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Inclinations of Circumbinary Planets: Assembly of Protoplanetary Discs and Secular Binary-Disc Interaction

Dong Lai[1] **and Francois Foucart**[2]

[1]Department of Astronomy, Cornell University, Ithaca, NY 14853, USA
email: dong@astro.cornell.edu

[2]CITA, University of Toronto, Canada

Abstract. The *Kepler* satellite has discovered a number of transiting planets around close binary stars. These circumbinary systems have highly aligned planetary and binary orbits. In this paper, we explore how the mutual inclination between the planetary and binary orbits may reflect the physical conditions of the assembly of protoplanetary discs and the interaction between protostellar binaries and circumbinary discs. Given the turbulent nature of star-forming molecular clouds, it is possible that the infalling gas onto the outer region of a circumbinary disc rotates around a different axis compared to the central protostellar binary. Thus, the newly assembled circumbinary disc can be misaligned with respect to the binary. However, the gravitational torque from the binary produces warp and twist in the disc, and the back-reaction torque tends to align the disc and the binary orbital plane. We present a new, analytic calculation of this alignment torque, and show that the binary-disc inclination angle can be reduced appreciably after the binary accretes a few percent of its mass from the disc. Since mass accretion onto the proto-binary is very likely to occur, our calculation suggests that in the absence of other disturbances, circumbinary discs and planets around close (sub-AU) stellar binaries are highly aligned with the binary orbits, while discs and planets around wide binaries can be misaligned.

Keywords. accretion, accretion discs – hydrodynamics – planetary systems: protoplanetary discs – stars: binary

1. Introduction

The extremely precise photometry and nearly continuous observations provided by the *Kepler* satellite have led to the discovery of a number of transiting planetary systems around stellar binaries. At the time of this writing, six such circumbinary systems were known, including Kepler-16 (with stellar binary period 41 d and planet orbital period 229 d; Doyle *et al.* 2011), Kepler-34 (28 d, 289 d), Kepler-35 (21 d, 131 d; Welsh *et al.* 2012), Kepler-38 (19 d, 106 d; Orosz *et al.* 2012a), Kepler-47 (stellar binary orbit 7.45 d, with two planets of periods 49.5 d and 303.2 d; Orosz *et al.* 2012b), and KIC 4862625 (20 d, 138 d; Schwamb *et al.* 2012, Kostov *et al.* 2012). The stars in these systems have masses of order the solar mass or smaller, and planets have radii ranging from $3.0R_\oplus$ (Kepler-47b) to $0.76R_J$ (Kepler-34b).

By virtue of their detection methods, all the Kepler circumbinary systems have highly aligned planetary and stellar orbits, with the mutual orbital inclinations constrained between $\Theta \sim 0.2^\circ$ (for Kepler-38b) and $\Theta \lesssim 2^\circ$ (Kepler-34b and Kepler-35b). In Kepler-16, the measurement of Rossiter-McLaughlin effect further indicates that spin of the primary is aligned with the stellar binary (Winn *et al.* 2011). A natural question arises: Do misaligned ($\Theta \gtrsim 5^\circ$) circumbinary planetary systems exist? If so, under what conditions can they form?

One might expect that circumbinary systems natually form with highly aligned orbits, since the associated orbital angular momenta originate from the protostellar cores. However, several lines of evidence suggest misaligned configurations may be present in some systems:

(i) Solar-type main-sequence binaries with large separations ($\gtrsim$ 40 AU) often have misaligned rotational equators relative to the orbital plane (Hale 1994). Misalignments are also observed in some short-period binaries, such as DI Hercules (with orbital period of 10 days; Albrecht *et al.* 2009; see also Albrecht *et al.* 2011; Konopacky *et al.* 2012; Triaud *et al.* 2013).

(ii) Some binary young stellar objects (YSOs) are observed to contain circumstellar discs that are misaligned with the binary orbital plane (e.g., Stapelfeldt *et al.* 1998). Also, several unresolved YSOs or pre-MS binaries have jets along different directions, again suggesting msialigned discs (e.g., e.g., Davis, Mundt & Eislöffel 1994; Roccatagliata *et al.* 2011).

(iii) Imaging observations of circumbibary debris discs show that the disc plane and the binary orbital plane are aligned for some systems (such as α CrB, β Tri and HD 98800), and misaligned for others (such as 99 Herculis, with mutual inclination $\gtrsim 30°$; see Kennedy *et al.* 2012a,b). Also, the pre-main sequence binary KH 15D is surrounded by a precessing circumbinary disc inclined to the binary plane by 10°-20° (e.g., Winn *et al.* 2004; Chiang & Murray-Clay 2004; Capelo *et al.* 2012), and the FS Tauri circumbinary disc appears to be misaligned with the circumstellar disc (Hioki *et al.* 2011).

While the aforementioned "misalignments" may have various origins (e.g., dynamical interactions between in a few body systems), in this paper we focus on the possible existence warped, misaligned discs around proto-stellar binaries. We consider scenarios for the assembly of circumbinary discs in the context of binary star formation (Section 2). These scenarios suggest that circumbinary discs may form with misaligned orientations with respect to the binary. We then study the mutual gravitational interaction between the msialigned disc and the binary and the long-term evolution of the binary-disc systems (Section 4). We discuss our results in Section 4 and conclude in Section 5.

2. Formation of Binary and Circumbinary Disc: Scenarios

Binary stars are thought to form by fragmentation inside the collapsing cores/clumps of molecular clouds, either due to turbulent fluctuation in the core ("turbulent fragmentation"; e.g., Goodwin *et al.* 2007; Offner *et al.* 2010) or due to gravitational instability in the resulting disc ("disc fragmentation"; e.g., Adams *et al.* 1989; Kratter *et al.* 2008). In the turbulent fragmentation scenario, the binaries form earlier and have initial separations of order 1000 AU. Disc fragmentation also lead to binary at large initial separations ($\sim$ 100 AU). In both cases, continued mass accretion and inward migration, either due to binary-disc interactions (e.g., Artymowicz & Lubow 1996) or dynamical interactions in few-body systems, are needed in order to produce close (sub-AU) binaries. Planet formation can take place in the circumbinary disc during or after the binary orbital decay.

In the simplest picture, the proto-binary and circumbinary disc rotate in the same direction. However, molecular clouds and the collapsing cores are turbulent (see McKee & Ostriker 2007; Klessen 2011). It is natural that the condensing and accreting cores contain gas which rotates around different directions. Even if the cores are not turbulent, tidal torques between neighboring cores in a crowded star formation region can change the rotation direction of the outer regions of the condensing/accreting cores. Thus the gas that falls onto the central protostellar core and assembles onto the disc at different

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times may rotate in different directions. Such "chaotic" star formation has been seen in some numerical simulations (Bate *et al.* 2003). In this scenario, it is reasonable to expect a rapidly rotating central proto-stellar core which fragments into a binary, surrounded by a misaligned circumbinary disc which form as a result of continued gas accretion.

The mutual gravitational interaction between a proto-binary and the circumbinary disc leads to secular evolution of the relative inclination between the disc and the binary plane. In most cases, this interaction, combined with continued mass accretion, tend to reduce the misalignment. We will address these issues in the next two sections. Note that previous works have focused on warped *circumstellar* discs inclined relative to the binary (e.g., Papaloizou & Terquem 1995; Bate *et al.* 2000; Lubow & Ogolvie 2000). The warped/twisted circumbinary discs studied below have qualitatively different behaviours.

3. Warped Circumbinary Discs and Disc-Binary Inclination Evolution

Consider a circumbinary disc surrounding a stellar binary. The two stars have masses M_1 and M_2, and are assumed to be on a circular orbit with semi-major axis a. The circumbinary disc has surface density $\Sigma(r)$, and extends from $r_{\rm in}$ to $r_{\rm out}(\gg r_{\rm in})$. The inner disc is truncated by the tidal torque from the binary, and typically $r_{\rm in} \sim 2a$ (Artymowicz & Lubow 1994; MacFadyen & Milosavljevic 2008). The orientation of the disc at radius r (from the center of mass of the binary) is specified by the unit normal vector $\hat{\boldsymbol{l}}(r)$. Averaging over the binary orbital period and the disc azimuthal direction, the binary imposes a torque on the disc element. To leading order in a/r, the torque per unit area at radius r is given by

$$\mathbf{T}_{\rm b} = -\frac{3}{4}\frac{GM_t\eta\Sigma a^2}{r^3}\,(\hat{\boldsymbol{l}}_b\cdot\hat{\boldsymbol{l}})(\hat{\boldsymbol{l}}_b\times\hat{\boldsymbol{l}}), \tag{3.1}$$

where $M_t = M_1 + M_2$ is the total mass and $\eta = M_1M_2/M_t^2$ the symmetric mass ratio of the binary, and $\hat{\boldsymbol{l}}_b$ is the unit vector along the orbital angular momentum of the binary. Under the influence of this torque, the angular momentum of a isolated disc element would precess at the frequency $-\Omega_p\cos\beta$, where β is the angle between $\hat{\boldsymbol{l}}_b$ and $\hat{\boldsymbol{l}}$, and

$$\Omega_p(r) \simeq \frac{3\eta}{4}\frac{a^2}{r^2}\,\Omega(r), \tag{3.2}$$

with $\Omega(r) \simeq \Omega_K = (GM_t/r^3)^{1/2}$ the disc rotation rate. Since Ω_p depends on r, the differential precession can lead to twisting and warping of the disc.

In Foucart & Lai (2013), we presented an analytic calculation of the steady-state twist/warp of the circumbinary disc. We considered a disc whose rotation axis at the outer radius ($r_{\rm out}$), $\hat{\boldsymbol{l}}_{\rm out} = \hat{\boldsymbol{l}}(r_{\rm out})$, is inclined relative to the binary direction $\hat{\boldsymbol{l}}_b$ by a finite angle, $\beta(r_{\rm out}) \equiv \Theta$. This corresponds to the situation where the outer disc region is fed by gas rotating around the axis $\hat{\boldsymbol{l}}_{\rm out}$. Skipping over the technical details here, we found that for standard disc and binary parameters ($\eta = 0.25$, $\alpha = 10^{-3}$-10^{-2}, $\delta = H/r = 0.1$ and $r_{\rm in} \simeq 2a$), the steady-state disc is almost flat, with its orientation determined by $\hat{\boldsymbol{l}}_{\rm out}$, i.e., the angular momentum axis of the gas falling onto the outer disc. The steady-state warp/twist is achieved on the timescale of bending wave propagation $t_{\rm warp} \sim 2/(\delta_{\rm out}\Omega_{\rm out})$. This timescale is much shorter than the age of the system or the gas accretion time $t_{\rm acc} \sim \left(r^2/\nu\right)_{\rm out} \sim 1/(\alpha\delta_{\rm out}^2\Omega_{\rm out})$.

On a timescale longer than $t_{\rm warp}$, the warped disc exerts a back-reaction torque on the binary, aligning $\hat{\boldsymbol{l}}_b$ with the disc axis (more precisely, with $\hat{\boldsymbol{l}}_{\rm out}$). We found that the total

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alignment torque can be written as

$$\begin{aligned} \mathcal{T}_{\rm align} &= \mathcal{T}_{{\rm acc},x} + \mathcal{T}_x \\ &\simeq (g + f\cos^2\Theta)\dot{M}(GM_t r_{\rm in})^{1/2}\sin\Theta, \end{aligned} \tag{3.3}$$

where $\mathcal{T}_{{\rm acc},x}$ arises from the mass accretion ($g \sim 1$ is a constant), and $\mathcal{T}_x$ is due to gravitational interaction, with

$$f = \frac{24}{(2p+3)(4p+5)}\eta^2\left(\frac{a}{\delta_{\rm in} r_{\rm in}}\right)^4. \tag{3.4}$$

In the above, we have assumed disc models with constant α, and assumed that the surface density and the dimensionless disc thickness have the power-law profiles

$$\Sigma \propto r^{-p}, \quad \delta = \frac{H}{r} \propto r^{(2p-1)/4}, \tag{3.5}$$

so that $\dot{M} \sim \nu\Sigma = \alpha H^2\Omega\Sigma$ =constant.

Assuming that the angular momentum of the binary, $L_b = \eta M_t(GM_t a)^{1/2}$, is much less than that of the disc (and the material falling onto the disc), the torque $\mathcal{T}_{\rm align}$ leads to alignment between $\hat{\boldsymbol{l}}_b$ and $\hat{\boldsymbol{l}}_{\rm out}$, on the timescale

$$t_{\rm align} = \frac{L_b \sin\Theta}{\mathcal{T}_{\rm align}} = \frac{\eta M_t}{\dot{M}}\left(\frac{a}{r_{\rm in}}\right)^{1/2}\frac{1}{(g + f\cos^2\Theta)}. \tag{3.6}$$

The secular evolution of $\Theta(t)$ is determined by the equation

$$\frac{d\Theta}{dt} = -\frac{\sin\Theta}{t_{\rm align}}. \tag{3.7}$$

For $\Theta \ll 1$, this can be easily solved: Starting from the initial angle $\Theta(t_i)$, the inclination evolves according to

$$\Theta(t) = \Theta(t_i)\exp\left[-\frac{\Delta M}{\eta M_t}\left(\frac{r_{\rm in}}{a}\right)^{1/2}(g + f)\right], \tag{3.8}$$

where ΔM is the total mass accreted through the disc during the time between t_i and t.

4. Discussion

Our calculations showed that a circumbinary disc formed with its rotation axis $\hat{\boldsymbol{l}}_{\rm out}$ (at large distance) inclined with respect to the binary angular momentum axis $\hat{\boldsymbol{l}}_b$ will attain a weakly warped/twisted state, such that the whole disc is nearly aligned with $\hat{\boldsymbol{l}}_{\rm out}$ (see Section 3). However, the interaction torque between the disc and the binary tends to drive $\hat{\boldsymbol{l}}_b$ toward alignment with $\hat{\boldsymbol{l}}_{\rm out}$. The timescale of this alignment is given by Eq. (3.6), and the relative binary-disc inclination Θ evolves according to Eq. (3.8).

Note that both the accretion torque and gravitational torque contribute to the alignment. If only the accretion torque were present (i.e., $g \sim 1$, $f = 0$), the alignment timescale would be of the same order as the mass-doubling time of the binary ($t_{\rm align} \sim 4\times10^7$ yr for $M_1 = M_2 = 1\,M_\odot$, $r_{\rm in} \simeq 2a$ and $\dot{M} \sim 10^{-8}M_\odot\,{\rm yr}^{-1}$), and a significant fraction of the binary mass would have to be accreted ($\Delta M \sim 0.4M_\odot$) in order to achieve an e-fold reduction of Θ [see Eq. (3.8)]. However, the gravitational torque dominates over the accretion torque, since the condition $f \gg 1$ can be satisfied for a wide range of disc/binary parameters (although $\alpha^2 f \ll 1$ must be satisifed for our equations to be valid). For example, for $p = 3/2$ (the density index for the minimum solar nebula), and $\eta = 1/4$ (equal mass binary), we have

$$f \simeq 14 \left(\frac{0.1}{\delta_{\rm in}}\right)^4 \left(\frac{2\,a}{r_{\rm in}}\right)^4 . \tag{4.1}$$

Thus, the alignment timescale is (for $f \gg 1$ and $\cos^2\Theta \simeq 1$)

$$t_{\rm align} \simeq 2.5 \left(\frac{\eta M_t}{0.5 M_\odot}\right) \left(\frac{\dot M}{10^{-8} M_\odot/{\rm yr}}\right)^{-1} \left(\frac{\delta_{\rm in}}{0.1}\right)^4 \left(\frac{r_{\rm in}}{2a}\right)^{3.5} {\rm Myrs} \tag{4.2}$$

(ηM_t is the reduced mass of the binary). The amount of mass accretion needed for an e-fold reduction of Θ is [see Eq. (3.8)]

$$(\Delta M)_e \simeq 0.05\,(\eta M_t) \left(\frac{\delta_{\rm in}}{0.1}\right)^4 \left(\frac{r_{\rm in}}{2a}\right)^{3.5} . \tag{4.3}$$

Thus, only a small fraction of the binary mass has to be accreted to achieve significant reduction of Θ.

5. Conclusions and Implications

In this paper, we have considered scenarios for the assembly of proto-planetary discs around newly formed stellar binaries. The shape and inclination of the disc relative to the binary will determine the orbital orientations of the circumbinary planets that are formed in the disc. Because of the turbulence in molecular clouds and dense cores, inside which protostellar binaries and circumbinary discs form, and also because of the tidal toques between nearby cores, it is possible, and even likely, that infalling gas onto the outer region of the circumbinary disc rotates in different directions compared to the binary. Thus in general, the newly assembled circumbinary disc will be misaligned with respect to the binary. However, the gravitational torque from the binary produces warp and twist in the disc, and the back-reaction torque associated with the warp and twist tends to align (under most conditions) the disc and the binary orbital plane. We have presented new calculations of the interaction between the warped/twisted disc and the binary, and showed that the disc warp is small under typical conditions. More importantly, we have derived new analytic expression for the binary-disc alignment torque and the associated timescale [see Eq. (4.2)]. Our results show that the misalignment angle can be reduced appreciably after the binary accretes a few precent of its reduced mass [see Eq. (4.3)].

Proto-binaries formed by fragmentation (either turbulent fragmentation or disc fragmentation; see Section 2) have initial separations much larger than 1 AU. Significant inward migration must occur to produce close (sub-AU) binaries. Since mass accretion necessaily takes place during disc-driven binary migration, our results then suggest that close binaries are likely to have aligned circumebinary discs, while wider binaries *can* can have misaligned discs. This can be tested by future observations.

The circumbinary planetary systems discovered by *Kepler* (see Section 1) all contain close (period $\lesssim 41$ d) binaries. If the planet form in the late phase of the circumbinary disc (as likely to be the case because of the relatively small planet mass in the *Kepler* systems), then the planet's orbit will be highly aligned with the binary orbit, even if the initial disc has a misaligned orientation. This is indeed what are observed. In general, we expect that circumbinary planets around close binaries to have very aligned orbits with respect to the binary, while planets around wider binaries can have misaligned orbits. Again, this can be tested by future observations. Of course, given the complexity of the various processes involved, one may see some exceptions. Also, in this paper we have not considered any dynamical processes (few body interactions) that may take place after

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the binary and planet formation. Such processes can also affect the multual inclinations of circumbinary planets.

Overall, our calculations in this paper illustrate that the mutual inclinations and other orbital characteristics of circumbinary planetary systems can serve as a diagnostic tool for the assembly and evolution of protoplanetary discs and the condition of formation of these planetary systems.

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