

Nature or nurture of coplanar Tutooines: the aligned circumbinary Kuiper belt analogue around HD 131511

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ABSTRACT

A key discovery of the *Kepler* mission is of the circumbinary planets known as ‘Tutooines’, which appear to be well aligned with their host stars’ orbits. Whether this alignment is due to initially coplanar circumbinary planet-forming discs (i.e. nature), or subsequent alignment of initially misaligned discs by warping the inner disc or torquing the binary (i.e. nurture), is not known. Tests of which scenario dominates may be possible by observing circumbinary Kuiper belt analogues (‘debris discs’), which trace the plane of the primordial disc. Here, the 140 au diameter circumbinary debris disc around HD 131511 is shown to be aligned to within 10° of the plane of the near edge-on 0.2 au binary orbit. The stellar equator is also consistent with being in this plane. If the primordial disc was massive enough to pull the binary into alignment, this outcome should be common and distinguishing nature versus nurture will be difficult. However, if only the inner disc becomes aligned with the binary, the HD 131511 system was never significantly misaligned. Given an initial misalignment, the \sim Gyr main-sequence lifetime of the star allows secular perturbations to align the debris disc out to 100 au at the cost of an increased scaleheight. The observed debris disc scaleheight limits any misalignment to less than 25° . With only a handful known, many more such systems need to be characterized to help test whether the alignment of circumbinary planets is nature or nurture.

Key words: planets and satellites: formation – planet-disc interactions – binaries: close – circumstellar matter – stars: individual: HD 131511 (HIP 72848).

1 INTRODUCTION

Planet formation appears to be a near ubiquitous process, being successful in single and multiple star systems (Mayor & Queloz 1995; Hatzes et al. 2003; Doyle et al. 2011), and across a wide range of stellar host masses (Delfosse et al. 1998; Frink et al. 2002; Beaulieu et al. 2006). It is therefore surprising that the discoveries of the first circumbinary planets were only made recently (Doyle et al. 2011), when the first evidence for successful circumbinary planetesimal formation was revealed 30 years ago by the discovery of a Kuiper belt analogue around the eclipsing A-type binary α CrB (Aumann 1985). This extended wait does not reflect a paucity of circumbinary planets however (Armstrong et al. 2014), merely a strong bias towards discovery of the lower hanging fruit that are planets around stars in single and wide multiple systems. Indeed, aside from their perhaps inevitable discovery with *Kepler* (e.g. Doyle et al. 2011), few surveys are specifically targeting nearby close binary stars with the goal of disentangling their spectra to push down to mass limits

that are competitive with the state of the art around single stars (e.g. Konacki 2005; Konacki et al. 2009).

The known circumbinary planets are well aligned with their binary host orbits, but this alignment is a heavy bias towards their discovery in eclipsing binary systems. An analysis of circumbinary planets finds that the occurrence rate is similar compared to single stars, but only if those planets are typically coplanar with the binary (Armstrong et al. 2014). If the planets have a wider range of inclinations, the occurrence rate goes up, and hence is higher than the single star rate. Given theoretical work that finds circumbinary planet formation is if anything harder than around single stars (e.g. Moriwaki & Nakagawa 2004; Scholl, Marzari & Thébault 2007; Paardekooper et al. 2012), an enhanced circumbinary planet occurrence rate would be a surprise, and a high degree of coplanarity seems more likely.

Such coplanarity is also expected, at least in the inner regions where these planets form, as a result of the torques exerted on a young circumbinary protoplanetary disc by the binary (and vice versa; Foucart & Lai 2013; Facchini, Lodato & Price 2013). Whether coplanarity is expected farther out in the disc is less clear; it may be that alignment is simply a natural outcome of binary star formation, but interaction with the surrounding environment, for

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example the late infall of gas on to the protoplanetary disc may lead to misalignment. Whether this alignment can be corrected is uncertain, depending on poorly constrained parameters such as disc mass and viscosity (e.g. Bate et al. 2000; Facchini et al. 2013; Foucart & Lai 2013). The alignment of inner ($\lesssim 10$ au) disc regions is potentially probed empirically by the known circumbinary planets. However, the state of more distant regions, beyond where the known close-in planets probably form, relies on the detection of small-body populations; the gas-poor Kuiper belt analogues ('debris discs') seen around main-sequence binaries that are thought to trace the original plane of the protoplanetary disc.

Here, star–binary–disc alignment in the spectroscopic binary system HD 131511 is considered. The debris disc in this system has been studied previously, focusing on either the disc structure (Marshall et al. 2014) or whether the disc has an inclination similar to that inferred for the primary star (Greaves et al. 2014). A more detailed analysis of the disc geometry is used here to show that all system components are plausibly aligned. The ability of binary perturbations to bring an initially misaligned disc towards coplanarity during the primordial and debris disc phases, and the implications for any initial misalignment, are then considered.

2 THE HD 131511 SYSTEM

2.1 The stars

HD 131511 (HIP 72848) is a single-lined spectroscopic binary with a KOV primary (Gray et al. 2003), whose orbit was first derived using radial velocities (Kamper & Lyons 1981; Beavers & Salzer 1983; Katoh et al. 2013). The near to edge-on geometry of the orbit was subsequently derived using *Hipparcos* astrometry (Jancart et al. 2005), and the derived elements, along with the age (Mamajek & Hillenbrand 2008) and masses estimated from the $B - V$ colour are reproduced in Table 1. Using the observed rotation period (10.39 ± 0.03 d; Henry, Fekel & Hall 1995), $v \sin i$ ($4 \pm 1 \text{ km s}^{-1}$; Strassmeier et al. 1990), and stellar radius derived from fitting stellar atmosphere models, Greaves et al. (2014) found that the primary star is inclined by at least 70° , and though the position angle of the projected spin axis is unknown this calculation shows that the equator of the primary is consistent with being aligned with the binary orbit.

Table 1. HD 131511 binary properties; orbit (Nidever et al. 2002; Jancart et al. 2005), age (Mamajek & Hillenbrand 2008) and masses (Jancart et al. 2005). The ascending node Ω is measured east of north.

Parameter	Symbol (unit)	Value	1σ
Semimajor axis	a (mas)	16.54	0.18
Semimajor axis	a (au)	0.19	0.03
Eccentricity	e	0.51	0.001
Inclination	i ($^\circ$)	93.4	4.2
Ascending node	Ω ($^\circ$)	248.3	3.6
Longitude of pericentre	ω ($^\circ$)	219	0.1
Orbital Period	P (days)	125.396	0.001
Distance	d (pc)	11.51	0.06
Mass of A	$M_A (M_\odot)$	0.79	–
Mass of B	$M_B (M_\odot)$	0.45	–
Age	Gyr	1	0.3

2.2 The debris disc

Most debris discs are detected via infrared (IR) excesses above the level expected from the stellar photosphere. HD 131511 was reported to have an IR excess at $24 \mu\text{m}$ by Koerner et al. (2010). However, this was due to an incorrect prediction for the photospheric flux density, presumably from the use of saturated 2MASS data (they found 133 mJy, where the true value is closer to 200 mJy). This error was corrected by Gáspár, Rieke & Balog (2013), who found no $24 \mu\text{m}$ excess, but reported a 3.2σ significant $100 \mu\text{m}$ excess. A similar level of excess at $70 \mu\text{m}$ is also seen, meaning that the excess is robust.

The disc is in fact resolved with the *Herschel* Photodetector Array Camera and Spectrometer (PACS; Pilbratt et al. 2010; Poglitsch et al. 2010),¹ and the properties have been reported in Greaves et al. (2014) and Marshall et al. (2014). Greaves et al. (2014) derived just the inclination of the disc in order to compare it with the stellar inclination, while Marshall et al. (2014) modelled the radial structure, finding that the images lack a signal-to-noise ratio sufficient to constrain more than the radial disc location.

The disc structure is best constrained at $100 \mu\text{m}$ where the disc/star contrast is highest, and original and star-subtracted PACS images at this wavelength are shown in Fig. 1. These data are the same as used by both Greaves et al. (2014) and Marshall et al. (2014) so the reader is referred to those papers for details regarding data reduction. Marshall et al. (2014) concluded that the disc is consistent with being a radially narrow ring with a radius of 60–70 au. Both studies concluded that the disc is highly inclined ($>70^\circ$) and a position angle of 66° east of north was derived in the latter study.

3 SYSTEM GEOMETRY AND ALIGNMENT

The derived position angle and inclination of the disc is consistent with the ascending node and inclination of the binary orbit, and the inclination of the primary star's spin axis. There is of course an ambiguity in the ascending node of the debris disc, because there is currently no way to infer the side of the star on which the dust is coming towards us, so it could be that the planetesimal disc in fact orbits in the opposite sense to the binary. Using the same dust ring model that was used in Greaves et al. (2014) and Marshall et al. (2014), this level of consistency is quantified in more detail in Fig. 2, which shows a series of two-dimensional marginalizations over a five-dimensional grid search for the best-fitting disc parameters that reproduce the image in Fig. 1. The parameters varied were the brightness and radius of a 10-au-wide dust ring, the vertical opening angle of the dust belt, and the position angle and inclination of the belt. At each location in this space, a high-resolution disc model was created and convolved with the PACS $100 \mu\text{m}$ beam (an observation of γ Dra), and the χ^2 goodness-of-fit metric then computed from the difference between the model and the data.

The lack of a strong disc signal means that a simple narrow ring is a good fit to the data (Marshall et al. 2014), which has a radius of about 70 au, but could be as small as 50 au or as large as 100 au. The contours in Fig. 2 show the 1, 2 and 3 σ confidence regions computed from the $\Delta\chi^2$ compared to the best-fitting disc parameters. The white cross in the lower-right panel shows the binary orbit position angle and inclination. The disc and binary are

¹ *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

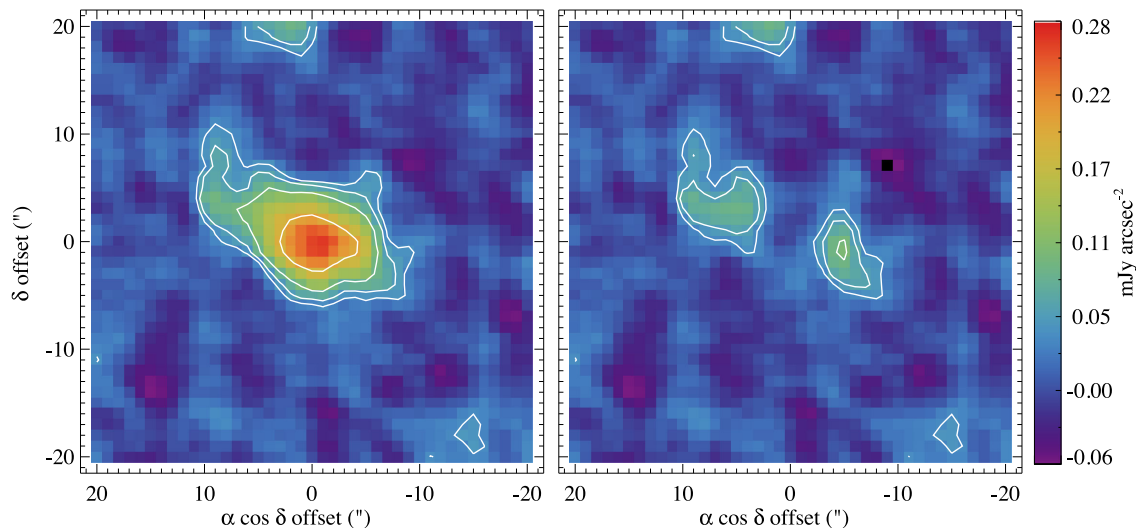


Figure 1. *Herschel* 100 μm images of HD 131511, north is up and east is left. The left-hand panel shows the raw image with contours at 2, 3, 5 and 10 times the pixel rms of 1.9×10^{-2} mJy arcsec $^{-2}$. The right-hand panel shows the same image and contours after a peak-scaled point source has been subtracted, leaving residuals at the disc ansae as a clear sign of a resolved disc that is near to edge-on.

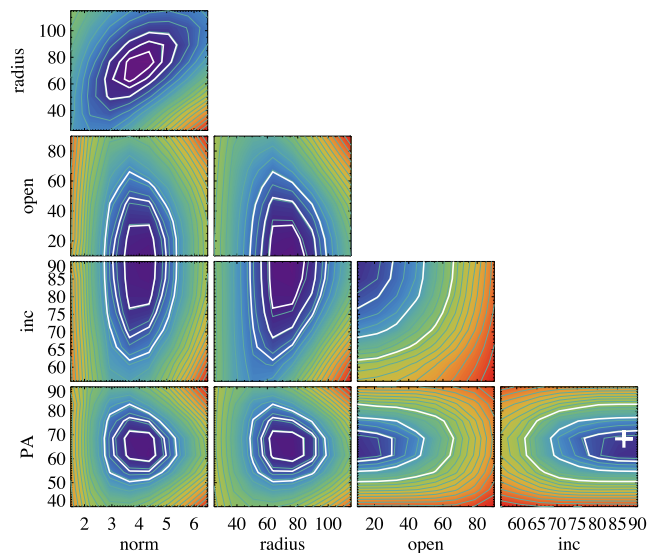


Figure 2. Significance contours for varying disc normalization (arbitrary units), radius (in au), disc opening angle, inclination and PA (all in degrees). Each panel shows contours for two parameters when marginalized over the other three. White contours are 1, 2 and 3σ . The white cross marks the orientation of the HD 131511 binary orbit.

therefore consistent with being aligned, but at the 2σ level the disc could be up to about 20° less inclined than the binary, and have a position angle about 10° different. The disc opening angle is less than about 50° . Though the position angle of the star is unknown, the possible inclination discrepancy between the binary orbit and stellar equator is around 20° .

Thus, this analysis shows for the first time that the circumbinary debris disc around HD 131511 is consistent with being aligned with the binary orbital plane. By quantifying the uncertainties in important disc parameters, the main conclusions of this modelling are that the disc opening angle could be as large as 50° , and that any undetected misalignment could be as large as 20° .

4 DISCUSSION

Having noted that HD 131511 is consistent with having the equator of the primary star, the 0.2 au binary orbit, and the 70 au radius debris disc in the same plane, the origin and dynamics of the system, and other similar systems, are considered.

4.1 Protoplanetary disc alignment

Circumbinary protoplanetary disc formation may be a messy process, and the possibility of late gas infall means that binary–disc coplanarity is not a guaranteed initial condition (e.g. Foucart & Lai 2013). The probable coplanarity as inferred from the *Kepler* planets suggests that at a minimum the inner regions of the planet-forming discs can become aligned with the binary, and thus the system loses the signature of any initial disc misalignment. The time-scale with which alignment occurs, and the degree and extent of alignment, is uncertain. Foucart & Lai (2013) explored a low-viscosity case, finding that the disc is not strongly warped, and that the binary is pulled into alignment with the binary on a time-scale comparable with the lifetimes of primordial discs, albeit with considerable uncertainty due to very strong dependence on (for example) the disc scaleheight and inner edge location. With larger viscosity, Facchini et al. (2013) find that large warps are possible, and that the disc inner edge is not generally aligned with the binary (though they restrict their analysis to disc masses low enough that the binary orbit is unaffected).

Thus, the degree to which circumbinary protoplanetary discs are typically aligned with binary orbits, and the time-scale for any alignment, is uncertain. The estimates of Foucart & Lai (2013) suggest that an initially misaligned disc may not exhibit a large warp, and that the binary can become aligned with the primordial disc via interaction at the inner edge before it is dispersed. If this case is typical then all discs around close binaries could become aligned before they disperse, and perhaps before planets form. However, the disc may not have enough mass to pull the binary into alignment, and may also have a significant warp. In this case, the disc becomes aligned with the binary relatively slowly, though the time-scales are uncertain. Bate et al. (2000) estimate that alignment may occur on the same time-scale as the secular nodal precession induced in

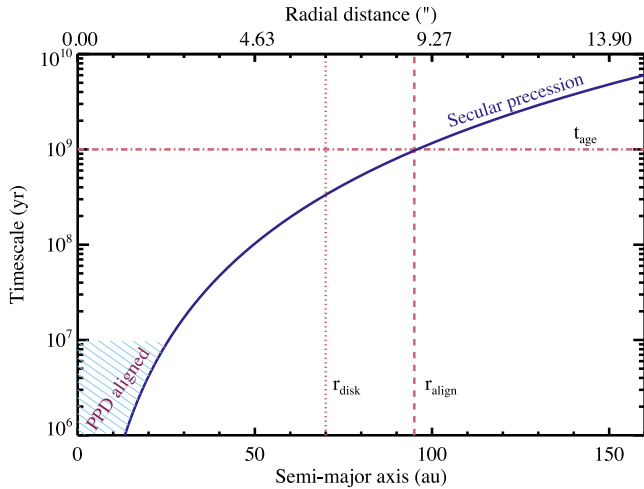


Figure 3. Protoplanetary disc alignment and secular precession times for circumbinary orbits as a function of semimajor axis. A circumbinary protoplanetary disc can be aligned within a few tens of au during the $\sim 10^7$ year disc lifetime. Planetesimals can on average become aligned (i.e. have executed one full cycle of secular precession) within ~ 1 Gyr if they reside within 95 au. Therefore, the debris disc may have become aligned due to secular perturbations on the main-sequence.

the disc by the binary (discussed below), though depending on the origin of damping within the disc (e.g. if the parametric instability does not operate; Gammie, Goodman & Ogilvie 2000) could also be a lot longer.

For the specific example of HD 131511, the secular precession time is shown in Fig. 3, calculated according to Farago & Laskar (2010) using the binary parameters from Table 1. An estimate for where the primordial disc can become aligned with the binary is shown by the hatched region, assuming that the alignment timescale is the same as the precession time, and allowing for disc lifetimes up to 10^7 years (e.g. Zuckerman, Forveille & Kastner 1995; Pascucci et al. 2006). With this estimate, disc regions beyond a few tens of au do not become aligned within reasonable protoplanetary disc lifetimes. Compared to the primordial disc lifetimes, the much longer main-sequence lifetimes of stars means that the debris disc that forms in, and then emerges from the protoplanetary disc can be strongly affected by secular perturbations to much larger radial distances.

4.2 Debris disc alignment

In the absence of the dissipation present in a gaseous disc secular perturbations from the binary cause disc particle inclinations and lines of nodes to oscillate rather than damp, with a time-scale that depends on semimajor axis. The eccentricities and pericentre arguments also vary, but are less relevant because the eccentricities imposed depend inversely on the separation ratio between the particles and the binary (e.g. Moriwaki & Nakagawa 2004), and are hence very small at ~ 70 au around HD 131511 ($\lesssim 10^{-3}$).

The effect of the perturbations on the disc particles can be viewed in two ways. If the reference plane is pictured as that of the original disc plane (so the binary is inclined), then the inclinations of the particles oscillate about the binary plane as their lines of nodes circulate (libration is possible for large initial misalignments and high binary eccentricities). This is the picture usually applied in planetary systems, for example the warp in the β Pictoris disc (e.g. Mouillet et al. 1997). If the reference plane is taken to be that of the

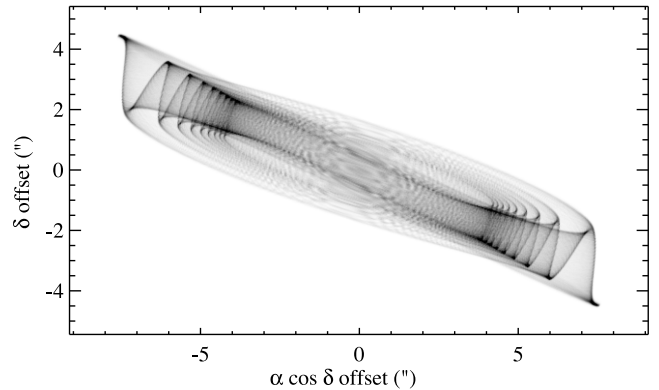


Figure 4. Simulation of mm-wave structure for an initially flat 50–100 au disc with particles on circular orbits around the HD 131511 binary after 1 Gyr. The initial misalignment was 10° with a line of nodes with respect to the binary pericentre of 0° . A blackbody temperature law and 1 mm wavelength was assumed in creating the image.

binary, the particle orbits are initially inclined, and precess about the binary angular momentum vector. Only if the binary is eccentric do their inclinations also change as they precess (e.g. Farago & Laskar 2010; Kennedy et al. 2012a). Thus, given enough time any disc will appear to become aligned at the cost of an increased scaleheight, with an opening angle equal to twice the initial misalignment.

The secular precession time, the time taken for a particle to undergo one full oscillation in inclination (and a complete circulation of the line of nodes), for particles orbiting HD 131511 at a range of distances is shown in Fig. 3. The estimated disc radius of 70 au is shown, and at the stellar age of around 1 Gyr particles out to about 95 au can have their inclinations vary significantly. Thus, the alignment of the disc with the binary orbit is not necessarily primordial, but given that the disc is seen to have an opening angle smaller than about 50° , any initial misalignment must have been smaller than about 25° .

Fig. 4 shows a synthetic mm-wave image of a 50–100 au circumbinary disc around HD 131511 as it would appear if the initial misalignment was 10° . The wavy structure arises as the particles' orbits' nodes precess, becoming less distinct closer to the star where the precession is fastest and the most precession cycles have taken place. Observed with a resolution greater (i.e. worse) than a few seconds of arc, such a disc would simply appear to be aligned with the binary. At higher resolution (~ 1 arcsec) the vertical structure would be resolvable and hence the initial misalignment could be inferred or constrained from the scaleheight. At yet higher resolution the wavy radial structure might be seen, though whether it actually exists or is smoothed out would depend on various complicating factors that are not included in this model, such as the (uncertain) eccentricity of the disc particles and whether radiation or stellar wind forces strongly affect mm-size dust.

4.3 Other circumbinary debris discs

Aligned circumbinary discs were previously found around HD 98800BaBb (Andrews et al. 2010), α CrB (HD 139006) and β Tri (HD 13161; Kennedy et al. 2012b), while a misaligned disc has been found around 99 Her (Kennedy et al. 2012a). In the cases of α CrB and β Tri, the disc as resolved with *Herschel* is sufficiently well separated from the binary that perturbations do not affect it within the stellar lifetime and that the alignment is primordial. The same cannot be said for the HD 98800 hierarchical quadruple system; the

disc that orbits the BaBb pair is relatively compact, probably due to truncation by the AaAb pair (Andrews et al. 2010). Perturbations from the BaBb pair probably protect the disc from strong perturbations from the AaAb pair (Verrier & Evans 2008, 2009), though greater reddening seen towards the disc hosting pair may be a sign of disc warping and that this protection is not absolute (Akeson et al. 2007). In any case, dynamics in the HD 98800 system will be more complex if enough gas is present, and several studies suggest that the system is in fact in the late stages of dispersing a gaseous planet-forming disc rather than a ‘true’ gas-poor debris disc (Furlan et al. 2007; Yang et al. 2012).

Adding HD 131511 to this sample, the debris discs seen around three (four including HD 98800) close binaries are seen to be aligned, while the single wider case of 99 Her is strongly misaligned. With such a small sample the trend can simply be noted, as can the goal of building the numbers in order to make quantitative statements about the origins of circumbinary alignment. With nearly all resolved debris discs residing in systems within a few hundred parsecs, *GAIA* is the most promising in this regard, both for discovering and characterizing binary systems, and also for discovering circumbinary planets (Sahlmann, Triaud & Martin 2014). The best case scenario would see discoveries of systems where coplanarity tests of planet and disc orbits could be made across a wide range of radial distances.

5 CONCLUSIONS

The measurable components of the HD 131511 system are aligned. The binary orbit is well known, and the debris disc geometry is consistent with being in the same plane. While the position angle of the stellar spin axis is unknown, the inclination is also consistent with the equator being aligned with the binary orbit. The time-scale for alignment during the primordial gaseous phase may be too long compared to the gas disc lifetime beyond a few tens of au, so if the debris disc traces the plane of the gas disc any initial misalignment was limited to less than 25°. The sample of systems where such tests have been made remains small, and many more are needed to make a strong test of whether the alignment of circumbinary planet orbits is nature or nurture.

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