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Star–planet–debris disc alignment in the HD 82943 system: is planetary system coplanarity actually the norm?

G. M. Kennedy,[1]★ M. C. Wyatt,[1] G. Bryden,[2] R. Wittenmyer[3] and B. Sibthorpe[4]

[1]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[2]*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[3]*Department of Astrophysics, School of Physics, University of NSW, Sydney 2052, Australia*
[4]*SRON Netherlands Institute for Space Research, NL-9747 AD Groningen, the Netherlands*

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ABSTRACT

Recent results suggest that the two planets in the HD 82943 system are inclined to the sky plane by $20 \pm 4^\circ$. Here, we show that the debris disc in this system is inclined by $27 \pm 4^\circ$, thus adding strength to the derived planet inclinations and suggesting that the planets and debris disc are consistent with being aligned at a level similar to the Solar system. Further, the stellar equator is inferred to be inclined by $28 \pm 4^\circ$, suggesting that the entire star–planet–disc system is aligned, the first time such alignment has been tested for radial velocity discovered planets on $\sim$au wide orbits. We show that the planet–disc alignment is primordial, and not the result of planetary secular perturbations to the disc inclination. In addition, we note three other systems with planets at $\gtrsim$10 au discovered by direct imaging that already have good evidence of alignment, and suggest that empirical evidence of system-wide star–planet–disc alignment is therefore emerging, with the exception of systems that host hot Jupiters. While this alignment needs to be tested in a larger number of systems, and is perhaps unsurprising, it is a reminder that the system should be considered as a whole when considering the orientation of planetary orbits.

Key words: planets and satellites: formation – circumstellar matter – stars: individual: HD 82943 – planetary systems.

1 INTRODUCTION

Planetary systems are known to emerge from the disc-like structures of gas and dust that surround young stars. It has therefore generally been expected that, as in the Solar system, all components of exo-planetary systems should share a common angular momentum direction; the planets and debris disc should orbit in the same direction and in the same plane as the stellar equator. Of course, the most well studied system, our Solar system, is not perfectly aligned with a single plane. A variation of nearly 10° when the Sun's equator and Mercury's orbit are included suggests a benchmark for star–planet–disc alignment in other systems.

The discovery of star–planet misalignment for transiting gas giants has been a surprising counterpoint to the expectation of alignment. Though nearly all of the first dozen transiting systems were found to be aligned (see Fabrycky & Winn 2009, and references therein), proof that alignment is not always the case (e.g. Triaud et al. 2010) has prompted theoretical work that attempts to explain their existence (e.g. Fabrycky & Tremaine 2007; Lai, Foucart & Lin 2011; Thies et al. 2011; Batygin 2012). Misalignment could be indicative of processes acting after the formation of the planetary system, and be specific to the way in which some hot Jupiters form. For example, the planets could originate on orbits that are aligned with the star, but be circularized after being forced to low perihelia via long-term dynamical interactions with other planets or stellar companions that excite their eccentricities and inclinations, naturally forming misaligned systems (Fabrycky & Tremaine 2007). Alternatively, the misalignment could originate from a primordial misalignment of the gaseous protoplanetary disc (Lai et al. 2011; Thies et al. 2011; Batygin 2012), implying that hot Jupiters could have migrated through the gas disc to their observed locations without experiencing strong dynamical interactions with other bodies. Since the stellar rotation-planet orbit alignment has only been tested outside the Solar system using the Rossiter–McLaughlin effect and starspot occultation (Nutzman, Fabrycky & Fortney 2011), measurements that are generally only possible on close in transiting planets, it is not yet possible to tell if the observed misalignment is representative of planetary systems in general.

One prediction of the primordially misaligned disc scenarios is that debris discs, presumed to have their origins within the gaseous protoplanetary disc, could be misaligned with their parent stars. However, the test for star–disc alignment has until recently been much harder. It involves comparing the inclination of the star

★E-mail: gkennedy@ast.cam.ac.uk

inferred from the stellar radius, projected rotation velocity, and rotation period, to that of the resolved debris disc that orbits that star. This test is not usually possible because debris discs are only detected around ∼15 per cent of Sun-like stars, and until the launch of *Herschel*[1] few of these were resolved. In addition, the position angle of the stellar inclination is rarely measured (but see Le Bouquin et al. 2009). Therefore, star–disc alignment is shown in a statistical sense rather than for individual systems. In the cases where this test has become possible, the conclusion is that the stellar and disc inclinations are generally similar, and hence that both share the same orbital plane as the primordial protoplanetary disc (Watson et al. 2011, Greaves et al., in preparation).[2]

The final alignment test, that of planet–disc alignment, is in general the least common due to the rarity of systems in which it is possible. Curiously, however, all three systems with directly imaged planets (around A-stars) allow this test. Despite uncertainties about the orbit and nature of the planet around Fomalhaut (Kalas et al. 2008; Kennedy & Wyatt 2011; Janson et al. 2012), the current understanding has Fomalhaut b consistent with, though by no means guaranteed to be, aligned with the spectacular debris ring (which is inclined by 66°; Kalas et al., 2013). In addition, the position angle of the stellar rotation axis of $65 \pm 3°$ (Le Bouquin et al. 2009) is perpendicular to the debris disc major axis of $156 \pm 0\overset{\circ}{.}3$ (Kalas, Graham & Clampin 2005), suggesting that the stellar equator is also aligned with the ring. In the HR 8799 system, the favoured orbits are near face-on (Marois et al. 2008; Lafrenière et al. 2009; Fabrycky & Murray-Clay 2010), as is the debris disc (Su et al. 2009). In fact, the favoured planetary inclination of 13–23° is very similar to the debris disc inclination derived from *Herschel* observations (Matthews et al., in preparation). Further, HR 8799 itself is also inferred to be nearly pole-on, with an inclination of 13–30° (Reidemeister et al. 2009). Finally, the planet around β Pictoris is consistent with being aligned with the edge-on disc (Lagrange et al. 2010; Currie et al. 2011), but may be slightly misaligned (∼5°), if it is the origin of the disc warp seen at ∼70 au (Mouillet et al. 1997; Dawson, Murray-Clay & Fabrycky 2011). Therefore, in the cases where it is possible to test star–planet–disc alignment, at radial scales well beyond the realm of hot Jupiters, alignment at our benchmark level is the conclusion in all three cases.

In summary, with the caveat that some hot Jupiters may be misaligned with their host stars due to their formation mechanism, it appears that, as expected, empirical evidence of star–planet–disc alignment as the norm in planetary systems is emerging. However, with only four cases that argue for alignment, and the example that the first hot Jupiters were found to be aligned, more examples are clearly needed to test the primordially misaligned models. The planets in the three aligned systems discussed above are all at $\gtrsim$10 au around A-type stars, so tests at scales between the realm of direct imaging and transits (i.e. ∼au scales), and around Sun-like stars are especially lacking.

Here, we focus on alignment in the HD 82943 system, whose planets orbit the Sun-like host star at ∼au distances. Recent results from Tan et al. (2013) suggest that, assuming that their orbits are coplanar, the two giant planets in this system are inclined to the sky plane by $i = 20 \pm 4°$. We show that the debris disc as resolved by *Herschel* imaging is inclined by $27 \pm 4°$, thereby adding strength to the inferred planet inclinations, and arguing that the planets and disc are aligned. In addition, we show that the inferred stellar inclination is 28°, so probably aligned with the planets and disc. Based on the assumption of star–planet–disc alignment in 'typical (i.e. non-hot Jupiter) systems, we suggest that the most probable system-wide inclination can be inferred if the inclination of just one component has been measured.

2 THE HD 82943 SYSTEM

2.1 The star

HD 82943 is a nearby (27.5 pc) Sun-like main-sequence dwarf star (F9V). Mayor et al. (2004) quote an age of 2.9 Gyr, while Holmberg, Nordström & Andersen (2009) derive an upper limit of 2.8 Gyr. The age is clearly uncertain, but relatively unimportant for our analysis because it is only used in considering how long the planets have had to influence the debris disc. We therefore adopt an age of 3 Gyr.

The stellar rotational velocity is $v \sin i = 1.35$–1.7 km s^{-1} (Mayor et al. 2004; Butler et al. 2006). Using the inferred period of 18 d (Mayor et al. 2004) and the stellar radius of 1.15 R$_\odot$ derived from SED fitting (see section 2.3), the inclination of the stellar pole from our line of sight is $28 \pm 4°$, if only the range of $v \sin i$ is used to calculate the uncertainty. The rotation period was derived from the $R'_{\rm HK}$ activity indicator rather than directly measured, which Noyes et al. (1984) show results in period uncertainties of a few days. A three-day uncertainty yields an inclination uncertainty of ≈5° here, so while direct verification of the period would be beneficial, our derived inclination is unlikely to change significantly.

2.2 The planets

Two $M \sin i \approx 1.8$ Jupiter-mass planets were discovered to orbit HD 82943 in 2004 (Mayor et al. 2004). The orbital periods are similar to the Earth's – 219 and 435 d – meaning that these are not hot Jupiters. These planets were recognized to be in a 2:1 mean motion resonance, and studies followed that aimed to understand their dynamics and the true constraints on the orbital parameters, even showing that the observed radial velocities may be explained by two planets in a 1:1 resonance (i.e. a Trojan pair, Ferraz-Mello, Michtchenko & Beaugé 2005; Lee et al. 2006; Goździewski & Konacki 2006; Beaugé et al. 2008). Where they considered the 2:1 resonance, these studies did not consider the system inclination relative to the sky plane. However, because they are in resonance and relatively massive, the planets' mutual perturbations should result in significant departures from purely independent Keplerian orbits. These departures are sensitive to the planet masses, hence providing an opportunity to constrain the planet inclinations with sufficiently high signal-to-noise ratio data that span a sufficiently long time period (e.g. Rasio et al. 1992).

Recently, Tan et al. (2013) presented additional data for the HD 82943 system. Because more than eight orbital periods of the outer planet have now been observed, they attempted to constrain the planetary inclinations. Their method involved deriving rough orbital parameters using Keplerian orbits, and using these as a starting point for a χ^2 minimization method using a dynamical model that accounts for planet–planet interactions. With the assumption that the two planets are mutually aligned (coplanar), they concluded that the most likely inclination of the two planets is near to face-on, specifically at $20 \pm 4°$. Naturally, the low inclination means that $\sin i$

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

[2] It is also possible to test binary orbital plane–disc alignment if the binary orbit is well characterized [see Andrews et al. (2010) and Kennedy et al. (2012a,b)].

is relatively small, and that the planet masses are both quite hefty at 4.8 Jupiter masses. If the assumption of mutual alignment of the planets is relaxed, Tan et al. (2013) found that no useful inclination constraints could be made, but they argued that mutual alignment is more plausible, essentially because the mutually aligned model has fewer free parameters. The similar inclination measured for the debris disc below adds strength to their conclusion of mutual planet alignment.

The inclination derived for the coplanar configuration is consistent with the stellar inclination derived above. However, because neither the position angle of the stellar pole nor the planetary line of nodes can be derived from the current observations, the conclusion of alignment relies on the argument that it is unlikely that both inclinations would be similar and close to face-on (there is a 0.5 per cent chance that two systems randomly drawn from a distribution uniform in $\cos i$ will be between 20 and 30°.). To independently derive the inclination of the planets would require either direct imaging or astrometry, the latter being more likely given the small angular size of the planetary orbits (though the perturbation is of the order of hundreds of micro-arcseconds).

2.3 The debris disc

The debris disc around HD 82943 was first discovered by Beichman et al. (2005), as part of a program to observe planet-host stars, with photometry using the Multiband Imaging Photometer for *Spitzer* (Rieke et al. 2004; Werner et al. 2004). An infrared excess above the stellar photosphere at 70 μm was seen, with the excess attributed to the presence of a significant surface area of small grains in a debris disc. The excess was not detected at 24 μm so the disc temperature and fractional luminosity were not constrained (see their fig. 9). The system was subsequently observed with the *Spitzer* Infra-Red Spectrograph (IRS; Houck et al. 2004), though the spectrum has never been published. Here, we use the CASSIS-processed version of these data (Lebouteiller et al. 2011), which show a significant excess beyond about 25 μm.

In November 2011, HD 82943 was observed by *Herschel* (Pilbratt et al. 2010) using the Photodetector and Array Camera & Spectrometer (PACS) instrument (Poglitsch et al. 2010, see Table 1) as part of the Search for Kuiper Belts around Radial-velocity Planet Stars (SKARPS). The overall goal of the survey is to look for correlations between debris disc and planet properties by observing systems known to host planets discovered by radial velocity. The observations used the standard 'mini scan-map', which comprises two sets of parallel scan legs, each taken with a 40° difference in scan direction. The raw timelines were projected on to a grid of pixels (i.e. turned into images) using a near-standard HIPE pipeline (Ott 2010). The fluxes at 70 and 160 μm were measured using aperture photometry (radii of 15 and 20 arcsec), yielding fluxes of 129 ± 4 mJy and 87 ± 7 mJy at 70 and 160 μm, respectively.

Fig. 1 shows the spectral energy distribution for HD 82943, including the *Spitzer* and *Herschel* data. We fit PHOENIX models from the *Gaia* grid (Brott & Hauschildt 2005) to optical and near-IR data using least-squares minimization, finding a stellar effective temperature of 5990 K and a radius of 1.15 $R_\odot$. We then use the stellar photosphere model to predict the flux density at longer wavelengths (e.g. 7.2 ± 0.2 and 1.35 ± 0.03 mJy at 70 and 160 μm), thereby demonstrating that the *Spitzer* and *Herschel* data are significantly in excess of the level expected. We fit a simple blackbody model to the excess fluxes, finding a fractional luminosity of $L_{\rm disc}/L_\star = 10^{-4}$ and a temperature of 57 ± 2 K, with the small uncertainty due to detection over a reasonably wide range of wavelengths (20–160 μm). In Fig. 1 we have multiplied the blackbody disc spectrum by (λ_0/λ) beyond $\lambda_0 = 210$ μm (Wyatt 2008), to account for inefficient long-wavelength emission by small grains and ensure a more realistic prediction of the far-IR/sub-mm disc brightness. Assuming that it lies in a single narrow ring, the blackbody temperature implies that the disc lies at a stellocentric radius of 30 au. We show below that the disc actually lies farther away, consistent with the bulk of emission coming from grains that emit inefficiently at wavelengths longer than their size, which must emit at hotter-than-blackbody temperatures to maintain energy equilibrium.

Table 1. *Herschel* observations of HD 82943. Each Obs ID represents a single scan direction, and the two differ by 40°.

Obs ID	Date	Instrument	Duration (s)
1342232212	2011 Nov 10	PACS 100/160	1686
1342232213	2011 Nov 10	PACS 100/160	1686

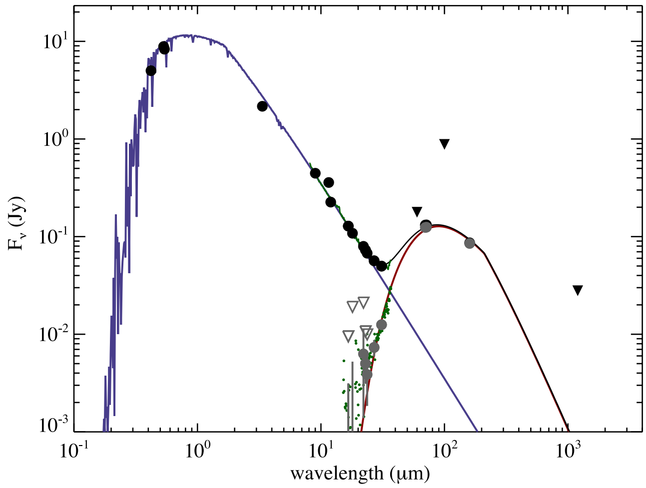

Figure 1. Spectral energy distribution for HD 82943. Dots are fluxes and triangles 3σ upper limits. Black symbols are measured fluxes and grey symbols are star-subtracted (i.e. disc) fluxes. The 5990 K stellar photosphere model is shown in blue, the 57K blackbody disc model in red, and the star+disc spectrum in black. The green line shows the observed IRS spectrum, and the green dots show the star-subtracted spectrum.

In addition to yielding photometric measurements, the disc is well resolved by *Herschel* at 70 μm, but less so at 160 μm. There is in addition some apparent low-level background contamination to the NE at 160 μm. Such contamination is in fact fairly common for *Herschel* observations at this wavelength; here we are less than a factor of 2 above the confusion limit of 1.4 mJy (as predicted by the *Herschel* Observation Planning Tool). The 70 μm image is shown in the left-hand panel of Fig. 2. To show that the image is resolved, the right-hand panel shows the image after a peak-normalized point source (calibration star γ Dra, processed in the same way as the data and rotated to the same position angle) was subtracted, leaving a clear ring of extended emission. In addition to showing that the disc is resolved, the azimuthal symmetry of the remaining ring shows that the disc is near to face-on.

To estimate the inclination and position angle of the disc we use two independent methods. The first is simple; we fitted a 2D Gaussian to the star-subtracted image of the HD 82943 disc, finding a position angle of 147° and an inclination of 30°. The inclination is found using $\cos i = s_{\rm min}/s_{\rm maj}$, where $s_{\rm maj}$ and $s_{\rm min}$ are found

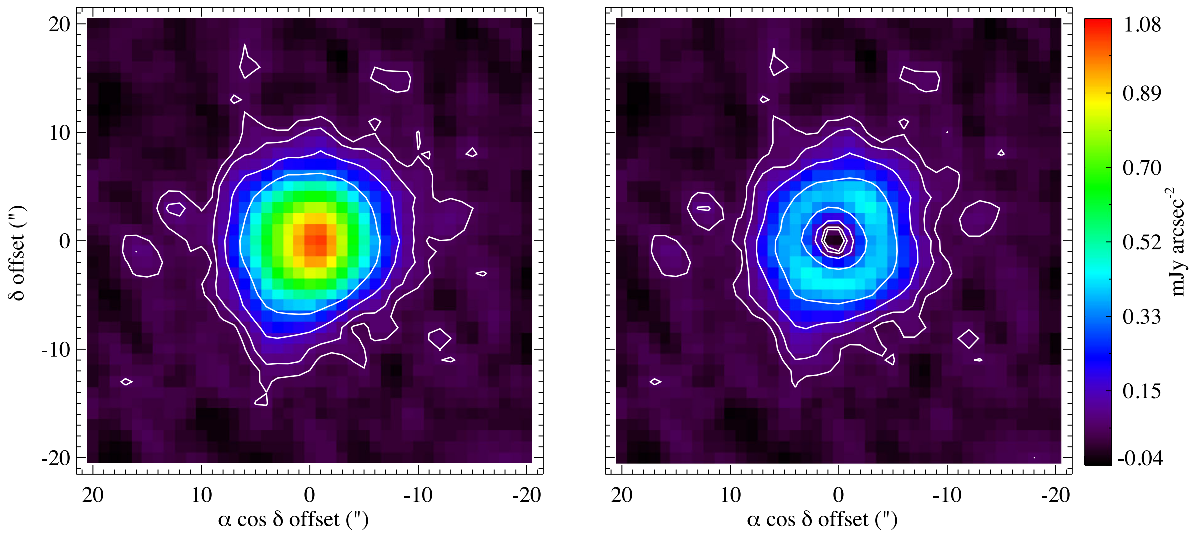

Figure 2. *Herschel* 70 μm images of HD 82943, North is up and East is left. The left-hand panel shows the raw image with contours at 3, 5, 10 and 20 times the pixel rms of 1.6×10^{-2} mJy arcsec^{-2}. The right-hand panel shows the same image and contours after a peak-scaled point source has been subtracted, leaving near-circular residuals as a clear sign of a near face-on disc.

from quadratically subtracting the PACS 70 μm beam full-width at half-maximum (FWHM) of 5.75 arcsec from the major and minor components of the fitted Gaussian FWHM ($s_{\rm maj}$ is also an estimate of the characteristic disc size, about 100 au). To estimate the uncertainty we then added the Gaussian fit image into an off-centre position in nine other 70 μm observations from our programme (all observations have the same depth). A Gaussian was then fitted at this position and the position angle and inclination derived. This method is a simple way of estimating how the disc geometry can vary due to different realizations of the same noise level. The inclinations vary from 25 to 31° with a mean of 28°, while the position angles vary from 133 to 153° with a mean of 147°.

As a second method we fit a physical model for the disc structure and estimate parameter uncertainties in a more traditional way. These models have been used previously to model *Herschel*-resolved debris discs (e.g. Kennedy et al. 2012b; Broekhoven-Fiene et al. 2013), and generate a high-resolution image of an azimuthally symmetric dust distribution with a small opening angle, as viewed from a specific direction. These models are then convolved with a point spread function model for comparison with the observed disc. The best-fitting model is found by a combination of by-eye coaxing and least-squares minimization. We found that the HD 82943 disc could not be well modelled by a simple ring, and hence use a dust distribution that extends from 67 to 300 au, with the face-on optical depth distributed as a power law that decays as $r^{-1.6}$ and is normalized to be 3.98×10^{-4} at 1 au. The temperature distribution is assumed to decay as $r^{-0.5}$ (i.e. like a blackbody, which is 278.3 K at 1 au), but is required to be hotter at the same distance by a factor $f_{\rm T} = 1.8$ (i.e. 567K at 1 au) to reconcile the temperature of the SED with the observed radial location of the dust (see Lestrade et al. 2012; Wyatt et al. 2012). That this factor is larger then unity is consistent with the result that the inner disc radius is significantly larger than the radius implied by the simple blackbody SED model, because it is also a signature of inefficient long-wavelength grain emission and small grains dominating the disc emission. The best disc model is inclined by 27° at a position angle of 152°, and the residuals when the best-fitting model are subtracted from the data show no significant departures from the background noise elsewhere in the map.

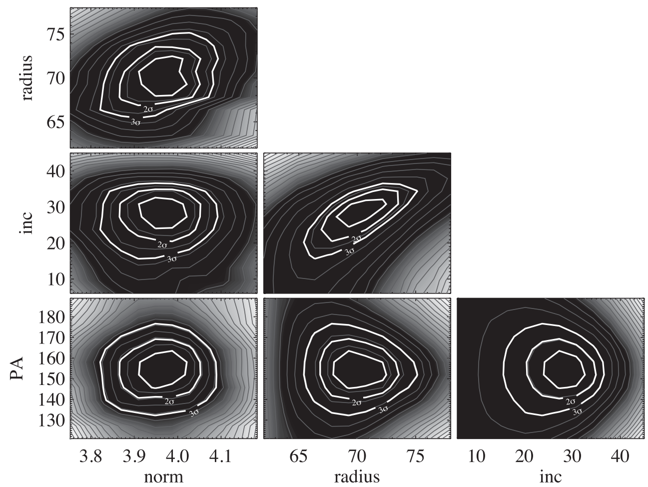

Figure 3. χ^2 contours for varying disc normalization ($\times 10^4$), inner radius (in au), inclination and PA (both in degrees). Each panel shows contours for two parameters when marginalized over the other two.

To estimate the uncertainty in several parameters, we then calculate a grid around the best-fitting location, varying the disc normalization, the inner radius, the inclination and the position angle. Each parameter is calculated at 12 values, giving a grid with 20 736 models. For each model we calculate the χ^2 from the model-subtracted residuals, accounting for correlated noise by increasing the noise by a factor of 3.6 over the pixel-to-pixel rms (see Fruchter & Hook 2002; Kennedy et al. 2012a). The results of this grid calculation are shown in Fig. 3, where the white contours show $\Delta\chi^2$ values corresponding to 1, 2 and 3σ departures from the best fit. The inclination is constrained to $27 \pm 4°$, while the PA is $152 \pm 8°$. These estimates agree well with the simple Gaussian fitting, with the difference in the range of position angles most likely because the PACS beam is slightly elongated, which will influence the results from naive Gaussian fitting. While the position angle is not particularly well constrained, we conclude that the inclination is.

The disc inclination is therefore similar to that of both the star and the planets. While the line of nodes has only been derived for

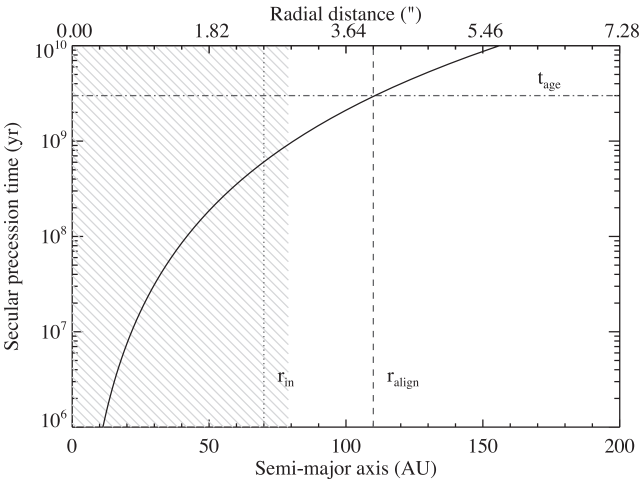

Figure 4. Secular precession time for planetesimals due to the outer planet (assuming 4.8 Jupiter masses). The hatched region shows the PACS 70 μm beam half-width at half-maximum, where the disc is unresolved. Planetesimals can start to be aligned (i.e. have executed one cycle of secular precession) within 3 Gyr if they reside within 110 au. Beyond 110 au, where the bulk of the resolved disc emission lies, the disc is not significantly affected and thus the alignment is primordial.

the disc, we take the similar inclinations to be highly suggestive of system-wide alignment. The chance of three randomly drawn inclinations to all be between 20 and 30° is 0.04 per cent, so the star–planet–disc alignment is very unlikely to be coincidental.

Combined with the possible near face-on planet orbits, one question is then whether the likely planet–disc alignment is due to nature or nurture. Given the adopted system age of 3 Gyr and the relatively massive planets, it may be that secular perturbations have over time pulled the average inclinations of parent bodies in the debris disc into alignment from an initially misaligned configuration. If this were the case, then the alignment of the planets and disc would be required by the dynamics if no other forces are acting. If the disc is too distant to have been affected, the alignment can be considered primordial and be used as evidence that disc–planet alignment was the natural outcome in this system.

A comparison of the secular precession time due to the outer planet with the system age and disc size is shown in Fig. 4. The secular precession time is calculated according to Farago & Laskar (2010), and the black line shows the radius at which particles will undergo one precession period as a function of age. The hashed area shows where the disc is within one half-width half-maximum of the *Herschel* PACS 70 μm beam, and hence approximately where the disc inclination is unconstrained. The disc inner edge at 67 au is marked, as is the radius of 110 au at which disc particles have undergone one secular precession cycle at the stellar age of 3 Gyr (called $r_{\rm align}$). The disc outer radius is poorly constrained because the power-law decay of the optical depth fades with increasing distance, but Fig. 2 shows that significant surface brightness exists out to at least 10 arcsec (275 au) in radius, well beyond the maximum distance where the disc could be aligned by secular perturbations. Though the stellar age is also uncertain, this uncertainty is unlikely to be important. For significantly younger ages the disc would be aligned to smaller distances than 110 au. Even for an age of 10 Gyr the disc would only be affected out to 150 au. To check that the inclination derived for the outer disc is not simply influenced by higher signal-to-noise ratio in the inner regions, we created a model in which the disc was separated at 110 au into two radial components, with each having independent inclinations. In the best-fitting model after χ^2 minimization the difference in inclinations for the two components is less than 1°. Thus, we conclude that the inclination of the disc is independent of the inclination of the known planets, and therefore that any planet–disc alignment is primordial.

3 CONCLUSIONS

We have shown that the debris disc surrounding HD 82943 is near face-on, with an inclination of 27 ± 4°. Assuming that the planet orbits are coplanar, the likely planet orbit inclinations of 20 ± 4° and the inferred stellar inclination of 28° argue for primordial system-wide alignment at a level similar to the Solar system. Though the line of nodes can only be derived for the debris disc, the chance of all three components randomly having near face-on inclinations is about 0.04 per cent.

As a rough estimate of the number of other planetary systems in which long-term radial velocity monitoring might be used to derive system inclinations, 33/90 systems with two or more planets in the Exoplanet Orbit Database[3] (Wright et al. 2011) have maximum/minimum period ratios less than 2.3. While the perturbations in many of these systems may not be detectable, at least some should allow inclination measurements similar to that made for HD 82943.

There are of course other possibilities for testing system alignment, with perhaps the best tests being in edge-on systems. For example, an edge-on disc is the best place to look for out-of-plane perturbations, such as the warp seen in the β Pictoris disc. These systems are also needed to use the Rossiter–McLaughlin effect to test for star–planet misalignment.

In the absence of evidence for strong dynamical influences, such as those that may form hot Jupiters, it seems that a picture of general alignment is emerging in extra-Solar planetary systems. However, given that the first hot Jupiters were also found to be aligned more systems need to be tested. If the trend of alignment continues, it will argue strongly that measurement of the inclination of any component of the planetary system, including the star itself, can act as a proxy for the inclination of the system as a whole.

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REFERENCES

Andrews S. M., Czekala I., Wilner D. J., Espaillat C., Dullemond C. P., Hughes A. M., 2010, ApJ, 710, 462
Batygin K., 2012, Nat, 491, 418
Beaugé C., Giuppone C. A., Ferraz-Mello S., Michtchenko T. A., 2008, MNRAS, 385, 2151
Beichman C. A. et al., 2005, ApJ, 622, 1160
Broekhoven-Fiene H. et al., 2013, ApJ, 762, 52
Brott I., Hauschildt P. H., 2005, in Turon C., O'Flaherty K. S., Perryman M. A. C., eds, Proc. of the Gaia Symp., Vol. 576, The Three-Dimensional Universe with *Gaia*. ESA, Noordwijk, p. 565
Butler R. P. et al., 2006, ApJ, 646, 505

[3] On 2013 April 11.

Currie T., Thalmann C., Matsumura S., Madhusudhan N., Burrows A., Kuchner M., 2011, ApJ, 736, L33
Dawson R. I., Murray-Clay R. A., Fabrycky D. C., 2011, ApJ, 743, L17
Fabrycky D. C., Murray-Clay R. A., 2010, ApJ, 710, 1408
Fabrycky D., Tremaine S., 2007, ApJ, 669, 1298
Fabrycky D. C., Winn J. N., 2009, ApJ, 696, 1230
Farago F., Laskar J., 2010, MNRAS, 401, 1189
Ferraz-Mello S., Michtchenko T. A., Beaugé C., 2005, ApJ, 621, 473
Fruchter A. S., Hook R. N., 2002, PASP, 114, 144
Goździewski K., Konacki M., 2006, ApJ, 647, 573
Holmberg J., Nordström B., Andersen J., 2009, A&A, 501, 941
Houck J. R. et al., 2004, ApJS, 154, 18
Janson M., Carson J. C., Lafrenière D., Spiegel D. S., Bent J. R., Wong P., 2012, ApJ, 747, 116
Kalas P., Graham J. R., Clampin M., 2005, Nat, 435, 1067
Kalas P. et al., 2008, Sci, 322, 1345
Kalas P., Graham J. R., Fitzgerald M. P., Clampin M., 2013, ApJ, 775, 56
Kennedy G. M., Wyatt M. C., 2011, MNRAS, 412, 2137
Kennedy G. M. et al., 2012a, MNRAS, 421, 2264
Kennedy G. M., Wyatt M. C., Sibthorpe B., Phillips N. M., Matthews B. C., Greaves J. S., 2012b, MNRAS, 426, 2115
Lafrenière D., Marois C., Doyon R., Barman T., 2009, ApJ, 694, L148
Lagrange A.-M. et al., 2010, Sci, 329, 57
Lai D., Foucart F., Lin D. N. C., 2011, MNRAS, 412, 2790
Le Bouquin J.-B., Absil O., Benisty M., Massi F., Mérand A., Stefl S., 2009, A&A, 498, L41
Lebouteiller V., Barry D. J., Spoon H. W. W., Bernard-Salas J., Sloan G. C., Houck J. R., Weedman D. W., 2011, ApJS, 196, 8
Lee M. H., Butler R. P., Fischer D. A., Marcy G. W., Vogt S. S., 2006, ApJ, 641, 1178
Lestrade J.-F. et al., 2012, A&A, 548, A86
Marois C., Macintosh B., Barman T., Zuckerman B., Song I., Patience J., Lafrenière D., Doyon R., 2008, Sci, 322, 1348
Mayor M., Udry S., Naef D., Pepe F., Queloz D., Santos N. C., Burnet M., 2004, A&A, 415, 391
Mouillet D., Larwood J. D., Papaloizou J. C. B., Lagrange A. M., 1997, MNRAS, 292, 896
Noyes R. W., Hartmann L. W., Baliunas S. L., Duncan D. K., Vaughan A. H., 1984, ApJ, 279, 763
Nutzman P. A., Fabrycky D. C., Fortney J. J., 2011, ApJ, 740, L10
Ott S., 2010, in Mizumoto Y., Morita K.-I., Ohishi M., eds, ASP Conf. Ser., Vol. 434, Astronomical Data Analysis Software and Systems XIX. Astron. Soc. Pac., San Francisco, p. 139
Pilbratt G. L. et al., 2010, A&A, 518, L1
Poglitsch A. et al., 2010, A&A, 518, L2
Rasio F. A., Nicholson P. D., Shapiro S. L., Teukolsky S. A., 1992, Nat, 355, 325
Reidemeister M., Krivov A. V., Schmidt T. O. B., Fiedler S., Müller S., Löhne T., Neuhäuser R., 2009, A&A, 503, 247
Rieke G. H. et al., 2004, ApJS, 154, 25
Su K. Y. L. et al., 2009, ApJ, 705, 314
Tan X., Payne M. J., Hoi Lee M., Ford E. B., Howard A. W., Johnson J. A., Marcy G. W., Wright J. T., 2013, ApJ, preprint (arXiv e-prints)
Thies I., Kroupa P., Goodwin S. P., Stamatellos D., Whitworth A. P., 2011, MNRAS, 417, 1817
Triaud A. H. M. J. et al., 2010, A&A, 524, A25
Watson C. A., Littlefair S. P., Diamond C., Collier Cameron A., Fitzsimmons A., Simpson E., Moulds V., Pollacco D., 2011, MNRAS, 413, L71
Werner M. W. et al., 2004, ApJS, 154, 1
Wright J. T. et al., 2011, PASP, 123, 412
Wyatt M. C., 2008, ARA&A, 46, 339
Wyatt M. C. et al., 2012, MNRAS, 424, 1206

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