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CAVITY SIZE IN CIRCUMBINARY DISCS

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Abstract. What sets the cavity size in circumbinary discs? We investigate this by simulating circumbinary discs using smoothed particle hydrodynamics (SPH). In agreement with previous findings, we find that the cavity is largest when the binary is highly eccentric or the disc has low viscosity. We also find that discs with a low initial inclination with respect to the binary orbital plane tend towards a coplanar orbit, either through warping or tearing, leading to a cavity that is the same size as an initially coplanar disc.

Keywords: accretion, accretion discs - binaries - hydrodynamics - methods: numerical

1 Introduction

Recent highly resolved observations of the cavities in circumbinary discs, such as the one found in HD 142527 (Casassus et al. 2013; Avenhaus et al. 2017), and later attempts to model them (Price et al. 2018a) show that binaries can be responsible for cavities many times larger than their projected separation.

The formation of these cavities is thought to be a competition between Lindblad torques, which act to open the cavity, and viscous torques, which act to close it. Artymowicz & Lubow (1994) predicted that this competition results in a cavity that is largest both for the most eccentric binaries and the least viscous discs, with computational studies confirming this basic picture (Artymowicz & Lubow 1994; Pierens & Nelson 2013).

Miranda & Lai (2015) generalised this model to include discs that are misaligned to the binary orbital plane, but few computational studies have been performed to investigate the effects of inclination, focusing mainly on polar discs (Martin & Lubow 2017).

To this end we perform a series of three dimensional smoothed particles hydrodynamics (SPH) simulations to understand the effects of disc inclination, disc scale height, and binary eccentricity on the cavity size.

2 Methods

Using the SPH code `PHANTOM` (Price et al. 2018b) we set up a disc of one million particles with $R_{\rm in} = 1.4$ AU and $R_{\rm out} = 14.5$ AU around a binary with semi-major axis $a = 1$ AU. We take a binary with mass ratio $q = 0.1$, where $q = M_2/(M_1 + M_2)$ and $M_1 = 1\ {\rm M}_\odot$ is the mass of the primary. We take a disc mass of $M_{\rm disc} = 0.0001$ ${\rm M}_\odot$ with surface density varying as $\Sigma \propto R^{-1}$. We prescribe a vertically isothermal equation of state, that is $P = c_s^2(R)\rho$, with sound speed varying as $c_s \propto R^{-0.25}$. This gives a temperature profile $T \propto R^{-0.5}$ and a disc aspect ratio varying as $H/R \propto R^{0.25}$. This allows us to set the sound speed, temperature and aspect ratio by specifying the aspect ratio at $R_{\rm in}$. We simulate discs with $H/R_{\rm in} = 0.01, 0.02, 0.04, 0.05, 0.06, 0.08, 0.10$ and 0.12.

We prescribe an α disc, i.e. $\nu = \alpha c_s H$, where ν is the disc viscosity, α is the Shakura & Sunyaev (1973) viscosity parameter, c_s is the sound speed in the disc, and H is the scale height of the disc. We model the disc viscosity with an artificial viscosity parameter, α^{av} such that $\alpha = (\alpha^{av}/10)(\langle h\rangle/H)$, where $\langle h\rangle$ is the mean smoothing length. Since $H \equiv c_s/\Omega$, where Ω is the Keplerian frequency, we have $\nu = (\alpha^{av}/10)\langle h\rangle H\Omega$. This allows us to vary the viscosity by varying the scale height, with an increasing scale height leading to a stronger viscosity.

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3 Results

3.1 Time Evolution and Binary Eccentricity

Fig. 1 shows snapshots of the cavity opening process. We see that a cavity is quickly opened within $10 - 100$ binary orbits, but only reaches an equilibrium at late stages of evolution.

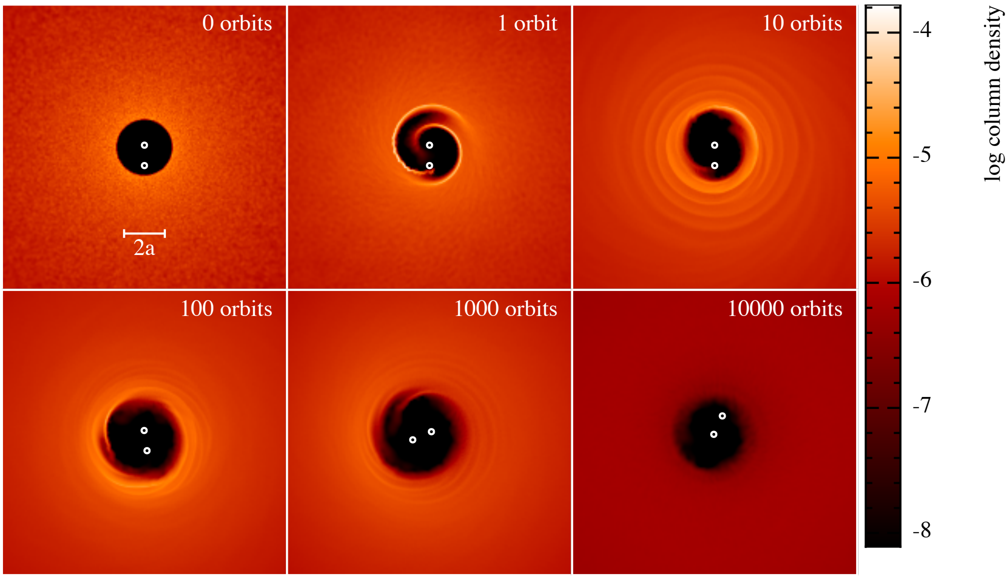

Fig. 1. Surface density rendered face-on views of the time evolution of a coplanar disc with aspect ratio $H/R = 0.05$ at R_{in}.

Fig. 2 shows the evolution of the cavity size as a function of time for the disc in Fig. 1, and compares it to discs with differing binary eccentricities. The panel on the left shows the first 100 binary orbits. We see that, as in Fig. 1, a cavity is quickly opened on this short time, and the size appears to be steady at $2 - 3$ times the binary semi-major axis. The panel on the right, however, shows the importance of evolving the viscous time ($\sim 10,000$ binary orbits). On this longer timescale we see that, for eccentric binaries, the cavity continues to grow after thousands of binary orbits, eventually settling at $2.5 - 3.5$ times the binary semi-major axis. Circular binaries are unique in that they reach their maximum cavity size after only hundreds of binary orbits.

Examining the right panel of Fig. 2 also allows us to see the late stage effects that binary eccentricity has on the cavity size. Consistent with the previous works of Artymowicz & Lubow (1994) and Miranda & Lai (2015) we find that the cavity size increases with binary eccentricity, with the sharpest increase occurring at the lowest eccentricities.

3.2 Disc Scale Height

The left panel of Fig 3 shows the cavity size as a function of disc aspect ratio after 100 binary orbits. We see that at this time the cavity size does not depend on the aspect ratio. This is because the viscous time is on the order of 10,000 binary orbits, so changing the scale height, and thus the viscosity, does not affect the cavity size at this early evolutionary stage.

The right panel of Fig. 3 shows the dependence of cavity size on disc aspect ratio after 1,000 binary orbits. While this is an order of magnitude less than the viscous time some dependence is already seen. For thin discs ($H/R \leq 0.06$) an increasing scale height leads to a decreasing cavity size. Thicker discs, however, have a cavity size that is independent of the scale height, though this may no longer be the case after the viscous time is fully resolved.

3.3 Inclination

Fig. 4 shows snapshots of the time evolution of discs initially inclined to the binary orbital plane. Both discs have a scale height $H/R = 0.05$ at $R_{\rm in}$ and orbit a binary with mass ratio $q = 0.5$. The left panel has an initial

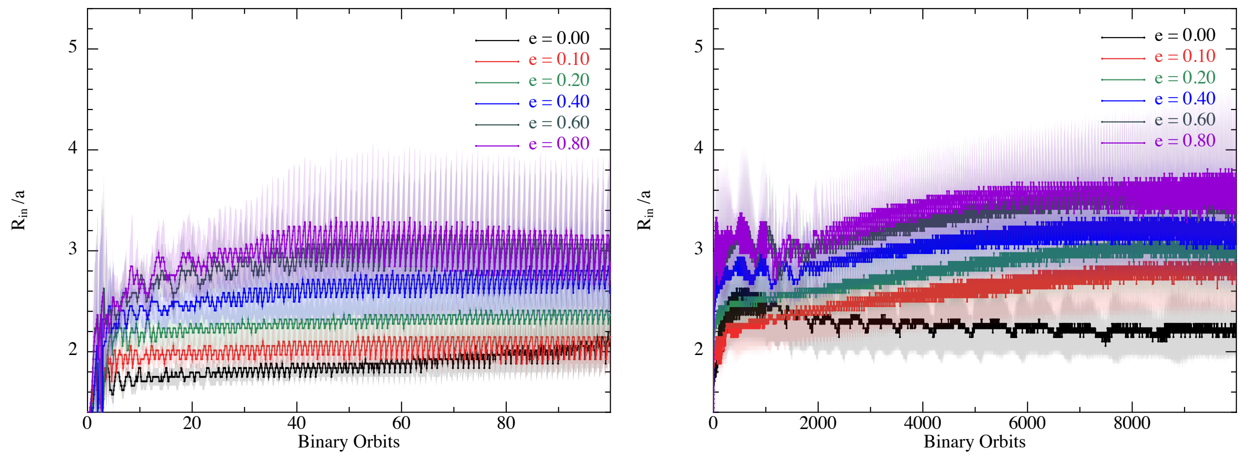

Fig. 2. Cavity size (in units of binary semi-major axis) as a function of time for coplanar discs with aspect ratio $H/R = 0.05$ at R_{in}, surrounding a binary with mass ratio $q = 0.1$ and various eccentricities. The shaded regions represents the error bars. **Left:** First 100 binary orbits. **Right:** Up to 10,000 binary orbits.

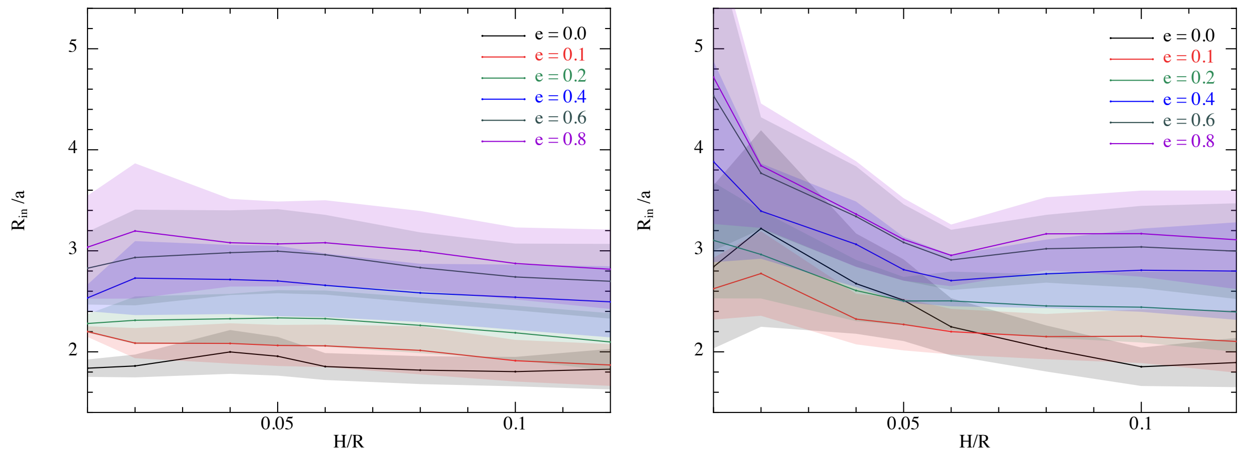

Fig. 3. Cavity size (in units of binary semi-major axis) as a function of disc aspect ratio for coplanar discs surrounding a binary with mass ratio $q = 0.1$. The shaded regions represents the error bars. **Left:** After 100 binary orbits. **Right:** After 1,000 binary orbits.

inclination of $i = 22.5°$ and the right panel has an initial inclination of $i = 45°$. In both cases the inner disc tends to align with the binary orbit. At 22.5° this alignment is driven by a warp in the disc, while at 45° the inner disc tears away, leaving an aligned inner disc and a misaligned outer disc.

The alignment of the inner disc with the binary orbital plane leads to a cavity size which is independent of the initial disc inclination, as shown in Fig. 5. This means that the cavity size gives no knowledge of the initial angle between the binary and the disc, however evidence of warps or tears within the disc may indicate some previous misalignment.

It is important to note that we only consider discs with a low initial inclination that evolve to a coplanar orbit. Highly inclined discs can evolve to a polar orbit (e.g. Martin & Lubow 2017), which may lead to a different cavity size.

4 Conclusions

We have performed a suite of 3D SPH simulations to examine the opening of a cavity in a circumbinary accretion disc, revisiting the original numerical and analytic study by Artymowicz & Lubow (1994) and comparing our results to those of Miranda & Lai (2015) for inclined discs. We considered the effects of binary eccentricity,

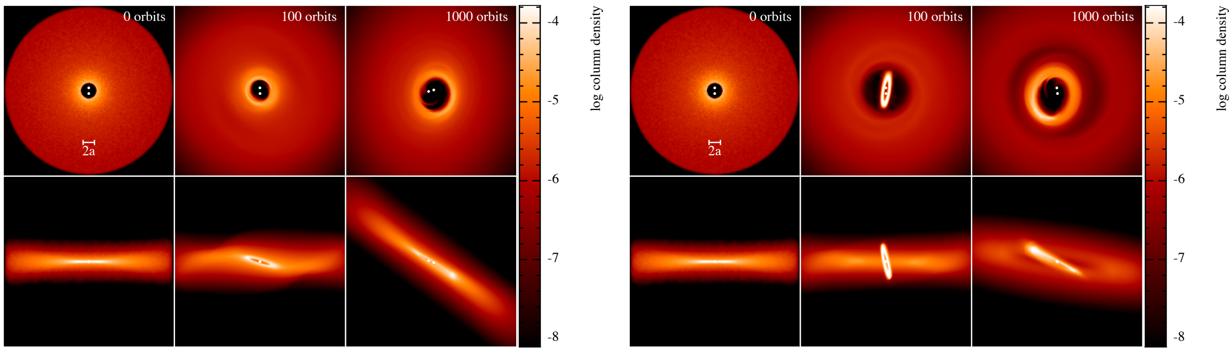

Fig. 4. Surface density rendered face-on (top row) and side-on (bottom row) views of initially inclined discs with aspect ratio $H/R = 0.05$ at R_{in} around binaries with mass ratio $q = 0.5$. **Left:** Initial inclination of $i = 22.5°$. **Right:** Initial inclination of $i = 45°$.

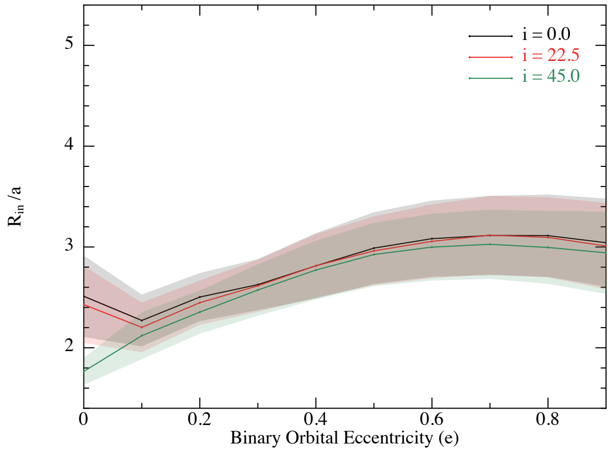

Fig. 5. Cavity size (in units of binary semi-major axis) as a function of of binary eccentricity discs with aspect ratio $H/R = 0.05$ at R_{in}, surrounding a binary with mass ratio $q = 0.1$ and various initial inclinations, after 1,000 binary orbits. The shaded regions represents the error bars.

disc viscosity, and disc inclination. Consistent with previous works, we found that the cavity size increases with binary orbital eccentricity. The effects of disc viscosity depend on the timescale considered. On a dynamical timescale the cavity size is independent of disc viscosity, while on a viscous timescale the cavity size is largest for the discs with weakest viscosity. Finally, we found that the inner regions of discs with a low initial inclination ($\leq 45°$) tend towards a coplanar orbit, either by warping or tearing, leading to a cavity size that is independent of initial inclination.

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