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EXOTIC CIRCUMBINARY DISCS IN MISALIGNED SYSTEMS

A. Rocher[1] and N. Cuello[2]

Abstract. Circumbinary discs are often thought to be coplanar with the binary orbital plane. However, recent observations have revealed a few systems with significant misalignment between the binary and the disc. Recent theoretical studies explored under which conditions a misaligned circumbinary disc can become polar (Zanassi & Lai 2018). Here, we present 3D Smoothed Particle Hydrodynamics (SPH) simulations for different (aligned and misaligned) scenarios. In particular, considering an initially misaligned disc, we focus on the resulting disc alignment and its structure. This is then compared with discs that have the same final orientation but that have not experienced any alignment. Finally, we provide some clues about how planet formation might proceed in these exotic systems.

Keywords: protoplanetary discs, circumbinary discs, binaries, numerical hydrodynamics

1 Introduction

Circumbinary discs (CBDs) are thought to be coplanar with the binary orbital plane. In such a configuration, the CBD angular moment vector is orthogonal with the binary orbital plane. However, recent observations found highly misaligned systems between the disc and the binary orbital plane as in 99 Herculis (Kennedy et al. 2012), IRS 43 (Brinch et al. 2016) and HD142527 (Avenhaus et al. 2017). Surprisingly, in 99 Herculis, the debris disc around the eccentric binary ($e_{\mathrm{B}} = 0.77$) is almost in a polar configuration. This means that the disc angular momentum vector is coplanar with the binary orbital plane. These puzzling discoveries triggered the search for robust theoretical mechanisms able to explain this kind of disc alignment. Martin & Lubow (2017) demonstrated through numerical simulations that — under some specific initial conditions — a circumbinary disc can tidally evolve towards polar conguration. This mechanism has then been further investigated by Zanazzi & Lai (2018) and Lubow & Martin (2018), who provided an analytical framework to describe the polar alignment of CBDs.

2 Polar alignment conditions

We consider a circular circumbinary disc around an eccentric binary in the xy-plane with a disc aspect ratio $H/R \approx 0.1$, where H is the scale height of the disc and R the radial distance to the centre of mass. The CBD is described by means of two angles: the inclination angle between the disc and the binary orbital plane called I; and the angle between the disc plane and the direction of the ascending node* called Ω. These two angles are also called tilt and twist angles, respectively.

Zanazzi & Lai (2018) analytically described the evolution of misaligned CBDs around eccentric binaries. They introduced a parameter noted Λ that indicates which will be the final disc configuration around a binary with eccentricity e_{B}. This parameter depends on the orbital configuration and reads as follows:

$$\Lambda = (1 - e_{\mathrm{B}}^2)\cos^2 I - 5\, e_{\mathrm{B}}^2 \sin^2 I \sin^2 \Omega \tag{2.1}$$

If $\Lambda > 0$ the disc will tend to align with respect to the binary plane. Conversely, when $\Lambda < 0$ the disc will tend towards polar alignment. By setting $\Lambda = 0$, it is possible to obtain the disc critical inclination angle $I_{\mathrm{crit}} = \arctan\sqrt{(1 - e_{\mathrm{B}}^2)/(5e_{\mathrm{B}}^2)}$. This quantity defines the limit between coplanar and polar alignment regimes for a given CBD. Therefore, this criterion also constrains the value of the twist angle Ω. To sum up, there are two main conditions to obtain polar alignment $I_{\mathrm{crit}} < I < \pi - I_{\mathrm{crit}}$ and $\sin^2\Omega > \arcsin\left[(\tan^2 I_{\mathrm{crit}})/(\tan^2 I)\right]$. If both conditions are fulfilled, then the disc is expected to become polar with respect to the binary.

[1] Univ Lyon, Univ Lyon 1, ENS Lyon, CNRS, Centre de Recherche d'Astrophysique de Lyon UMR5574, 69230 St-Genis Laval, France
[2] Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Santiago, Chile

*measured in the xy-plane

3 Hydrodynamical simulations of misaligned circumbinary discs

Assuming an initially tilted disc[†], we compute the evolution of its alignment for a given initial inclination (I_0) and initial twist (Ω_0). We perform 3D hydrodynamical simulations with the PHANTOM Smoothed Particle Hydrodynamics (SPH) code (Price et al. 2018). We choose the same parameters for the binary and the CBD as Martin & Lubow (2017). We consider an equal mass binary $M = M_1 + M_2 = 1\,M_\odot$ in the xy-plane with an eccentricity equal to $e_B = 0.5$, and a semi-major axis $a_\mathrm{B} = 0.1$ au, which gives a binary period $T_\mathrm{B} = 11.55$ days. We use 10^6 gas particles to simulate the CBD. The inner and the outer radii of the disc are equal to $R_\mathrm{in} = 2\,a_\mathrm{B}$ and $R_\mathrm{out} = 5\,a_\mathrm{B}$, respectively. Initially, the disc surface density follows a power-law profile given by $\Sigma \propto R^{-3/2}$. In addition, the disc mass is set to $M_\mathrm{d} = 0.001\,M_\odot$. We further assume that the disc is locally isothermal, i.e. that the sound speed follows a radial power-low $c_\mathrm{s} \propto R^{3/4}$, with $H/R = 0.1$ at $R = R_\mathrm{in}$. Finally, we use a mean Shakura-Sunyaev disc viscosity equal to $\alpha \approx 0.01$ (Shakura & Sunyaev 1973).

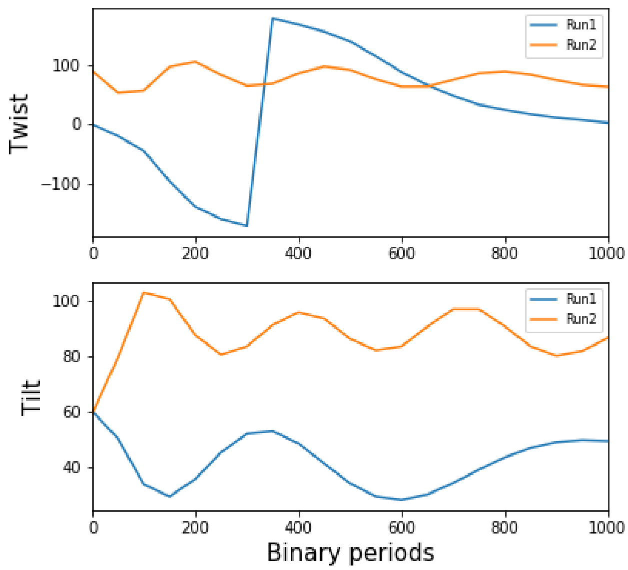

Fig. 1. Evolution of twist (**top panel**) and tilt (**bottom panel**) angles for run 1 ($I_1 = 60°$ and $\Omega_1 = 0°$) in blue and for run 2 ($I_1 = 60°$. $\Omega_1 = 90°$) in orange.

We consider two simulations: one with an initial tilt $I_1 = 60°$ and an initial twist angle $\Omega_1 = 0°$ (called run 1), and another one with $I_2 = 60°$ and $\Omega_2 = 90°$ (run 2). Based on the conditions presented in Sect. 2, we expect the CBD to tend towards a coplanar configuration in run 1; while, in run 2, the CBD should tend towards a polar configuration. Figure 1 shows the evolution of the twist (upper panel) and tilt (lower panel) for both simulations after 1000 binary periods. In run 1, the disc slowly tends towards lower inclinations while Ω circulates; whereas, in run 2, the disc quickly (compare to run 1) becomes polar $I = 90°$ and Ω librates. Run 1 will tend towards $I = 0°$ after several thousands of binary orbits (not shown in Fig. 1). The state of the disc for the run 2 after 1000 binary periods is shown in Fig.2 (middle row). This is to be compared with a CBD which was initially in a polar configuration (i90, bottom row). After 1000 binary orbits, the CBD in run 2 is almost indistinguishable from the one in i90.

In our simulations, we notice that the inner cavity of the disc in polar configuration is smaller than the one in the coplanar case. This result is consistent with previous analytical work by Miranda & Lai (2015). Therefore, the process of planet formation is expected to be affected by polar alignment (Cuello & Giuppone, submitted).

4 Discussion and Conclusion

We studied the conditions upon which a misaligned circumbinary disc — around an eccentric binary — tends towards polar alignment. Using 3D SPH simulations we followed the evolution of the inclination of several circumbinary discs with different initial conditions. Our results are in agreement with the theoretical predictions described in Sect. 2. Since the resonant torques in the polar configuration are different (e.g. smaller inner cavity) this eventually modifies the process of planet formation in CBDs. As a matter of fact, the mechanism of disc alignment leads to polar configurations where we expect to form planets on polar orbits. It is worth stressing that polar alignment in circumbinary discs is more efficient for equal-mass binaries and high eccentricities (Lubow & Martin 2018). Consequently, equal-mass binaries with high eccentricities should be considered as promising targets for searching for extrasolar polar planets.

[†]likely outcome after an inclined retrograde stellar flyby for instance (Xiang-Gruess (2016); Cuello et al., submitted).

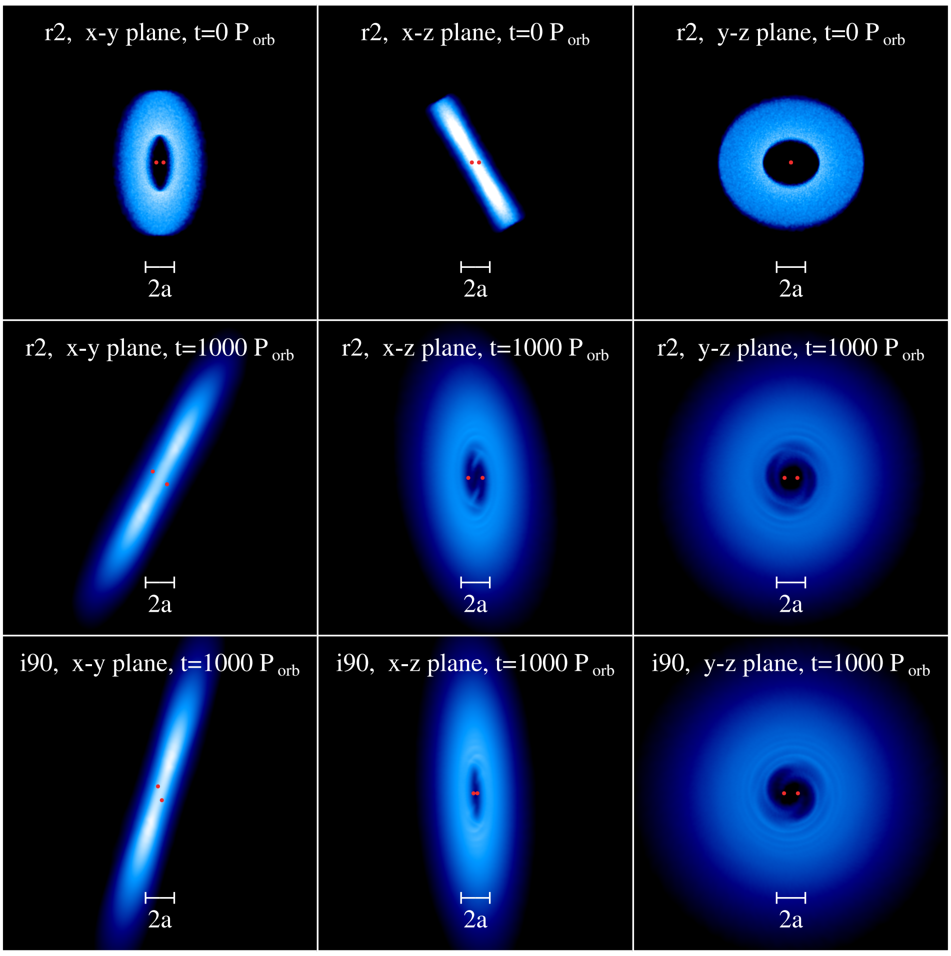

Fig. 2. Circumbinary disc configurations for run 2 at $t = 0$ (**upper row**) and $t = 1000\,T_\mathrm{B}$ (**middle row**) in the xy-plane (**left column**), xz-plane (**middle column**) and yz-plane (**right column**). T_B corresponds to a binary period. These are to be compared with the configuration of a circumbinary disc, which was initially polar ($I_\mathrm{polar} = 90°$, $\Omega_\mathrm{polar} = 90°$), at $t = 1000\,T_\mathrm{B}$ (**lower row**). The stars of the binary are represented by red dots.

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