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EXOTIC TATOOINES IN MISALIGNED CIRCUMBINARY DISCS

N. Cuello[1, 2] and C. A. Giuppone[3]

Abstract. Circumbinary discs are often assumed to be coplanar with the inner binary orbital plane. However, recent observations and theoretical works suggest that misaligned configurations might be more common than previously thought. Interestingly, it has been shown that polar configurations — where the disc and binary orbital planes are orthogonal — are dynamically stable. In this work, we study the stability and the evolution of a single planet around a stellar binary (also called a Tatooine planet) for inclined configurations. Then, we test the theoretical predictions of disc alignment through 3D hydrodynamical simulations of inclined circumbinary discs around eccentric binaries. Our results show that — under some specific initial conditions — the circumbinary disc exhibits an unexpected behaviour. Namely, for retrograde highly inclined circumbinary discs, the disc breaks and becomes polar. Ultimately, the mechanism of polar alignment is expected to affect planet formation in these systems.

Keywords: planets, binaries, evolution, stability, protoplanetary discs, hydrodynamics

1 Introduction

It is now commonly accepted that planets form in protoplanetary discs. Circumstellar and circumbinary discs are routinely detected around young stars (Avenhaus et al. 2018). Since stellar formation occurs within turbulent molecular clouds, planet formation is expected to be affected by this environment as well (Bate 2018). As a matter of fact, stellar flybys are likely to occur during this phase (Pfalzner 2013). During this kind of encounters the protoplanetary disc can be severely affected as shown by Clarke & Pringle (1993). More recently, Xiang-Gruess (2016) and Cuello et al. (submitted) found through 3D Smooth Particles Hydrodynamical (SPH) simulations that flybys can efficiently tilt and twist the disc by several tens of degrees.

Consequently, if such encounters are frequent, then a given circumbinary disc (CBD) can potentially become misaligned. Given that planet formation is expected to occur within CBDs (Martin 2018), misaligned circumbinary planets are a likely outcome (Addison et al. 2018). Therefore, it is relevant to explore whether misaligned planets are dynamically stable or not around (eccentric) stellar binaries.

2 Stability of inclined Tatooines

We model a single Tatooine planet as a test particle around a stellar binary with eccentricity $e_{\rm B} = 0.5$ and semi-major axis $a_{\rm B} = 0.1$ au. We set the individual masses to M_1 and M_2, with the condition $M_1 + M_2 = 1\,M_\odot$. For the planet orbital parameters we use Jacobi coordinates. We call a the semi-major axis with respect to the binary, and i the inclination with respect to the binary orbital plane. The longitude of the ascending node (also called twist) is noted Ω. Initially, we set the planet on a circular orbit as one would expect in a relaxed disc. Then, we construct a 2D-mesh of initial conditions for different pairs of planetary orbital parameters. The three-body equations of motion are numerically integrated with a Bulirsch-Stoer integrator (double precision, with tolerance 10^{-12}). Each orbit is integrated for 80 000 binary periods. For more details on the initial setup, please refer to Cuello & Giuppone (submitted).

To assess whether or not the expected behaviour of the planet is chaotic, we compute the MEGNO value $\langle Y \rangle$ (Mean Exponential Growth of Nearby Orbits) for each of the initial conditions considered. This indicator

[1] Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Santiago, Chile,
[2] Núcleo Milenio de Formación Planetaria (NPF), Chile,
[3] Universidad Nacional de Córdoba, Observatorio Astronómico, IATE, Laprida 854, 5000 Córdoba, Argentina,

is useful because it identifies chaotic orbits at a low CPU-cost (Cincotta & Simó 2000). Our results show that, when $\Omega = 0°$, the prograde orbits are stable only beyond $3.5\,a_{\rm B}$; whereas retrograde orbits are stable closer to the binary centre of mass ($a \sim 2.2\,a_{\rm B}$). Alternatively, when $\Omega = 90°$, new stable regions appear between 0.2 and 0.3 au. Finally, by changing the values of M_1 and M_2, we study the impact of the binary mass ratio (q) on the stability of the planetary orbit. Considering $q = 0.5$ and $q = 0.2$, we find that the resonances become stronger with increasing q. That is the reason why the polar regions ($i \sim 90°$) are depleted on long time-scales (i.e. high MEGNO values). For further details, see section 2.1. in Cuello & Giuppone (submitted).

To sum up, our results are in excellent agreement with the ones previously reported by Doolin & Blundell (2011). Additionally, in Cuello & Giuppone (submitted) we consider massive planets and discuss in detail the dynamical behaviour of exotic Tatooines.

3 Disc breaking and unexpected polar alignment

In order to test the analytical predictions for the CBD alignment, we run 3D-hydrodynamical simulations with the PHANTOM Smoothed Particle Hydrodynamics (SPH) code Price et al. (2018). This method is well-suited for misaligned systems since there is no preferred geometry and angular momentum is conserved, as opposed to non-Lagrangian numerical schemes. To be able to compare our results with Martin & Lubow (2018), we chose the very same binary and disc parameters: an equal mass binary ($M_1 = M_2$) in the $x - y$ plane with total mass $M = M_1 + M_2 = 1\,M_\odot$ and eccentricity equal to $e_{\rm B} = 0.5$. Moreover, we set the semi-major axis to $a_{\rm B} = 0.1$ au. Both stars are represented by sink particles with accretion radii equal to $0.25\,a_{\rm B}$. The disc inner and outer radii are equal to $R_{\rm in} = 2\,a_{\rm B}$ and $R_{\rm out} = 5\,a_{\rm B}$, respectively. The surface density profile initially follows a power-law profile $\Sigma \propto R^{-3/2}$. In this work, we model the gaseous disc with 10^6 gas particles — a detailed discussion about resolution effects can be found in Martin & Lubow (2018). The disc mass is equal to $0.001\,M_\odot$, therefore we neglect self-gravity effects. Moreover, we assume that the disc is locally isothermal and follows $c_{\rm s} \propto r^{-3/4}$, with $H/R = 0.1$ at $R = R_{\rm in}$. Finally, we adopt a mean Shakura-Sunyaev disc viscosity $\alpha_{\rm SS} \approx 0.01$. For more details about the PHANTOM disc setup, please refer to Price et al. (2018).

The disc is initially inclined according to the two angles i and Ω introduced in Section 2. For the set of simulations considered in Cuello & Giuppone (submitted), we find that all the CBDs tend towards equilibrium configurations within the separatrix region, except in one simulation. The criterion that defines which kind of alignment is expected is described in Zanazzi & Lai (2018) and it involves the initial tilt (i_0) and twist (Ω_0) values. In the "anomalous" simulation, $i_0 = 120°$ and $\Omega_0 = 0°$. Hence, according to Zanazzi & Lai (2018), the disc should anti-align with respect to the binary. However, we see that after 165 binary orbits (noted $T_{\rm b}$) the disc breaks. In fact, the inner regions of the CBD suddenly fulfil the condition for polar alignment, whereas the outer regions do not. When this happens, the disc stops behaving as a solid body. In Cuello & Giuppone (submitted) we show that, after 165 $T_{\rm b}$, the tilt of the disc starts to oscillate around 90° and that the twist librates instead of circulating. Then, after a few hundreds of binary periods, the whole CBD becomes almost perfectly polar. The behaviour of this highly inclined and retrograde CBD is unexpected in the sense that it could not be theoretically predicted, given the initial conditions chosen.

4 Conclusions and future work

The main conclusions of this investigation can be summarised as follows:

- Polar circumbinary planets, also called polar Tatooines, are remarkably stable on long time-scales at distances of the order of just a few binary separations (0.1 au in this study).
- Assuming CBDs are perturbed during their evolution, a broad range of these discs are expected to become polar. It is therefore reasonable to expect Tatooines on polar orbits.
- Regarding the CBD alignment, the symmetry between retrograde and prograde configurations is broken under some specific initial conditions (as shown in Figure 1). This is due to non-linear effects that were not accounted for in previous analytical works.

The mechanism of polar alignment of CBDs has deep implications for planet formation around eccentric binaries. Namely, Tatooines could form closer to the binary and, more importantly, have orbits orthogonal to the binary orbital plane. From the observational perspective, this could explain the seeming lack of circumbinary planets compared to the overwhelming number of planets around single stars. As a concluding remark, we note that equal-mass binaries with high eccentricities are the most promising targets for discovering polar Tatooines.

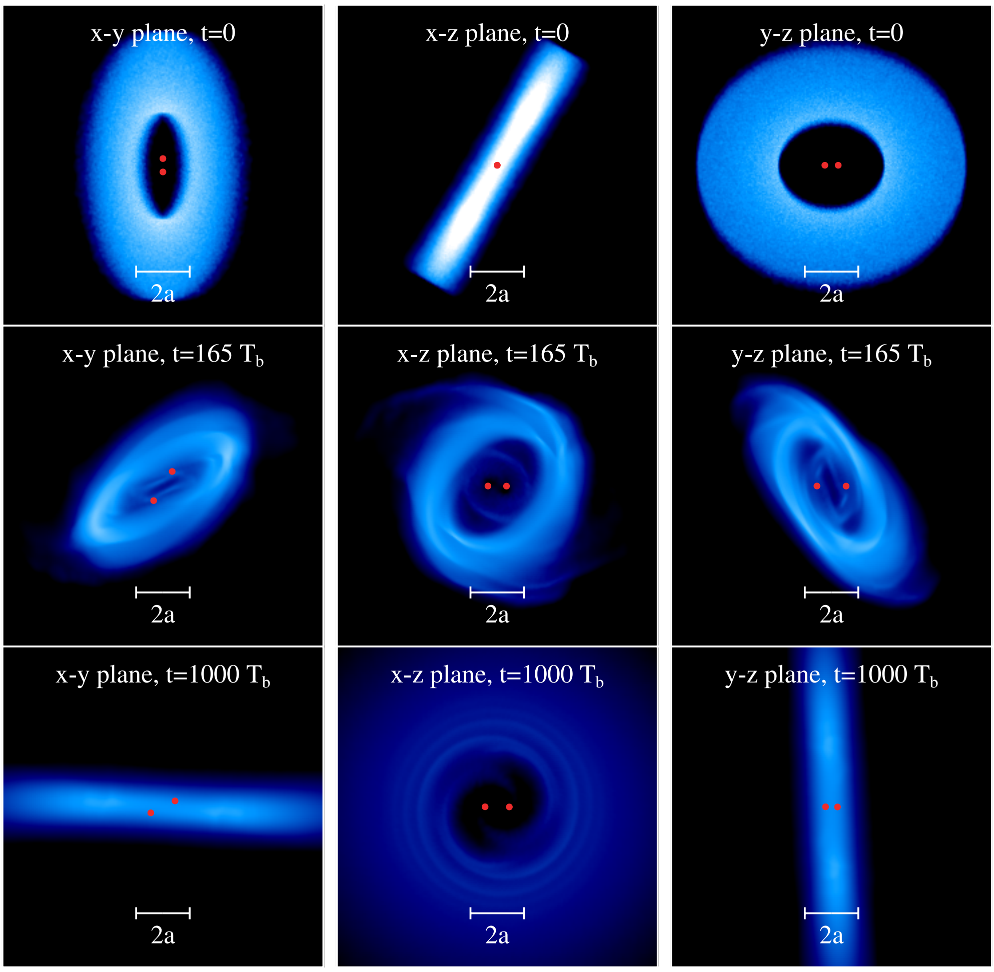

Fig. 1. Circumbinary disc evolution for a highly inclined retrograde configuration. Initially, the binary plane lies in the xy-plane and the disc is highly inclined ($i_0 = 120°$, $\Omega_0 = 0°$). After 165 binary orbits, the tilt is different between the inner and the outer regions of the disc. This is interpreted as disc breaking induced by the binary. Then, the inner regions experience a fast polar alignment, causing the whole disc to become polar after roughly 400 binary orbits.

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