Eccentric Adventures in Circumbinary Discs

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Abstract. Circumbinary environments are increasingly of interest to astrophysicists seeking to understand how both star and planet formation mechanisms act. The discovery of numerous circumbinary planets by the Kepler mission indicates that such systems are more common than previously thought, as theory suggests that binary forcing should strongly inhibit planet formation. I present the results of 3D SPH simulations of circumbinary discs applied to two real systems: Kepler-16 and HD 104237. In the former, summarising the results published in Dunhill & Alexander (2013), I show how we can use the extremely low eccentricity of the planet Kepler-16b to place a lower limit on the surface density of the disc in which the planet. For the latter I show how the simulations presented in Dunhill et al. (2014) allows us to predict long-term accretion variability timescale for accreting eccentric binaries. I also discuss how the periodic accretion in these systems allows them to preserve their primordial mass ratios.

1. Introduction

The study of circumbinary discs is increasingly important in shaping our understanding of how both planets and their parent stars form. The presence of a binary greatly increases the dynamical activity of a system, and as such these systems give an excellent testbed for investigating what effect this has. The discovery by the *Kepler* mission of an increasing number of circumbinary planets (e.g. Doyle et al. 2011) has challened our understanding of planet formation in this context, as while theoretical models find it very difficult indeed to build planets in circumbinary discs (e.g. Paardekooper et al. 2012; Marzari et al. 2012, 2013) current estimates suggest that around 10 per cent of close binaries host planetary systems (Armstrong et al. 2014).

Accretion in young binary systems plays a very important role in setting the binary mass ratio $q = M_{\rm B}/M_{\rm A}$, as the observed statistics for binaries in the field do not necessarily match the primordial mass ratios of newly formed stellar pairs (e.g. Bate 2014). Understanding how this ratio evolves between formation and dispersal of the natal circumbinary disc is vital if we are to successfully model the formation and evolution of binary stars. Simulations of this process predominantly find that the primordial mass ratio is pushed towards unity (that is, closer to equal masses in the binary components) by accretion from a circumbinary disc (Clarke 2012). This is due to the ease with which the secondary component accretes the infalling gas, as it lies farther from the binary barycentre and closer to the disc edge. Its differential velocity with respect to the gas is also low, allowing it to accrete efficiently.

The first of the circumbinary planets announced by *Kepler*, Kepler-16b, shows strong signs of having formed far out in its parent protoplanetary disc and moved inwards to its current orbital position through disc-driven migration. The system is extremely closely aligned, with the binary and planetary orbital planes aligned to within 0.3° (Doyle et al. 2011) and the binary angular momentum vector aligned to the spin vector of the primary star to with 3° (Winn et al. 2011). Combined with the planet's location at the very edge of dynamical stability (Holman & Wiegert 1999; Doyle et al. 2011), this is strongly indicative of a quiet dynamical history for the system combined with gentle disc migration.

Previous simulations of migrating circumbinary planets found that their eccentricity grows on short timescales (Pierens & Nelson 2008), but the measured eccentricity of Kepler-16b is extremely low indeed ($e = 0.0069$; Doyle et al. 2011). Even considering the osculation of the planet's orbital elements due to the non-Keplerian binary potential, the eccentricity of the planet will not rise above $e \simeq 0.07$ (Leung & Lee 2013).

In this proceedings I summarise the results of Dunhill & Alexander (2013) and Dunhill et al. (2014). In these papers smoothed particle hydrodynamics (SPH) simulations of circumbinary planetary migration and accretion onto an eccentric binary respectively highlight important mechanisms at play that help to explain observations. I discuss the implications of these results and the insights they give into circumbinary planet formation and accretion.

2. Migrating circumbinary planets

In Dunhill & Alexander (2013) we presented high resolution 3D SPH simulations of an analogue to the Kepler-16 system accompanied by a circumbinary disc. In contrast to the results of Pierens & Nelson (2008) we found that the high viscosity (Shakura & Sunyaev $\alpha = 0.01$) in our disc prohibits the planet from opening a full gap in the disc. The co-orbital material is then efficient at damping the planet's eccentricity[1].

We then derived a minimum surface density $\Sigma_{\rm min}$ for the disc through which the real Kepler-16b migrated through, by measuring the disc torques $\Gamma_{\rm d}$ from our simulations and making some simple assumptions about the planet's migration history. $\Gamma_{\rm d}$ scales linearly with the surface density in our simulations over 4 orders of magnitude in Σ. Approximating the angular momentum gained by the planet from the damping torque as $J_{\rm p} = M_{\rm p}\left(GM_{\rm b}\,a_{\rm p}(1-e^2)\right)^{1/2}$, and differentiating this with respect to eccentricity we find (to first order in e) that

$$\frac{{\rm d}J}{{\rm d}e} \simeq -eM_{\rm p}\sqrt{GM_{\rm b}\,a_{\rm p}} \tag{1}$$

so

$$\Delta J = \left|\frac{{\rm d}J}{{\rm d}e}\right| e = e^2 M_{\rm p}\sqrt{GM_{\rm b}\,a_{\rm p}}\,. \tag{2}$$

We now make the assumption that the planet's eccentricity has always been low due to this damping torque (i.e. $e < 0.1$), giving us $\Delta J = 2.3\times 10^{47}$ g cm^{2}s^{-1} for Kepler-16b. Taking some timescale for the eccentricity damping, $\tau_{\rm e}$, we require that

$$\Gamma_{\rm d} \gtrsim \frac{\Delta J}{\tau_e}. \tag{3}$$

[1]An animation of one of the simulations from Dunhill & Alexander (2013) can be found online at `http://www.acdunhill.com/kepler-16b`.

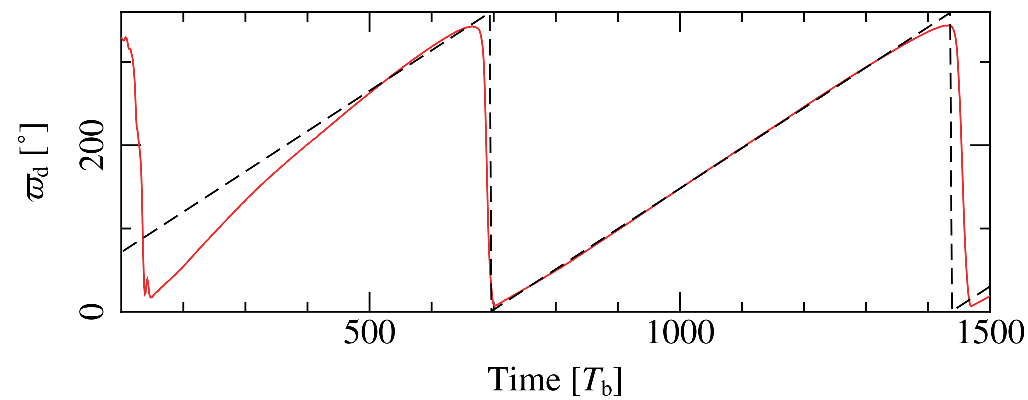

Figure 1. Evolution of the disc argument of periapse ϖ_d in the region of uniform precession (solid red) compared to a fit at late times with $\dot{\varpi} = 0.48° \, T_b^{-1}$ (dashed black).

For our fiducial simulation model with $\Sigma = 100$g cm^{-2}, we measure a net damping torque $\Gamma_d \simeq 6 \times 10^{36}$ g cm^{2}s^{-2}.

The remaining unknown is the damping timescale τ_e. Assuming that this is comparable to the migration timescale τ_{mig} gives us an order-of-magnitude estimate of the surface density required to keep the planet's eccentricity low. We adopt $\tau_e \sim 10^5 \, \Omega^{-1}$ as a conservative estimate, where Pierens & Nelson (2008) found $\tau_{mig} \sim 10^4 \, \Omega^{-1}$ for similar mass planets. Even this gives us a minimum surface density of $\Sigma_{min} \sim 10$ g cm^{-2} at the orbit of the planet. Bearing in mind that the planet must have formed far out in the disc (e.g. Paardekooper et al. 2012), this requires a disc mass of the order $0.05 - 0.1 M_b$, which is roughly canonical for discs around single stars

However, surveys of disc masses have shown that circumbinary discs are generally less massive than single star-discs – typically around $M_d \lesssim 10^{-3}$ M$_\odot$ (Andrews & Williams 2005; Kraus et al. 2011, 2012). This constraint on the disc mass for planet-forming circumbinary discs has strong implications for the processes involved in overcoming the barriers to planet formation in these discs, and clearly indicates that disc mass plays an important role.

3. Disc accretion onto eccentric binaries

In Dunhill et al. (2014) we performed SPH simulations of the disc around the eccentric young stellar binary HD 104237. This nearby ($d \sim 120 pc$) Herbig star has a mass ratio $q = 0.64$, eccentricity $e = 0.6$ and an orbital period $T_b = 20$ days (Böhm et al. 2004; Garcia et al. 2013). The system is close to face-on ($i \lesssim 20°$; Grady et al. 2004), making it an excellent system to study the accretion process on timescales of the binary orbital period. Additionally, the short period of the system makes it possible to probe the longer-term evolution of accretion in systems of this type.

The eccentric, unequal-mass binary quickly drives an eccentric, de-centered shape in the inner cavity edge. This then begins to precess under the non-Keplerian potential

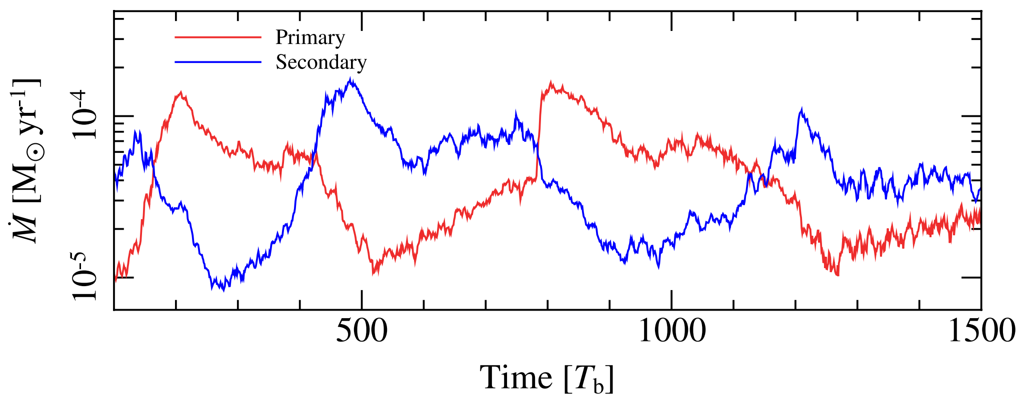

Figure 2. Evolution of the mass accretion rate $\dot{M}$ onto the two binary components (red is onto the primary, blue the secondary) measured from our SPH simulation. The periodicity is clearly tied to the disc precession shown in Figure 1.

of the binary[2]. The precession is uniform between $4 \lesssim R \lesssim 6$ binary semimajor axes a_b. I plot the evolution of the disc argument of periapse ϖ_d in Figure 1 in this region of uniform precession, compared to a fit of $\dot{\varpi} = 0.48^\circ\, T_b^{-1}$.

This precession has a strong effect on the accretion process within the cavity itself. As explained in Dunhill et al. (2014), the accretion process follows a steady pattern: one binary component pulls in an accretion stream from the cavity edge, which is then kicked across the cavity. Part of the this stream is then pulled back by the other component, which accretes most of it just before the binary reaches pericentre. However, due to the precession of the cavity, which component plays which role in this changes as a function of the cavity's position angle. Comparing the cavity precession from Figure 1 with the evolution of the accretion rate onto each binary component shown in Figure 2, we see that there is a periodicity in the accretion dictated purely by the disc precession.

The precession period for our disc is very well matched by the analytic prediction provided by Leung & Lee (2013) for circumbinary planets. We can therefore use their prescription to predict that there should be a long-term accretion variability, driven by the disc precession, for any sufficiently eccentric binary accreting from a circumbinary disc. In the case of HD 104237, we expect the timescale for this variability to be on the order of ~ 20 years. It is possible that the cavity precession itself may be observable on timescales of 2 – 4 years, given the proximity of the system and its short period.

A further result of our simulations is that averaging the accretion rates over the precession period, we find that that $\langle \dot{M}_A \rangle / \langle \dot{M}_B \rangle \sim 1$, where $\dot{M}_A$ and $\dot{M}_B$ are the accretion rates onto the primary and secondary respectively, showing that both components accrete the same mass over long time scales. This provides a viable mechanism to preserve the mass ratio for such eccentric binaries, rather than driving q towards unity.

Interestingly, there is a hint that eccentric binaries do indeed have more extreme (that is, less equal) mass ratios than their circular counterparts. Halbwachs et al. (2003) found that there is a preference for high eccentricity orbits for high mass ratio binaries ($q < 0.8$). Although tentative, this is direct evidence that this precession-accretion

[2]An animation showing this precession can be found online at `http://www.acdunhill.com/hd104237`.

mechanism helps to set the mass ratios for eccentric binaries. This result also has applications for searches for binary supermassive black holes, where the common assumption that the secondary component accretes at a higher rate clashes with the expected high eccentricities of these binaries (Roedig et al. 2011).

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