The curiously circular orbit of Kepler-16b

A.C. Dunhill* and R.D. Alexander

Department of Physics & Astronomy, University of Leicester, Leicester, LE1 7RH

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ABSTRACT

The recent discovery of a number of circumbinary planets lends a new tool to astrophysicists seeking to understand how and where planet formation takes place. Of the increasingly numerous circumbinary systems, Kepler-16 is arguably the most dynamically interesting: it consists of a planet on an almost perfectly circular orbit \( e = 0.0069 \) around a moderately eccentric binary \( e = 0.16 \). We present high-resolution 3D smoothed-particle hydrodynamics simulations of a Kepler-16 analogue embedded in a circumbinary disc, and show that the planet’s eccentricity is damped by its interaction with the protoplanetary disc. We use this to place a lower limit on the gas surface density in the real disc through which Kepler-16b migrated of \( \Sigma_{\text{min}} \sim 10 \text{ g cm}^{-2} \). This suggests that Kepler-16b, and other circumbinary planets, formed and migrated in relatively massive discs. We argue that secular evolution of circumbinary discs requires that these planets likely formed early on in the lifetime of the disc and migrated inwards before the disc lost a significant amount of its original mass.

Key words: hydrodynamics – planets and satellites: individual (Kepler-16b) – planets and satellites: dynamical evolution and stability – planet-disc interactions – protoplanetary discs – binaries: close.

1 INTRODUCTION

Most Sun-like stars form in multiple systems (e.g. [Duquennoy & Mayor 1991; Ghez, Neugebauer, & Matthews 1993; Leinert et al. 1993; Simon et al. 1995]. The question of how planet formation in these systems differs from single stars is therefore a pertinent one, and has been the subject of much recent theoretical and numerical work. This has considered both S-type circumstellar orbits (planets orbiting only one star in the binary; e.g. Kley & Nelson 2008; Müller & Kley 2012) and P-type circumbinary orbits (e.g. Paardekooper, Thébault, & Mellema 2008; Pierens & Nelson 2008; Marzari, Thébault, & Scholl 2008; Fragner, Nelson, & Kley 2011). While it seems that planet formation is relatively uninhibited in the former case, at least for relatively wide binary separations (see e.g. α Cen Bb, an earth-mass planet in a circum-secondary orbit; Dumusque et al. 2012), the latter poses a significant challenge. In particular, planetesimals growth at small semimajor axis (within a factor of a few of the binary semimajor axis) is strongly inhibited by the large velocity dispersion induced by the central binary (Paardekooper et al. 2008; Marzari et al. 2008).

The recent detection of a number of planets orbiting main-sequence binary stars by the Kepler mission (Doyle et al. 2011; Welsh et al. 2012; Orosz et al. 2012; Schwamb et al. 2013) challenges this theoretical understanding. All of the six systems reported to date contain planets in relatively short-period orbits around close eclipsing binaries (binary semimajor-axes \( a_0 < 0.25 \) au, planet semimajor-axes \( a_p \leq 1 \) au). While transit surveys such as Kepler are naturally biased towards finding short-period systems first, it is noteworthy that these planets are predominantly found just on the edge of dynamical stability (Holman & Wiegert 1999). Moreover, the fraction of close binaries hosting circumbinary planets is estimated to be \( \geq 1–10 \) per cent (Welsh et al. 2012), implying that planets form readily in circumbinary discs.

Four of the seven of the circumbinary planets discovered by Kepler to date have low eccentricities, \( e_p < 0.05 \). Of the exceptions, Kepler-34b and PH1 both orbit eccentric binaries \( e_b \gtrsim 0.2 \), while Kepler-47c is the outer planet in a two-planet system and is therefore a special case; the remainder are in near-circular orbits around low- or moderate-eccentricity binaries. At close separations circumbinary orbits are highly non-Keplerian, so directly measuring their eccentricities does not necessarily give a clear picture of the orbits. The planet’s eccentricity \( e_p \) comprises the sum of two components, referred to as the forced and free eccentricities (\( e_{f,0} \) and \( e_{f,0} \)). The forced eccentricity is driven by the potential of the central binary, and only the free eccentricity is a parameter of the planet’s orbit alone (Murray & Dermott 1999). However, an analysis of the orbits of Kepler-16b, Kepler-34b and Kepler-35b by Leung & Lee (2013) found that \( e_{f,0} \) is an order of magnitude higher for Kepler-34b than the others, consistent with its higher measured eccentricity.

Of particular interest is Kepler-16, the first of these systems discovered. It is a closely packed system and is aligned to a very high degree: the planes of the binary and planetary orbits, are aligned to within 0.3° (Doyle et al. 2011) and the binary orbit is aligned to the spin of the primary star to within 3° (Winn et al. 2011). The total stellar mass is approximately 0.9\( M_\odot \), with a mass...
centricity. Although the measured orbital parameters are expected of Pierens & Nelson (2008), who found that a Saturn-mass planet cannot have formed in its current orbit, and must presumably have
inhibiting planetesimal growth. The broad conclusion from these papers is that Kepler-16b cannot have formed in its current orbit, and must presumably have formed at larger radius and migrated inwards. This picture is consistent with the highly aligned nature of the system, as well as the fact that it is at the very edge of stability – the planet is located at the natural inner edge for a circumbinary disc. However, this picture of gentle disc-driven migration is complicated by the work of Pierens & Nelson (2008), who found that a Saturn-mass planet migrating through such a disc is likely to attain a significant eccentricity. Although the measured orbital parameters are expected to osculate under the influence of the binary, Leung & Lee (2013) have shown that the maximum eccentricity is still low ($e_p < 0.07$). Moreover, Popova & Shevchenko (2012) find that the planet’s eccentricity cannot ever have been much greater than $e_p = 0.05$ without its orbit becoming unstable.

These arguments point very strongly towards a picture where Kepler-16b’s orbit has never been significantly eccentric, which in turn suggests that its free eccentricity was damped to near zero due to the interaction with its parent protoplanetary disc. In order to investigate this further, we have carried out high resolution smoothed particle hydrodynamics (SPH) simulations of an analogue to the Kepler-16 system embedded in a circumbinary disc, seeking to characterise how the disc would have affected the angular momentum of the planet (and thus its eccentricity) as it migrated. In section 2.1, we describe the numerical method used, and present the results of our simulations in section 3. We discuss the implications of these results in section 4, and outline our conclusions in section 5.

2 METHOD

We follow the method of Dunhill, Alexander, & Armitage (2013), using a modified version of the hybrid N-body/SPH code Gadget-2 (Springel 2005). The code has been adapted so that it calculates gravity for the N-body particles via direct summation, and uses an explicit Navier-Stokes viscosity on top of a Morris & Monaghan (1997) artificial viscosity. The Navier-Stokes viscosity is parameterized as a Shakura & Sunyaev (1973) $\alpha$-disc, following the method of Lodato & Price (2010). This method allows us to explore discs with $\alpha \geq 0.005$ (Dunhill et al. 2013), and in the simulations described below we chose $\alpha = 0.01$.

We adopt a system of code units such that the unit of distance is 0.22431 au (equal to the binary semimajor-axis; Doyle et al. 2011). The unit of mass is equal to the sum of the masses of the the binary components and the planet, and the time unit is set to 41.08 days, the orbital period of the binary. This sets the gravitational constant $G = 4\pi^2$ in code units. The planet and the binary components were modelled as N-body particles, and thus their orbital elements were free to evolve throughout the simulations.

2.1 Disc model

Using this code we have performed simulations of a Kepler-16 analogue system embedded in a circumbinary disc. The discs were modelled using $10^7$ SPH particles. Initial particle positions in the disc plane were generated by randomly sampling the distribution $\Sigma(R) = \Sigma_0 \left(R/a_b\right)^{-\gamma}$, where $\Sigma$ is the surface density, $\Sigma_0 = 100$ g cm$^{-2}$ is the surface density at the radius of the planet’s orbit, $R$ is the radius from the barycentre of the binary, $a_b$ is the planet semimajor axis and the power-law index $\gamma = 1$. Initial positions in the vertical ($z$) direction were similarly generated by randomly sampling the density distribution

$$\rho(z) = \rho_0 \exp \left( -\frac{z^2}{2H^2} \right)$$

where $\rho_0$ is the midplane density and $H$ is the scale-height of the disc. We use a locally isothermal equation of state where temperature $T$ is a function only of $R$, such that $T \propto R^{-1/2}$. This gives a flared disc with thickness $H/R \propto R^{1/4}$. Particles were initially given zero velocity in the $z$ direction, and azimuthal values $v_{\phi}$ such that

$$\frac{v_{\phi}^2}{R} = \frac{GM_b}{R^2} + \frac{1}{\rho} \frac{\partial P}{\partial R}$$

where $M_b$ is the total binary mass and $P$ is the local pressure in the disc.

In order to reduce the impact of numerical transients, we allowed our discs to relax for a period of 100 binary orbits before inserting the planet into the simulation. Although the initial surface density profile has $\gamma = 1$, by the time the disc had relaxed this had become $\gamma \sim 3/2$, as expected for a circumbinary decration disc (Pringle 1991). In addition, in order to prevent the planet undergoing a transient burst of accretion immediately following its insertion, we modified the (relaxed) surface density profile to include a gap at the initial orbital semimajor-axis of the planet, using the parameterization of Lubow & D’Angelo (2006), before inserting the planet.

2.2 Model parameters

We ran a total of 4 such simulations for a period of 400 orbits of the planet (approximately 2200 binary orbits). In each run the physical parameters of the binary are those reported by Doyle et al. (2011), and both the planet and disc were coplanar with the binary. The sink radii of the binary components were set to 0.25 in code units (i.e.,

| Table 1. Table of model parameters. $M_p$ is the planet mass in units of the mass of Jupiter, $M_{\text{Jup}}$, and $e_0$ is the initial eccentricity of the planet’s orbit. |
| Model name | $M_p [M_{\text{Jup}}]$ | $e_0$ |
|-------------|------------------------|-------|
| REFERENCE   | 0.333                  | 0.0   |
| MASSIVE     | 1.0                    | 0.0   |
| ECCENTRIC   | 1.0                    | 0.05  |

1 Animations of these simulations can be seen and downloaded from http://www.astro.le.ac.uk/users/acd23/K16.html
the osculating eccentricity $e_p$ consists of forced and free components. They found that this occurs between $e_{\text{forced}} = |e_{\text{free}}| \approx 0.006$, and $e_{\text{free}} = e_{\text{forced}} \approx 0.066$. We see good agreement with this in our models with no initial eccentricity, for both low and high planet masses, suggesting that torques from the disc do not alter the planet’s orbit significantly on dynamical time-scales. In our initially eccentric model we see a similar osculating eccentricity, but with a larger amplitude (as expected), giving $e_{\text{max}} \approx 0.12$ for $e_0 = 0.05$.

As the planet’s eccentricity evolution is dominated by the binary forcing pattern, it is difficult to determine if there is any underlying longer-timescale change in the planet’s eccentricity due to the interaction with the disc. In order to test this, we have compared the eccentricity in our simulations with that from a pure N-body run (that is, the same set-up as in our reference model but with no circumbinary disc). This is shown in Figure 3 where we plot the orbit-averaged reference planet eccentricity ($e_{\text{hydro}}$) divided by the orbit-averaged N-body planet eccentricity ($e_{\text{N-body}}$). Relative to the N-body model (which closely matches the analytic solution of Leung & Lee (2013), the reference model shows initial eccentricity damping (at the per cent level) due to the relaxation of the disc initial conditions, followed by periodic oscillations. This periodicity matches the oscillation period seen in Figure 2, and consequently we do not attach great significance to the minima seen in Figure 3 (as these represent ratios of pairs of very small numbers). The maxima, however, are more reliable, and after the decay of initial transients these eccentricity peaks show a shallow decline with time. Due to the orbital precession induced by the disc, the eccentricity cycles from the reference model and the N-body run are slightly out of phase by the end of our simulations. This causes the ‘sharpening’ of the maxima seen in Figure 3 but the phase difference is sufficiently small that the peak values are not strongly affected. We therefore conclude that the disc damps the planet eccentricity (relative to the N-body run) at the 1 per cent level over the duration of our simulations.

3.1 Torque analysis

The planet’s orbit is dominated by the binary forcing throughout our simulations, as discussed above, but we can gain additional insight into its behaviour on longer time-scales by looking at the torques exerted on the planet by the disc. Figure 4 shows the orbit-averaged disc torques on the planet for each of our simulations. The torque $\Gamma$ is defined such that a negative torque corresponds to eccentricity growth (Armitage 2010), while positive torques damp the planet’s eccentricity. Although the details vary between models, the same broad trend is seen in all our simulations. The torques undergo periodic oscillations on the time-scale of the eccentricity osculation seen in Figure 2 with the maximum torque corresponding to the peak eccentricity. The underlying trend, however, is that the torques are initially negative, but increase with time and eventually settle into a quasi-steady (oscillating) state. In the case of our reference model, this has a net positive torque, with a time-averaged value of $\langle \Gamma_{\text{osc}} \rangle \approx 6 \times 10^{-9}$ g cm$^2$s$^{-2}$. In a sense this is to be expected: the planet orbits near the inner disc edge, and the presence of more material exterior to the planet’s orbit favours positive torques. These provide angular momentum to the planet, in principle allowing it to reduce its eccentricity or to migrate outwards. However, our model setup assumes that the planet has previously migrated from a formation point further out in the disc, and this configuration disfavours outward migration, so the long-term effect of these positive torques is to damp the planet’s eccentricity.
Our massive and eccentric models show the same basic trend of torque growth but here the net torque at the end of the simulation runs is negative. This is consistent with the results of Pierens & Nelson (2008), who found generally negative torques in their 2D disc models that resulted in the growth of eccentricity. Both our massive and eccentric models and the Saturn-mass run from Pierens & Nelson (2008) were in the gap-opening regime due to high-mass planets and low disc viscosity respectively (see Figure 5 for a comparison between our reference and massive models with respect to their gap opening). In contrast, our reference model is not fully in the gap-opening regime, and so feels additional torques from co-orbital gas not present in the massive, eccentric or Pierens & Nelson’s runs. We address numerical concerns with simulating non-gap opening planets in isothermal discs in Section 4.1.

In all of our simulations, the absolute values of $\Gamma$ are smaller than the tidal torques from the binary by a factor $\sim 10^4$, and additional calculations (run for shorter durations) show that the disc torques scale linearly with $\Sigma$ over a wide range (at least 3 orders of magnitude) in disc surface density. We therefore conclude that if the planet is not in the gap-opening regime, the disc-planet interaction in the Kepler-16 system generally leads to damping of the planet’s free eccentricity, with the damping time-scale determined primarily by the local disc surface density.

### 3.2 Disc properties

We can now use this result to infer a limit on the gas surface density of the real disc in which Kepler-16b formed. Previous simulations of circumbinary planets have found that eccentricity grows on a time-scale comparable to (or shorter than) the migration time-scale $\tau_{\text{ mig}}$ (e.g., Pierens & Nelson 2008). If the planet’s orbit never became significantly eccentric during its migration, then we require that the eccentricity be damped on a time-scale $\tau_e \lesssim \tau_{\text{ mig}}$. In order to connect this to the disc torques, we must calculate the angular momentum $\Delta J$ gained by the planet from the damping torque. To first-order the potential is Keplerian, so we approximate the planet’s angular momentum as $J_p = M_p \sqrt{GM_b a_p (1 - e^2)}$. We then differentiate to find

$$\frac{\partial J_p}{\partial e} \bigg|_{a_p} = -M_p \sqrt{GM_b a_p} \left(1 - e^2\right)^{3/2} e,$$

so to first-order in $e$

$$\frac{dJ}{de} \approx -eM_p \sqrt{GM_b a_p},$$

and

$$\Delta J = \left| \frac{dJ}{de} \right| e = e^2 M_p \sqrt{GM_b a_p}.$$  

In order to maintain a low eccentricity we require a damping torque

$$\Gamma_d \gtrsim \frac{\Delta J}{\tau_e}.$$  

We find that $\Gamma_d$ scales linearly with the disc surface density (in the limit $M_d \ll M_b$), as discussed above, so this allows us to place a lower limit on $\Sigma$. The planet is unlikely to have attained an eccentricity higher than $e = 0.1$ (e.g., Popova & Shevchenko 2012), which gives $\Delta J = 2.3 \times 10^{37} \text{ g cm}^{-2}$. For our reference model, which has $\Sigma_p = 100 \text{ g cm}^{-2}$, the net damping torque is $\Gamma_d \approx 6 \times 10^{36} \text{ g cm}^{-2}$ (see Figure 4), so we can substitute these values into Equation (7) and re-arrange (assuming $\Gamma_d \approx \Sigma$) to find

$$\Sigma_p \gtrsim 120 \left(\frac{\tau_e}{10^4 \Omega_b}\right)^{-1} \text{ g cm}^{-2}.$$  

This is a surprisingly large surface density, and implies that Kepler-16b formed in a massive circumbinary disc. Pierens & Nelson (2008) found that the migration and eccentricity growth time-scale for a Saturn-mass planet is $\sim 10^5 \Omega_b^{-1}$, which we adopt as a reference value above. The true migration time-scale is not known, and the planet may well have migrated more slowly. However, even a conservative assumption of $\tau_e \sim 10^5 \Omega_b^{-1}$ requires $\Sigma_p \gtrsim 10 \text{ g cm}^{-2}$, and we regard this as a reasonably robust lower limit to the surface density of Kepler-16b’s parent disc.
The torques oscillate on the same time-scale as the eccentricity, and after initial transients have decayed settle into a pattern with a net positive torque of $6 \times 10^{36}$ g cm$^2$ s$^{-2}$ for our reference model. The torques on the planet from the binary are $\sim 10^4$ times stronger, but additional runs show that the disc torques scale linearly with the surface density over a wide dynamic range in $\Sigma$. Lower-resolution test runs indicate that the torques in the reference model are approximately converged, and the massive and eccentric models are almost converged by the end of the simulation.

Figure 4. Orbit-averaged disc torques, normalised to the planet mass, as a function of time (in planetary orbital periods) for the models described in Table 1. The torques oscillate on the same time-scale as the eccentricity, and after initial transients have decayed settle into a pattern with a net positive torque of $6 \times 10^{36}$ g cm$^2$ s$^{-2}$ (for our reference model). The torques on the planet from the binary are $\sim 10^4$ times stronger, but additional runs show that the disc torques scale linearly with the surface density over a wide dynamic range in $\Sigma$. Lower-resolution test runs indicate that the torques in the reference model are approximately converged, and the massive and eccentric models are almost converged by the end of the simulation.

4 DISCUSSION

4.1 Limitations of the model

A major source of uncertainty in our model is our treatment of the disc thermodynamics. We adopt a locally (vertically) isothermal equation of state, but in the single-star case it is well known that a full radiative hydrodynamical treatment can give different results for low-mass planets below the gap-opening limit (e.g. Bitsch & Kley 2010, 2011a,b). For Saturn-mass planets, it seems that migration behaviour is broadly unaffected by the disc equation of state (Bitsch & Kley 2011a), but the disc structure can still be strongly affected – Marzari et al. (2013) compared their fully radiative treatment with the locally isothermal approximation of Pelupessy & Portegies Zwart (2013) and found significant differences, though the different initial surface density profiles also play a strong role.

Unfortunately the parameter space for radiative circumbinary disc models in 3-D is vast, and exploring even a modest subset of this space is not feasible. However, in single-star models the critical uncertainty where a gap is not opened is usually the (thermo)dynamics of gas in the co-rotation region (near the planet), but it is unclear if we are in this regime. We can investigate this in our simulations by comparing models with different planet masses. In Figure 5 we plot the midplane density for the reference and massive models after 200 planetary orbits. We see that the reference model, with a planet of approximately Saturn mass, only opens a partial gap in the disc, and only the more massive planet is truly in the gap-opening regime. The results of our reference model must therefore be taken with some caution. The torque analysis in Figure 4 shows that the torque oscillates on the same time-scale for all planet masses, but the net (time-averaged) torque is negative for the runs with higher planet mass, as seen in previous studies (e.g., Pierens & Nelson 2008). However, Bitsch & Kley (2011b) showed in the single-star case that an accurate treatment of the disc thermodynamics generally increases the disc torques for low-mass non gap-opening planets, suggesting that the net positive $\Gamma_d$ seen in our reference simulation is a robust result. Clearly, further investigation of this issue is still required.

A further limitation of our high-resolution 3-D treatment is that due to computational expense, we are only able to simulate time-scales of hundreds of planetary orbits. In contrast, Pierens & Nelson (2008) ran their 2-D simulations for tens of thousands of planetary orbits. Although we cannot follow changes in the planet’s orbit on such long time-scales, our torque analysis provides a clean way to probe longer time-scale behaviour in our models. However, it is notable that our result, that disc torques damp eccentricity, disagrees with Pierens & Nelson (2008), who found eccentricity growth and outward migration in comparable models. It is well known that a 2-D approach can lead to artificially high resonant torques (Tanaka, Takeuchi, & Ward 2002), but this is unlikely to be the origin of such a qualitative change in behaviour.

Instead, we attribute this apparent discrepancy to the different disc viscosities used. We chose $\alpha = 10^{-2}$, while Pierens & Nelson (2008) used $\alpha = 10^{-3}$. The different dimensionality (3-D versus 2-D) means that we cannot compare the gap-opening criteria in these simulations directly, and it is computationally unfeasible for us to simulate such low disc viscosities (see discussion in Dunhill et al. 2013). However, the critical planet mass for gap-opening typically decreases with lower viscosities, as the disc-planet torques more easily overcome the viscous torques in the disc. Comparing our Figure 4 with Figures 5 and 8 in Pierens & Nelson (2008), we see that their planets open much deeper and wider gaps in their discs, and therefore qualitatively different behaviour is not unexpected.

Measurements of real disc viscosities are uncertain at best, and are almost certainly not constant (particularly in the case of “dead zones” in disc midplanes). In general, however, our adopted value of $\alpha = 10^{-2}$ is consistent with the values inferred from observations of protoplanetary discs (e.g., Hartmann et al. 1998, King, Pringle, & Livio 2007). We note also that our simulations are specifically tailored to the observed parameters of the Kepler-16 system, and therefore differ from those of Pierens & Nelson (2008) who used $q = 0.1$, and initial eccentricities of $e_p = 0.08$ and $e_p = 0.02$. Their more extreme binary mass-ratio, in particular, may change the sys-
tem’s dynamics significantly (as the secondary orbits much closer to the inner disc edge); further exploration of the binary parameter space is necessary to understand these effects in more detail.

The relatively short duration of our simulations means that we cannot rule out the possibility that the positive torques on the planet drive some outward migration in addition to damping the planet’s eccentricity. However, as noted in Section 3.1, we find this unlikely, as our simulations consider a planet that has already migrated to the orbit we see it at today. Figure 6 shows that we do indeed see some small level of eccentricity damping in our simulations, although again we cannot rule out the possibility of outward migration at later times. If we do consider this as a possible outcome, it in fact strengthens our minimum surface density requirement. This is because if some fraction of the total disc torque is ‘diverted’ towards driving outward migration, the remaining torque which acts to damp eccentricity is smaller, requiring a higher surface density to maintain the same level of eccentricity damping.

Our analysis also neglects the possibility that the binary can drive eccentricity in the disc, which in turn can alter the angular momentum of the planet. No significant disc eccentricity is seen in any of our simulations, but Pierens & Nelson (2008) showed that a binary with mass ratio and eccentricity similar to Kepler-16 can excite a disc eccentricity of $e \approx 0.05$ on time-scales only slightly longer than the migration time-scale of the planet (i.e., several thousand planetary orbits). If we consider the limiting case where the planet absorbs all of the additional angular momentum within $\pm H$ of its orbit, we find that a disc eccentricity of $0.05$ corresponds to $\approx 10\%$ of the planet’s angular momentum for $\Sigma \approx 400\,g\,cm^{-2}$. Detailed consideration of this effect is beyond the scope of our simulations, but this suggests that disc eccentricity is unlikely to alter our conclusions significantly unless the disc is very massive. Instead, as the time-scale for disc eccentricity growth is relatively long, the most likely outcome is that a modest disc eccentricity will slow, but not reverse, the damping of the planet’s eccentricity.

Finally, we note that our simulations and analysis are predicated on the assumption that Kepler-16b’s eccentricity was damped during the disc phase, rather than at later times in the system’s evolution. This is supported by dynamical modelling of the system, which suggests that the planet’s eccentricity never exceeded 0.05 in the post-disc phase (Popova & Shevchenko 2012), but it is possible that an additional body (or bodies) in the system could influence the planet’s orbit. The simplest dynamical explanation for the low eccentricity is that the planet is at the low-e point of a Kozai cycle (Kozai 1962; Lidov 1962). This scenario is rather contrived, however, and requires the presence of a massive perturber on an inclined orbit in addition to the system being observed at a very specific time in its evolution. There is some evidence for an additional planetary-mass body in the system (Bender et al. 2012), but detailed dynamical modelling of its potential effects is not yet possible. We therefore cannot exclude a dynamical origin, but given the high degree of fine-tuning required we do not consider this a likely explanation for the low eccentricity of Kepler-16b.

4.2 Implications for circumbinary planet formation

Our results suggest that Kepler-16b formed in, and migrated through, a circumbinary disc with a relatively high surface density. Observations currently tell us little about the surface densities of circumbinary discs, particularly for young binaries with separations as close as Kepler-16. At larger separations ($a \geq 10\,au$), where young binaries are more readily observed, most circumbinary discs appear to be rather low mass: the majority of the circumbinary discs identified by Kraus et al. (2011, 2012) have masses $M_d \leq 10^{-3}\,M_\odot$ (Andrews & Williams 2005). At the other end of the binary period distribution, Rosenfeld et al. (2012) measured the mass of CO gas in the disc surrounding the very close (2.4-day period) binary V4046 Sgr to be $M_{\text{CO}} \sim 3 \times 10^{-6}\,M_\odot$, implying a total gas mass of $\sim 0.01 \sim 0.1\,M_\odot$. This system is particularly noteworthy because it is old ($\sim 12\,\text{Myr}$; Rosenfeld et al. 2012), yet it still retains a very massive disc.

However, all of these measurements are based on (sub-)millimetre observations, which only probe the outer regions of the disc, and estimates of disc surface densities at au radii can only be made by extrapolating inwards. Identifying young binaries at au separations remains challenging (e.g., Kraus et al. 2012) and, while some subset of our sample of circumstellar discs are presumably circumbinary, observations of discs in close binary systems remain scarce. Our limit on the surface density of Kepler-16b’s parent disc therefore provides a useful new insight into circumbinary disc physics in this poorly-explored regime.

We extend our analysis further by considering the radial distribution of mass in such a disc. Figure 6 shows a contour plot for different disc models with the form

$$\Sigma(R) = \Sigma_0 \left(\frac{R}{1\,au}\right)^{-\gamma},$$

where contours indicate the radius $R$ at which the surface density equals $\Sigma_{\text{min}} = 10\,g\,cm^{-2}$. The true radius at which Kepler-16b formed is unknown, although there is general agreement that it must have formed beyond approximately $10\,au$ (Meschiar 2012; Rafikov 2012; Marzari et al. 2013). We can see from Figure 6 that to satisfy $\Sigma(R \geq 10\,au) > \Sigma_{\text{min}}$, we require discs with $\Sigma_0 \geq 10^5\,g\,cm^{-2}$, even for shallow surface density gradients ($\gamma \leq 1$).

We have focused our attention on Kepler-16b because of its extremely low measured eccentricity, but in fact shares a number of characteristics with other circumbinary systems. Kepler-35b, -38b, and -47b have low eccentricities ($e_p < 0.05$) and similar semimajor-axis ratios $a_p/a_d \sim 3–4$. Moreover, the secular disc evolution models of Alexander (2012) find that photoevaporation rapidly erodes the inner regions of circumbinary discs, and high surface densities persist only for a short fraction of the discs’ lifetimes ($\lesssim 1\,\text{Myr}$). Taken together with our results, this suggests that these circumbinary planets must have formed early in the evolution of their parent discs, when the discs were still massive enough to
damp their eccentricities. At present the poor observational statistics for both circumbinary discs and circumbinary planets do not allow us to draw detailed conclusions regarding the frequency of such planets, but as our census of both discs and planets improves we expect circumbinary systems to continue to provide crucial insights into the physics of planet formation.

5 Conclusions

We have performed high resolution 3D SPH simulations of a Kepler-16-like system embedded in a circumbinary disc. Analysing the disc torques from these simulations and using observational constraints on the system’s history, we conclude that the planet must have maintained its low eccentricity by migrating through this disc without opening a significant gap, leading to the damping of eccentricity by co-orbital material. As this damping is directly proportional to the disc mass, we can set a limit on the local disc surface density in which Kepler-16b was once embedded, $\Sigma_{\text{min}} \sim 10$ g cm$^{-2}$. Applying this result to similar circumbinary systems also discovered by the Kepler mission, we conclude that this low limit may be used to provide constraints on the route planet formation takes in the circumbinary environment. We argue that the process requires relatively massive circumbinary discs, and that their secular evolution of implies that these planets form far out in the disc at early times, and migrated inwards before the disc mass was significantly depleted.

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References

Alexander R., 2012, ApJ, 757, L29
Andrews S. M., Williams J. P., 2005, ApJ, 631, 1134
Armitage P. J., 2010, Astrophysics of Planet Formation. Cambridge Univ. Press, Cambridge, UK
Bender C. F. et al., 2012, ApJ, 751, L31
Bitsch B., Kley W., 2010, A & A, 523, A30
Bitsch B., Kley W., 2011a, A&A, 530, A41
Bitsch B., Kley W., 2011b, A&A, 536, A77
Doyle L. R. et al., 2011, Science, 333, 1602
Dumusque X. et al., 2012, Nature, 491, 207
Dunhill A. C., Alexander R. D., Armitage P. J., 2013, MNRAS, 428, 3072
Duquennoy A., Mayor M., 1991, A&A, 248, 485
Fragner M. M., Nelson R. P., Kley W., 2011, A&A, 528, A40
Ghez A. M., Neugebauer G., Matthews K., 1993, AJ, 106, 2005
Hartmann L., Calvet N., Gullbring E., D’Alessio P., 1998, ApJ, 495, 385
Holman M. J., Wiegert P. A., 1999, AJ, 117, 621
King A. R., Pringle J. E., Livio M., 2007, MNRAS, 376, 1740
Kley W., Nelson R. P., 2008, A&A, 486, 617
Kozai Y., 1962, AJ, 67, 591
Kraus A. L., Ireland M. J., Hillenbrand L. A., Martinache F., 2012, ApJ, 745, 19
Kraus A. L., Ireland M. J., Martinache F., Hillenbrand L. A., 2011, ApJ, 731, 8
Leinert C., Zinnecker H., Weitzel N., Christou J., Ridgway S. T., Jameson R., Haas M., Lenzen R., 1993, A&A, 278, 129
Leung G. C. K., Lee M. H., 2013, ApJ, 763, 107
Lidov M. L., 1962, Planet. Space Sci., 9, 719
Lodato G., Price D. J., 2010, MNRAS, 405, 1212
Lubow S. H., D’Angelo G., 2006, ApJ, 641, 526
Marzari F., Thebault P., Scholl H., 2008, ApJ, 681, 1599
Marzari F., Thebault P., Scholl H., Picogna G., Baruteau C., 2013, A&A, 553, A71
Masset F. S., Ogilvie G. I., 2004, ApJ, 615, 1000
Meschiari S., 2012, ApJ, 752, 71
Morris J. P., Monaghan J. J., 1997, J. Comput. Phys., 136, 41
Müller T. W. A., Kley W., 2012, A&A, 539, A18
Murray C. D., Dermott S. F., 1999, Solar System Dynamics. Cambridge Univ. Press, Cambridge
Orosz J. A. et al., 2012a, ApJ, 758, 87
Orosz J. A. et al., 2012b, Science, 337, 1511
Paardekooper S.-J., Leinhardt Z. M., Thebault P., Baruteau C., 2012, ApJ, 754, L16
Paardekooper S.-J., Thebault P., Mellema G., 2008, MNRAS, 386, 973
Pelupessy F. I., Portegies Zwart S., 2013, MNRAS, 429, 895
Pierens A., Nelson R. P., 2008, A&A, 483, 633
Popova E. A., Shevchenko I. I., 2012, ArXiv:1207.0101
Price D. J., 2007, Proc. Astron. Soc. Aust., 24, 159
Pringle J. E., 1991, MNRAS, 248, 754
Rafikov R. R., 2012, ArXiv:1212.2217
Rosenfeld K. A., Andrews S. M., Wilner D. J., Stempels H. C., 2012, ApJ, 759, 119
Schwamb M. E. et al., 2013, ApJ, 768, 127
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Simon M. et al., 1995, ApJ, 443, 625
Springel V., 2005, MNRAS, 364, 1105
Tanaka H., Takeuchi T., Ward W. R., 2002, ApJ, 565, 1257
Welsh W. F. et al., 2012, Nature, 481, 174
Winn J. N. et al., 2011, ApJ, 741, L1

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