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Star - Planet - Debris Disk 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 $20 \pm 4^\circ$. Here, we show that the debris disk 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 disk 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 - disk 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-disk alignment is primordial, and not the result of planetary secular perturbations to the disk inclination. In addition, we note three other systems with planets at $\gtrsim$10AU discovered by direct imaging that already have good evidence of alignment, and suggest that empirical evidence of system-wide star - planet - disk 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: planetary systems: formation — circumstellar matter — stars: individual: HD 82943

1 INTRODUCTION

Planetary systems are known to emerge from the disk-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 disk 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 - disk 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 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 circularised 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 disk (Lai et al. 2011; Batygin 2012), implying that hot Jupiters could have migrated through the gas disk 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 et al. 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.

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One prediction of the primordially misaligned disk scenarios is that debris disks, presumed to have their origins within the gaseous protoplanetary disk, could be misaligned with their parent stars. However, the test for star - disk alignment has until recently been much harder. It involves comparing the inclination of the star inferred from the stellar radius, projected rotation velocity, and rotation period, to that of the resolved debris disk that orbits that star. This test is not usually possible because debris disks are only detected around ∼15% 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-disk 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 disk inclinations are generally similar, and hence that both share the same orbital plane as the primordial protoplanetary disk (Watson et al. 2011, Greaves et al, in preparation).[2]

The final alignment test, that of planet - disk 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 submitted). In addition, the position angle of the stellar rotation axis of $65 \pm 3^\circ$ (Le Bouquin et al. 2009) is perpendicular to the debris disk major axis of $156 \pm 0.3^\circ$ (Kalas et al. 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; Fabrycky & Murray-Clay 2010; Lafrenière et al. 2009), as is the debris disk (Su et al. 2009). In fact, the favoured planetary inclination of 13-23° is very similar to the debris disk 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 disk (Lagrange et al. 2010; Currie et al. 2011), but may be slightly misaligned (∼5°), if it is the origin of the disk warp seen at ∼70AU (Mouillet et al. 1997; Dawson et al. 2011). Therefore, in the cases where it is possible to test star - planet - disk 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 - disk 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$10AU 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 $i = 20 \pm 4^\circ$. We show that the debris disk as resolved by *Herschel* imaging is inclined by $27 \pm 4^\circ$, thereby adding strength to the inferred planet inclinations, and arguing that the planets and disk are aligned. In addition, we show that the inferred stellar inclination is 28°, so probably aligned with the planets and disk. Based on the assumption of star - planet - disk 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 (27.5pc) Sun-like main-sequence dwarf star (F9V). Mayor et al. (2004) quote an age of 2.9 Gyr, while Holmberg et al. (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 disk. We therefore adopt an age of 3Gyr.

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 days (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 $28 \pm 4^\circ$, 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 $\approx 5^\circ$ 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 days—meaning that these are not hot Jupiters. These planets were recognised 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 et al. 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

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[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 - disk alignment if the binary orbit is well characterised, see Andrews et al. (2010) and Kennedy et al. (2012a,b).

the planet masses, hence providing an opportunity to constrain the planet inclinations with sufficiently high S/N data that spans 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 minimisation 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 $\sin i$ 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 disk 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% 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 order hundreds of micro-arcseconds).

2.3 The Debris Disk

The debris disk 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* (Werner et al. 2004; Rieke et al. 2004). An infrared excess above the stellar photosphere at 70μm was seen, with the excess attributed to the presence of a significant surface area of small grains in a debris disk. The excess was not detected at 24μm so the disk 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 25μm.

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 disk 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 onto a grid of pixels (i.e. turned into images) using a near-standard HIPE pipeline (Ott 2010). The fluxes at 70 and 160μm were measured using aperture photometry (radii of 15” & 20”), yielding fluxes of 129 ± 4mJy and 87 ± 7mJy at 70 and 160μm respectively.

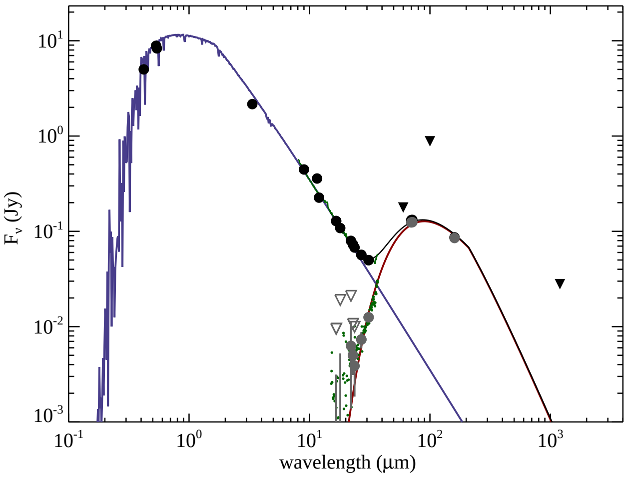

Figure 1. Spectral energy distribution for HD 82943. Dots are fluxes and triangles 3σ upper limits. Black symbols are measured fluxes and grey symbols are star-subtracted (i.e. disk) fluxes. The 5990K stellar photosphere model is shown in blue, the 57K blackbody disk model in red, and the star+disk spectrum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

Figure 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 minimisation, finding a stellar effective temperature of 5990K and a radius of $1.15R_\odot$. We then use the stellar photosphere model to predict the flux density at longer wavelengths (e.g. 7.2 ± 0.2 and 1.35 ± 0.03mJy at 70 and 160μm), 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 $L_{\rm disk}/L_\star = 10^{-4}$ and a temperature of 57 ± 2K, with the small uncertainty due to detection over a reasonably wide range of wavelengths (20-160μm). In Figure 1 we have multiplied the blackbody disk spectrum by (λ_0/λ) beyond $\lambda_0 = 210\mu$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 disk brightness. Assuming that it lies in a single narrow ring, the blackbody temperature implies that the disk lies at a stellocentric radius of 30AU. We show below that the disk 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 disk is well resolved by *Herschel* at 70μm, but less so at 160μm. There is in addition some apparent low-level background contamination to the NE at 160μm. Such contamination is in fact fairly common for *Herschel* observations at this wavelength; here we are less than a factor of two above the confusion limit

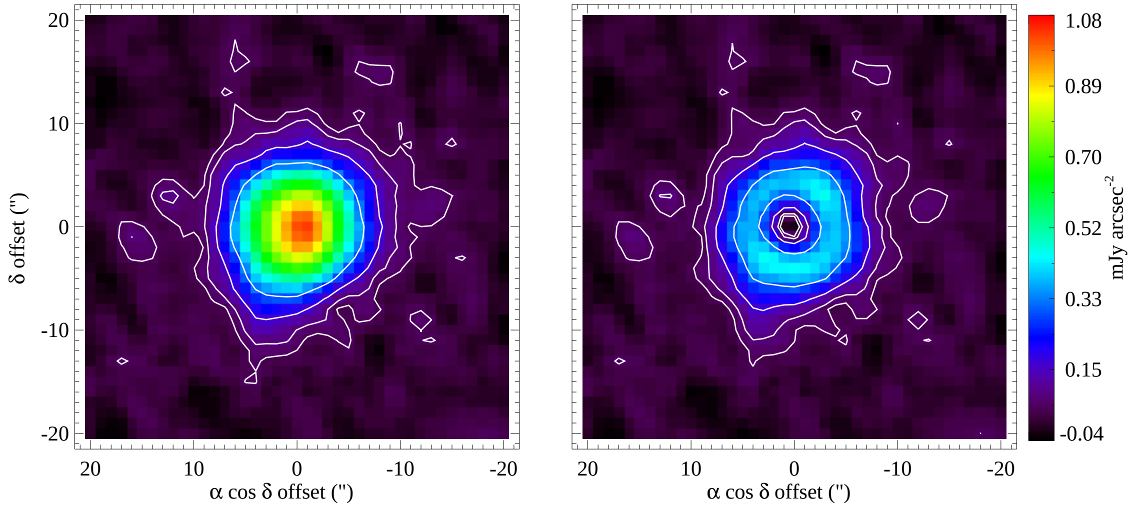

Figure 2. *Herschel* 70μm images of HD 82943, North is up and East is left. The left panel shows the raw image with contours at 3, 5, 10, and 20 times the pixel RMS of 1.6×10^{-2}mJy arcsec^{-2}. The right panel shows the same image and contours after a peak-scaled point source has been subtracted, leaving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

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

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

of 1.4mJy (as predicted by the *Herschel* Observation Planning Tool). The 70μm image is shown in the left panel of Figure 2. To show that the image is resolved, the right panel shows the image after a peak-normalised 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 disk is resolved, the azimuthal symmetry of the remaining ring shows that the disk is near to face-on.

To estimate the inclination and position angle of the disk we use two independent methods. The first is simple, we fitted a 2D Gaussian to the star-subtracted image of the HD 82943 disk, 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 from quadratically subtracting the PACS 70μm beam full-width at half-maximum (FWHM) of 5.″75 from the major and minor components of the fitted Gaussian FWHM ($s_{\rm maj}$ is also an estimate of the characteristic disk size, about 100AU). To estimate the uncertainty we then added the Gaussian fit image into an off-center position in 9 other 70μm 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 disk geometry can vary due to different realisations of the same noise level. The inclinations vary from 25-31° 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 disk structure and estimate parameter uncertainties in a more traditional way. These models have been used previously to model *Herschel*-resolved debris disks (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 PSF model for comparison with the observed disk. The best fitting model is found by a combination of by-eye coaxing and least-squares minimisation. We found that the HD 82943 disk could not be well modelled by a simple ring, and hence use a dust distribution that extends from 67 to 300AU, with the face-on optical depth distributed as a power-law that decays as $r^{-1.6}$ and is normalised to be 3.98×10^{-4} at 1AU. The temperature distribution is assumed to decay as $r^{-0.5}$ (i.e. like a blackbody, which is 278.3K at 1AU), but is required to be hotter at the same distance by a factor $f_{\rm T} = 1.8$ (i.e. 567K at 1AU) to reconcile the temperature of the SED with the observed radial location of the dust (see Wyatt et al. 2012; Lestrade et al. 2012). That this factor is larger then unity is consistent with the result that the inner disk 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 disk emission. The best disk 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 fit location, varying the disk normalisation, 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 Figure 3, where the white contours show $\Delta\chi^2$ values corresponding to 1, 2, and 3σ

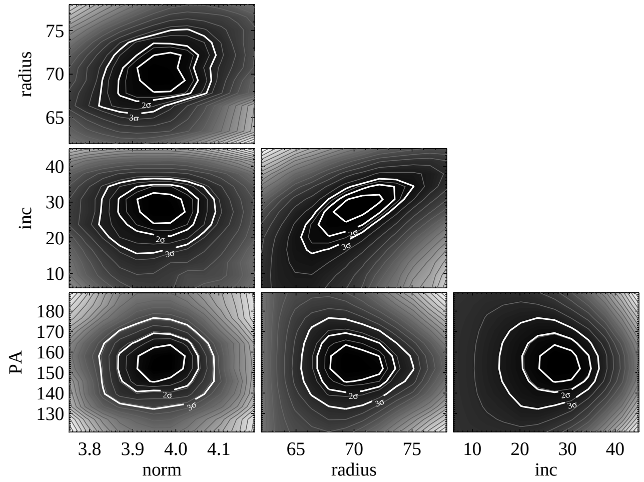

Figure 3. χ^2 contours for varying disk normalisation ($\times 10^4$), inner radius (in AU), inclination, and PA (both in degrees). Each panel shows contours for two parameters when marginalised over the other two.

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 disk inclination is therefore similar to that of both the star and the planets. While the line of nodes has only been derived for the disk, 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%, so the star - planet - disk alignment is very unlikely to be coincidental.

Combined with the possible near face-on planet orbits, one question is then whether the likely planet - disk alignment is due to nature or nurture. Given the adopted system age of 3Gyr and the relatively massive planets, it may be that secular perturbations have over time pulled the average inclinations of parent bodies in the debris disk into alignment from an initially misaligned configuration. If this were the case, then the alignment of the planets and disk would be required by the dynamics if no other forces are acting. If the disk is too distant to have been affected, the alignment can be considered primordial and be used as evidence that disk-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 disk size is shown in Figure 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 disk is within one half-width half-maximum of the *Herschel* PACS 70μm beam, and hence approximately where the disk inclination is unconstrained. The disk inner edge at 67AU is marked, as is the radius of 110AU at which disk particles have undergone one secular precession cycle at the stellar age of 3Gyr (called $r_{\rm align}$). The disk outer radius is poorly constrained because the power-law decay of the optical depth fades with increasing distance, but

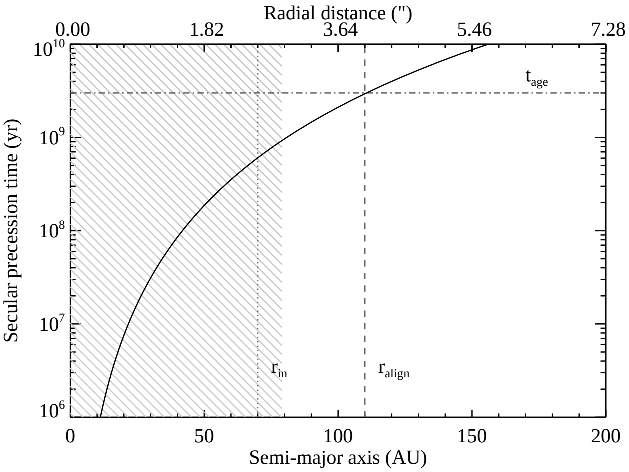

Figure 4. Secular precession time for planetesimals due to the outer planet (assuming 4.8 Jupiter masses). Planetesimals can start to be aligned (i.e. have executed one cycle of secular precession) within 3Gyr if they reside within 110AU. Beyond 110AU, where the bulk of the resolved disk emission lies, the disk is not significantly affected and thus the alignment is primordial.

Figure 2 shows that significant surface brightness exists out to at least 10" (275AU) in radius, well beyond the maximum distance where the disk 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 disk would be aligned to smaller distances than 110AU. Even for an age of 10Gyr the disk would only be affected out to 150AU. To check that the inclination derived for the outer disk is not simply influenced by higher S/N in the inner regions, we created a model in which the disk was separated at 110AU into two radial components, with each having independent inclinations. In the best fitting model after χ^2 minimisation the difference in inclinations for the two components is less than 1°. Thus, we conclude that the inclination of the disk is independent of the inclination of the known planets, and therefore that any planet - disk alignment is primordial.

3 CONCLUSIONS

We have shown that the debris disk surrounding HD 82943 is near face-on, with an inclination of $27 \pm 4^{\circ}$. Assuming that the planet orbits are coplanar, the likely planet orbit inclinations of $20 \pm 4^{\circ}$ 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 disk, the chance of all three components randomly having near face-on inclinations is about 0.04%.

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 will may not

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[3] On 11 April 2013

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 disk is the best place to look for out-of-plane perturbations, such as the warp seen in the β Pictoris disk. 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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