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The effect of binary eccentricity on the development of a warp in a protoplanetary disc

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ABSTRACT

Upon interaction with a non-spherically symmetric gravitational potential, such as that from a central misaligned binary, a protoplanetary disc experiences precessional torques leading to warps and even tears. Several low-viscosity simulations of misaligned protoplanetary discs were run with several values of binary eccentricity (e), along with a set of identical but aligned runs for comparison. In a wavelike protoplanetary disc the eccentricity was found to be a driving factor in the development of a warp, the amplitude of which increases with e.

Keywords: Protoplanetary disks (1300) — Circumstellar disks (235) — Binary stars (154) — Eccentricity (441)

1. INTRODUCTION

Most young stars or star systems host protoplanetary discs. Around a single star the disc usually remains flat. However, binary star systems introduce a non-spherically symmetric potential which warps or tears the disc if it is misaligned with respect to the binary orbital plane. The evolution of a warped disc depends on the viscosity parameter $\alpha_{\rm ss}$ (Shakura & Sunyaev 1973) and the disc aspect ratio (H/R). If $\alpha_{\rm ss} > H/R$ the warp propagates through the disc diffusively and if $\alpha_{\rm ss} < H/R$ the warp propagates as a bending wave (Papaloizou & Pringle 1983).

Aly et al. (2015) describe the effects of binary eccentricity on disc evolution as the disc differentially precessing about both the binary plane vector and the eccentricity vector, each to a degree prescribed by the magnitude of eccentricity. Specifically, they derive a condition for precession to mainly take place around the binary angular momentum vector if:

$$(1-\hat{e})^2(\hat{l}.\hat{h})^2 > 5\hat{e}^2(\hat{l}.\hat{e})^2, \tag{1}$$

where $\hat{l}$, $\hat{h}$, $\hat{e}$ are the ring specific angular momentum unit vector, binary specific angular momentum vector and binary eccentricity vector respectively. At high eccentricities this criterion is not satisfied, whereupon the disc will precess about the eccentricity vector. Aly et al. (2015) found that for a diffusive (high viscosity) disc, increasing the binary eccentricity does indeed result in precession around the eccentricity vector, causing the disc to tear into several distinct rings. This paper presents the results of simulations that model the effects of the binary eccentricity on a wavelike disc, to explore how circumbinary protoplanetary discs might behave.

2. METHOD

The Smoothed-Particle Hydrodynamics (SPH) code PHANTOM (Price et al. 2018) was used to run several simulations of protoplanetary discs around binary star systems. Each simulation featured a disc with an outer radius of $R_{\rm out} = 21$AU, with the disc misaligned to the binary orbit plane by 30°, and with a central binary with semi-major axis $a_{\rm b} = 1$AU and a mass ratio of $\mu = \frac{M_2}{M_1+M_2} = 0.3$. The only factor varied between simulations was the magnitude of eccentricity. The simulations used 10^7 SPH particles and the stars were represented by sink particles of masses 1.4 $M_\odot$ and 0.6 $M_\odot$.

3. RESULTS

The output of the simulations were visualised with SPLASH by creating density plots of every timestep. For analysis of the warp, a cross-sectional view was used (Fig. 1) where the binary orbit plane and initial disc section lie horizontally and so any warp will appear as a deviation from the horizontal. From Fig. 1 it is clear that a larger binary eccentricity increases the amplitude of the warp, even to a point of tearing at $e = 0.8$, yet for lower eccentricity values there is little additional warping and no tearing. Companion simulations were set up to span the same eccentricity values but with no initial misalignment. The bottom right plot of Fig. 1 shows the companion simulation for the $e = 0.8$ run. None of these aligned discs warped, which illustrates that a prerequisite for eccentricity to have an effect is that the disc already experiences precessional torques due to a misalignment. For each disc, the disc aspect ratio (H/R) was calculated as a function of disc radius. The viscosity parameter, $\alpha_{\rm ss}$, was calculated following Meru & Bate (2012). In all the simulations $H/R \simeq 0.05$ and $\alpha_{\rm ss} \lesssim 0.01$ satisfying the wavelike condition, meaning the results are applicable to protoplanetary discs.

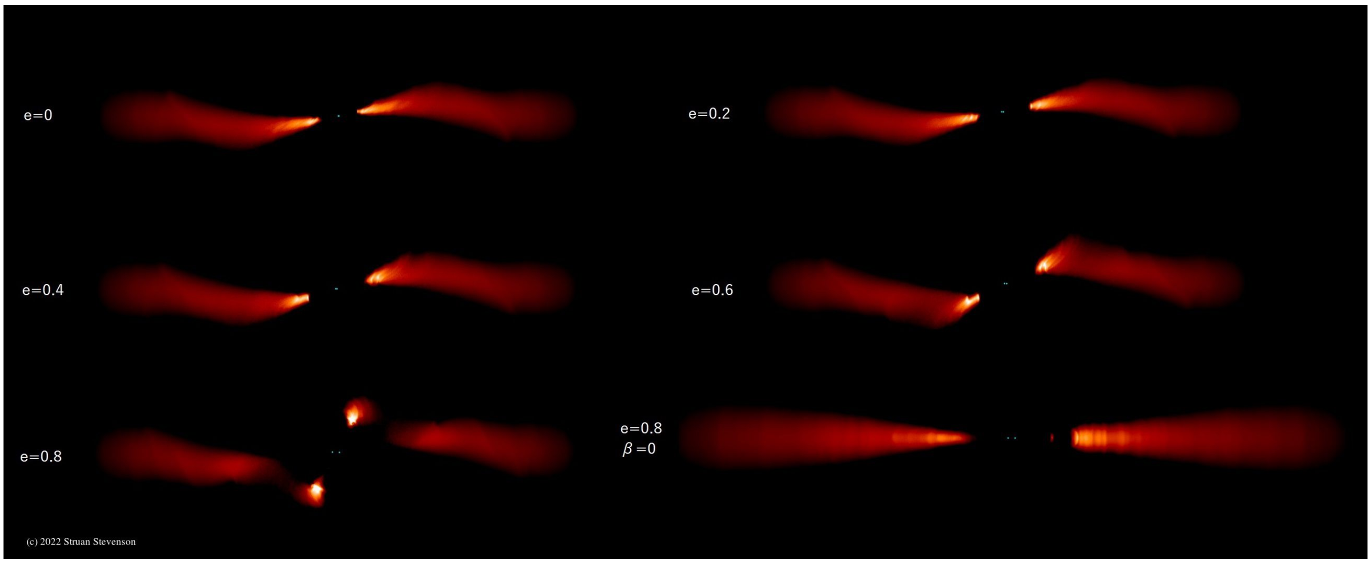

Figure 1. SPLASH density renderings of simulations after $\sim$ 100 orbits. For each simulation only eccentricity was varied, increasing from top left to bottom right. The cross section was taken along the x-axis, which is the line of intersection between the binary orbit plane and disc plane. The initial inclination in each simulation was 30°, except in the bottom-right plot where the disc was aligned to the binary plane. The stars are represented by sink particles, plotted as green dots in the figure.

4. DISCUSSION AND CONCLUSION

The simulations demonstrate that higher binary eccentricity values lead to larger warp amplitudes, agreeing with the prediction set out by Equation (1). At low eccentricities, precessional torques act about the angular momentum vector, and it is this that drives the initial warp. At higher eccentricities the disc precesses about the eccentricity vector instead. This can be seen immediately with a deepening warp in the $e = 0.2$ run. However, increasing eccentricity until precession takes place around the eccentricity vector completely tears the inner disc away, as in the $e = 0.8$ run. Theoretically, the value of e at which the condition in Equation (1) is no longer satisfied, lies in the range $0.6 < e < 0.8$.

In the diffusive disc simulations of Aly et al. (2015), discs with an initial inclination tore while the binary eccentricity was low, whereas the wavelike discs presented here only tore when $e = 0.8$. Aly et al. (2015) also found that the binary eccentricity drove eccentricity in the inner disc to the extent that matter was ejected from the disc after passing close to one binary component. This effect was not observed here, although the accretion rate is much increased as the disc inner edge becomes eccentric.

As a general result, it was found that for misaligned wavelike protoplanetary discs, binary eccentricity had a direct effect on the development of a warp. A larger binary eccentricity will increase the warp amplitude and may even tear the disc at high enough values.

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Software: PHANTOM (Price et al. 2018), SPLASH (Price 2007)

REFERENCES

Aly, H., Dehnen, W., Nixon, C., & King, A. 2015, MNRAS, 449, 65, doi: 10.1093/mnras/stv128

Meru, F., & Bate, M. R. 2012, MNRAS, 427, 2022, doi: 10.1111/j.1365-2966.2012.22035.x

Papaloizou, J. C. B., & Pringle, J. E. 1983, MNRAS, 202, 1181, doi: 10.1093/mnras/202.4.1181

Price, D. J. 2007, PASA, 24, 159–173, doi: 10.1071/AS07022

Price, D. J., Wurster, J., Tricco, T. S., et al. 2018, PASA, 35, e031, doi: 10.1017/pasa.2018.25

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337