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

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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 ± 4°. Here, we show that the debris disc in this system is inclined by 27 ± 4°, 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 ± 4°, suggesting that the entire star–planet–disc system is aligned, the first time such alignment has been tested for radial velocity discovered planets on ∼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 ≳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...
inferred from the stellar radius, projected rotation velocity, and activity indicator rather than directly measured, which Noyes et al. (2004) show results in period uncertainties of a few days. A three-day uncertainty yields an inclination uncertainty of \( \pm 5^\circ \) 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 \( \chi^2 \) 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 \( 20 \pm 4^\circ \). Naturally, the low inclination means that \( \sin i \)
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\(^\circ\)). 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 \( \mu \)m 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 \( \mu \)m 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 \( \mu \)m.

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\(^\circ\) 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 \( \mu \)m were measured using aperture photometry (radii of 15 and 20 arcsec), yielding fluxes of 129 \pm 4 mJy and 87 \pm 7 mJy at 70 and 160 \( \mu \)m, 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 \( \text{R}_\odot \). We then use the stellar photosphere model to predict the flux density at longer wavelengths (e.g. 7.2 \pm 0.2 and 1.35 \pm 0.03 mJy at 70 and 160 \( \mu \)m), 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 \( L_{\text{disc}}/L_*=10^{-4} \) and a temperature of 57 \pm 2 K, with the small uncertainty due to detection over a reasonably wide range of wavelengths (20–160 \( \mu \)m).

In Fig. 1 we have multiplied the blackbody disc spectrum by (\( \lambda_0/\lambda \)) beyond \( \lambda_0 = 210 \mu \text{m} \) (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.

In addition to yielding photometric measurements, the disc is well resolved by Herschel at 70 \( \mu \)m, but less so at 160 \( \mu \)m. There is in addition some apparent low-level background contamination to the NE at 160 \( \mu \)m. 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 \( \mu \)m 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 \( \gamma \) 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\(^\circ\) and an inclination of 30\(^\circ\). The inclination is found using \( \cos i=s_{\text{min}}/s_{\text{maj}} \), where \( s_{\text{maj}} \) and \( s_{\text{min}} \) are found.
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 ($s_{maj}$ 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 coaligning 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 $3.98 \times 10^{-4}$ 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 $f_T = 1.8$ (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.

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 $\chi^2$ 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 $27 \pm 4^\circ$, while the PA is $152 \pm 8^\circ$. 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...
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 secular precession cycle at the stellar age of 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.

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 (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.

ACKNOWLEDGEMENTS

We thank the referee for a concise review and help on transiting planet details. This work was supported by the European Union through ERC grant number 279973 (GMK & MCW). This research has made use of the Exoplanet Orbit Database and the Exoplanet Data Explorer at exoplanets.org.

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