

# Stability and dynamics of misaligned circumbinary discs

Nicolás Cuello<sup>1,2</sup> and Cristian A. Giuppone<sup>3,4</sup>

<sup>1</sup> Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Santiago, Chile, e-mail: ncuello@astro.puc.cl

<sup>2</sup> Núcleo Milenio de Formación Planetaria (NPF), Chile,

<sup>3</sup> Universidad Nacional de Córdoba, Observatorio Astronómico, IATE, Laprida 854, 5000 Córdoba, Argentina,

<sup>4</sup> CIDMA, Departamento de Física, Universidade de Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal.

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## ABSTRACT

**Context.** Due to observational biases, circumbinary planet detections are rather rare. In fact, up to now, only a handful of binary systems with planets have been reported (by *Kepler* mainly). However, planet formation is expected to occur around binary stars as well. Dynamical studies suggest that most of the circumbinary discs should be coplanar, i.e. the rotation vectors of the binary and the disc are aligned. Interestingly, some recent theoretical works show that under certain conditions circumbinary discs can become polar, which means that the rotation vectors are orthogonal.

**Aims.** In this work, we explore how these conditions could be reached and we assess how likely is the disc to become polar with respect to the binary.

**Methods.** We present 3D smoothed particle hydrodynamics (SPH) simulations of misaligned discs and follow their resulting alignments. In addition, we study the stability of the **inclined and polar** configurations through N-body simulations.

**Results.** We confirm previous predictions and show that a broad range of configurations lead to polar and retrograde discs. In such cases, the resulting planetary architectures should be polar and retrograde as well.

**Conclusions.** Despite their low probability of detection, we suggest that polar and retrograde (S-type) planets might be rather common around **those binary stars that suffered close encounters**.

**Key words.** protoplanetary discs – hydrodynamics – methods: numerical – planets and satellites: formation

## 1. Introduction

Planets are thought to be common by-products of the star formation process within molecular clouds (Chiang & Youdin 2010). At early evolutionary stages (class 0/I), the fraction of stellar binaries and higher-order multi-star systems is remarkably high: between 30% and 70% (Connelley et al. 2008; Chen et al. 2013). Consequently, protoplanetary discs can be severely affected by **stellar flybys** and binary formation (Pfalzner 2013; Bate 2018). Given the stochasticity of these processes, highly asymmetrical discs naturally form in time-scales of the order of a few hundreds of kyr. Therefore, planet formation is expected to occur in a broad variety of systems (see e.g. Cuello et al. 2018, Bate 2018). Currently, about a hundred planets have been detected in multiple-star systems (Martin 2018). There is however a striking tension with the more than 3700 planets detected around single stars (Batalha et al. 2013).

Planets can either be circumbinary (P-type) or circumstellar (S-type). The seeming lack of P-type planets has been ascribed to observational biases and dynamical processes. On the one hand, these are intrinsically difficult to observe through radial velocities (Eggenberger & Udry 2007; Wright et al. 2012) and transit methods (Martin & Triana 2014). In fact, for transits in non-coplanar systems, the arbitrary orientation of the planet chord coupled to the fact that most binaries do not eclipse renders P-type planet detection extremely challenging. On the other hand, Fleming et al. (2018) showed through stellar-tidal evolution models of short-period binaries **that the binary orbital period increases, expanding the region of dynamical instability around the binary**. This leads to dynamical instabilities, which

would explain the lower frequency of P-type planets compared to S-type planets. Based on the available data, typical planets found around binary stellar systems have a radius of the order of 10 Earth radii and orbital periods of about 160 days (Martin 2018). Around a binary system with total mass equal to  $1 M_{\odot}$ , this corresponds to an orbit with semi-major axis of approximately 0.35 au.

Additional studies suggest that the disc-binary interaction, namely the gravitational torque, should align the disc with the binary orbital plane in time-scales shorter than the disc lifespan (Foucart & Lai 2013). Therefore, until recently, misaligned circumbinary discs (CBDs) were considered as *exotic*. However, the observations of highly non coplanar systems such as 99 Herculis (Kennedy et al. 2012), IRS 43 (Brinch et al. 2016) and HD142527 (Avenhaus et al. 2017) suggest otherwise. Remarkably, the debris disc around the 99 Herculis is thought to be in a polar configuration with respect to the binary, i.e. the disc and the binary orbital planes are orthogonal. These discoveries are rather puzzling and deserve to be explained.

In the field of secular dynamics, the seminal work on planetary orbits around binary systems by Ziglin (1975) was recently expanded to higher expansions by Laskar & Boué (2010) and Farago & Laskar (2010). In particular, in the restricted and massive three-body problem, it is shown that equilibrium configurations can be reached at high inclinations. Further studies on circumbinary disc dynamics applied to polar orbits are in agreement with this statement (Li et al. 2014). Complementary **Solar System** studies proved that the orientation between the orbits (Naoz et al. 2017; Zanardi et al. 2017, 2018) and dissipative ef-