for run J1.

oscillates between inward and outward migration before settling into a non migratory state. The protoplanet remains orbiting with semimajor axis $a_p \simeq 1.2$, and is unable to migrate in towards the central binary. The resulting system is likely to consist of a central binary with $e_{bin} \le 0.2$, and a circumbinary planet orbiting with $a_p \simeq 1.2$ and $e_p \simeq 0.06$ after dispersal of the circumbinary disc.

The disc eccentricity in these models is driven by the central binary, and occurs only when the inner binary has significant eccentricity. Simulations performed without a protoplanet included also produced eccentric discs. In these cases, the disc inner cavity was retained, and only those calculations with $e_{bin} \ge 0.2$ gave rise to an eccentric disc. Such a model is shown in figure 10, which shows the results of a simulation with $q_{bin} = 0.1$, $e_{bin} = 0.2$, and $m_p = 0$. It is clear that the disc in this case also becomes eccentric, indicating that the disc eccentricity is driven by the eccentric binary, and is not caused by the protoplanet.

In previous work that examined the tidal interaction between a massive companion and a protostellar disc (Papaloizou, Nelson, & Masset 2001), an eccentric disc could be excited for companion masses with $q \ge 0.02$, corresponding to a companion of 20 Jupiter masses orbiting a solar mass star. This mode of disc–eccentricity driving occurred even for companions on circular orbits, and arose because of nonlinear mode coupling between an initially small $m = 1$ mode in the disc and the $m = 2$ component of the orbiting companion potential. To operate, this requires significant amounts of gas to be present at the 1:3 resonance location (which is at $r \simeq 2.08 \times a_{bin}$). The initial disc models in this paper have inner cavities that extend much beyond the 1:3 resonance of the binary, so this cannot be the cause of the disc eccentricity observed in runs J1 and K1, and those without protoplanets included such as shown in figure 10. Instead, the disc eccentricity is driven by the $m = 1$ component of the eccentric binary potential which excites a global $m = 1$ mode in the disc. Global $m = 1$ modes are known to be long–lived normal modes in disc models similar to those considered here (Papaloizou 2002), so it is not surprising that eccentric discs can be excited and maintained over long time periods.

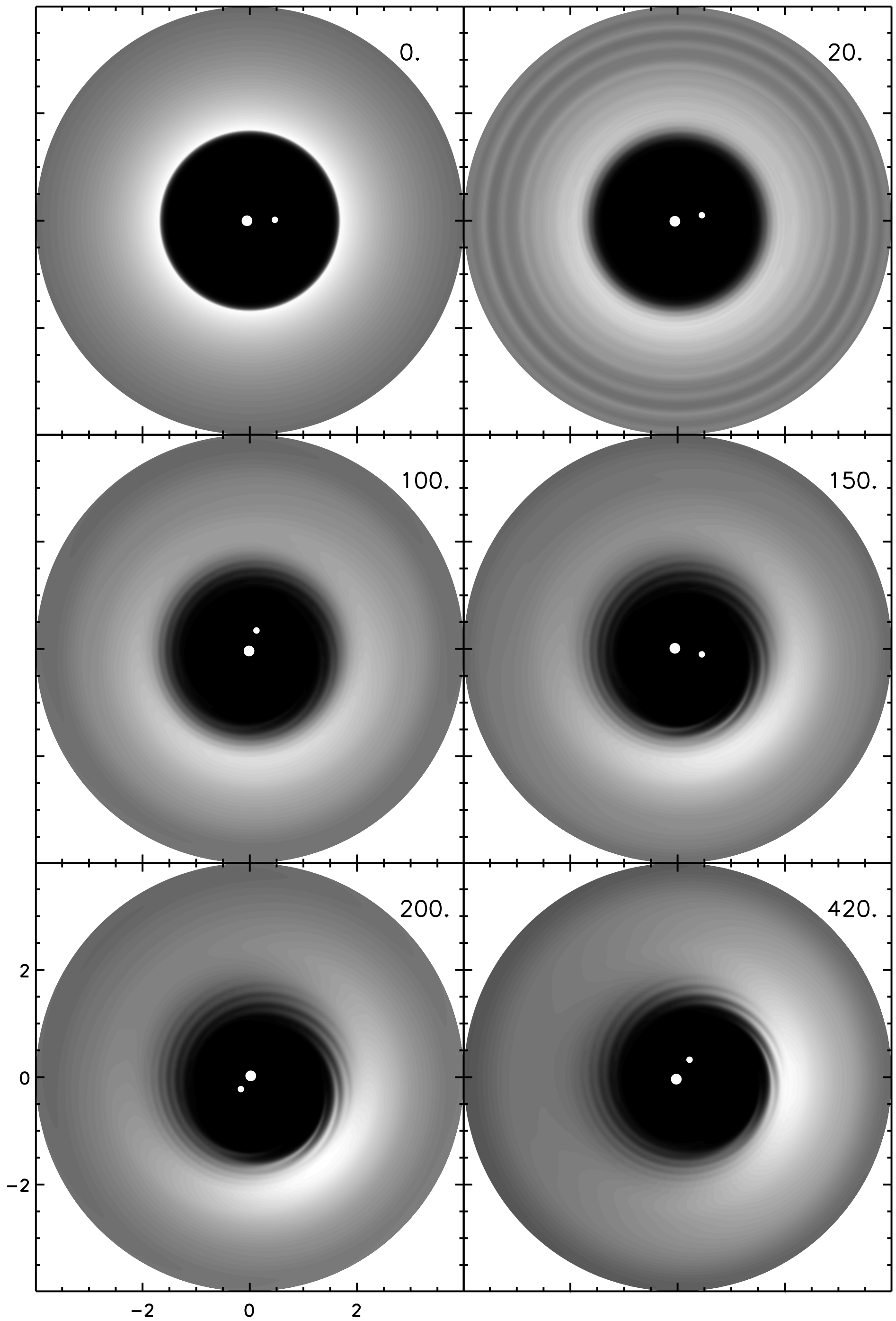

Figure 10. This figure shows the evolution of the disc and binary system for a run with no planet included, and $e_{bin} = 0.2$. Note the formation of the eccentric disc, indicating that the eccentric discs obtained when the planet is included are driven eccentric by the eccentric binary system.

4 DISCUSSION AND CONCLUSIONS

We have presented the results of hydrodynamic simulations that compute the evolution of giant protoplanets that form in circumbinary discs. The early evolution of such a system involves the formation of gaps by both the protoplanet and the binary system. As the protoplanet migrates towards the binary due to interaction with the circumbinary disc, these gaps join together to form a large inner cavity within which the protoplanet and binary system orbit. The simulations indicate that continued evolution of the system can lead to three distinct outcomes:

(*i*) Continued inward migration of the protoplanet through interaction with the circumbinary disc, temporary capture into the 4:1 mean motion resonance with the binary, followed by scattering of the protoplanet to larger radii or out of the system altogether through close interaction with the secondary star.

(*ii*) Continued inward migration of the protoplanet leading to capture in the 4:1 mean motion resonance. The resonance breaks and the planet orbits stably just outside the resonance for the rest of the simulation. Continuation of such calculations in the absence of the circumbinary disc indicate stability over millions of planetary orbits.

(*iii*) Formation of an eccentric disc when $e_{bin} \geq 0.2$, which leads to the protoplanet being unable to migrate inwards, and thus remaining in a stable orbit at large radius from the central binary system. Such planets are likely to be stable indefinitely.

These results have a number of important implications for planetary formation in close binary systems and and attempts to detect circumbinary planets. The presence of the binary companion induces the planet orbit to be eccentric. This is likely to mean that the mass accretion rate onto the protoplanet (which we do not explicitly calculate in this paper) will be higher than for protoplanets around single stars (as calculated by Bryden et al. 1999; Kley 1999; Lubow, Seibert, & Artymowicz 1999; Nelson et al. 2000). This is because an eccentric protoplanet will move into the gap wall once per orbit, enabling it to accrete more efficiently from the disc. One may then expect a tendency for circumbinary planet orbiting (relatively close to) close binary systems to be of larger mass than their single–star counterparts.

The early evolution of a giant protoplanet forming in a circumbinary disc involving the clearing of a large inner cavity may provide an explanation for the inferred gap size in the circumbinary disc around the close young binary system GW Ori (Mathieu et al. 1995). These authors use a circumbinary disc model to fit the spectral energy distribution, and the model requires the disc inner edge to be located at $r \simeq 3.3$ AU. The binary semimajor axis is $a_{bin} \simeq 1$ AU and the eccentricity $e_{bin} = 0.04 \pm 0.06$. Models of gap formation in circumbinary discs due to the tidal interaction with the binary system suggest the gap size should be $\simeq 2.1$ AU (e.g. Artymowicz & Lubow 1994). The inferred cavity size of ~ 3.3 AU may be accounted for if an additional planetary companion is orbiting around the central binary system, tidally maintaining the larger cavity, as illustrated by the results in this paper.

The formation of planets in circumbinary discs and their subsequent ejection, as illustrated by some of the simulations presented in this paper, may provide a source of 'free–floating planets' similar to those observed recently by (Lucas et al. 2001; Zapatero–Osorio et al. 2000).

Contrary to initial expectations, the simulations indicate that the inward migration of protoplanets induced by the circumbinary disc does not always lead to ejection of the protoplanet by the binary. The temporary capture into resonance of the protoplanet can lead to the excitation of its eccentricity. If the resonance breaks then the disc may induce outward migration into an apparently stable orbit just beyond the resonance. Inward migration back toward the binary is prevented by virtue of the finite eccentricity that the planet now possesses. This result may indicate preferred sites for the existence of circumbinary planets just beyond resonant locations (4:1 in particular) that could be used in targeted searches for circumbinary planets. It should be noted, however, that such behaviour was only observed for low binary mass ratios $q_{bin} = 0.1$. Larger binary mass ratios of $q_{bin} = 0.25$ resulted in the planet being gravitationally scattered.

The generation of an eccentric disc by an eccentric binary system, and the resulting stalled migration of the protoplanet, suggests that eccentric binary systems may be the best places to look for circumbinary planets. These are the most likely systems to contain planets which exist within the region of stability described by Holman & Wiegert (1999), since they do not migrate close to the central binary. Interestingly binaries with eccentricities between 0.2 – 0.3 appear to be the rule rather than the exception (e.g. Duquennoy & Mayor 1991; Mathieu et al. 2000), suggesting that surviving circumbinary giant planets may not be uncommon.

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