Alignment in star-debris disc systems seen by Herschel

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ABSTRACT

Many nearby main-sequence stars have been searched for debris using the far-infrared *Herschel* satellite, within the DEBRIS, DUNES and Guaranteed-Time Key Projects. We discuss here 11 stars of spectral types A to M where the stellar inclination is known and can be compared to that of the spatially-resolved dust belts. The discs are found to be well aligned with the stellar equators, as in the case of the Sun's Kuiper belt, and unlike many close-in planets seen in transit surveys. The ensemble of stars here can be fitted with a star-disc tilt of $\lesssim 10°$. These results suggest that proposed mechanisms for tilting the star or disc in fact operate rarely. A few systems also host imaged planets, whose orbits at tens of AU are aligned with the debris discs, contrary to what might be expected in models where external perturbers induce tilts.

Key words: planetary systems – circumstellar matter – infrared: stars

1 INTRODUCTION

The planets in the Solar System orbit near a plane aligned with the Sun's equator. This is tilted by only 7° with respect to the ecliptic plane (Beck & Giles 2005), with the midplane

of the more dynamically-excited Kuiper Belt aligned within 2° of the ecliptic (Brown & Pan 2004; Collander-Brown et al. 2003). However, many asteroids have very inclined orbits, attributed to scattering by planets or to the Kozai mechanism (dynamical exchange of high eccentricities and inclina-

tions). Such effects are of renewed interest with the discovery of extremely inclined orbits of some extrasolar planets, including cases so extreme as to be retrograde (e.g. Brown et al. 2012, Simpson et al. 2011, Triaud et al. 2010, Winn et al. 2010). These bodies are observed in transit, where the occulting planet blocks starlight with specific Doppler shifts (the Rossiter-McLaughlin effect). It is widely thought that perturbations from more distant (unseen) planets allow the Kozai mechanism to operate, or lead to mutual scattering, and potentially tidal orbital circularisation and stellar spin-axis reorientation (Winn et al. 2010; Albrecht et al. 2012).

Here we explore whether distant planetesimals can have orbits misaligned with the stellar spin axis. It has been proposed that interaction of the magnetic field of a young star with its circumstellar disc could tip the star (Foucart & Lai 2011; Lai et al. 2011). Alternatively, external accretion could give a randomised final angular momentum vector to the disc (Bate et al. 2010), or encounters with another disc/envelope system could cause dynamical perturbation (Thies et al. 2011). Evidence of such events could be found much later, for main-sequence stars where belts of planetesimals have formed from the circumstellar discs, as collisions generate debris that produces thermal emission at infrared and longer wavelengths. Further, where planets have been imaged or detected by astrometry, the inclinations of the orbital and belt planes can be compared to the stellar equator.

Results of star-disc alignment studies are so far sparse. Greaves et al. (2004) noted that the nearby old Solar-analogue τ Ceti appeared to have a rather edge-on debris disc while the star's small projected rotational velocity ($v \sin i_*$) suggested a more pole-on aspect. However, confusion with background objects hinders inclination estimation for this compact disc (Di Francesco et al., in prep.). Watson et al. (2011) examined 8 debris systems with Sun-like host stars, but found no cases where the disc and star were definitely misaligned. However, the data available spanned a wide range of wavebands and angular resolutions, potentially causing problems where interferometers resolved out disc flux, or dispersed small grains were seen in scattered light. It is therefore timely to make an update using newly-resolved discs from surveys made with the large and sensitive *Herschel* observatory (Pilbratt et al. 2010). The PACS camera (Poglitsch et al. 2010) provided uniform imaging at 5.6-11.4 arcsecond resolution at wavelengths of 70, 100, 160 μm. We identify here 11 main-sequence stars (some planet-hosting) that now have resolved debris discs along with information on the stellar inclination. The relative alignments are then compared to theoretical expectations.

2 DATA ANALYSIS

2.1 Disc Data

Herschel data were obtained for Key Projects awarded under Guaranteed Time (Olofsson 2010) and for the larger unbiased Open Time Key Programmes DEBRIS (Matthews et al. 2010) and DUNES (Eiroa et al. 2010, 2013). For spectral types AFGKM, debris detection rates are up to ∼25%, with numerous discs now spatially resolved with PACS (Booth et al. 2013; Eiroa et al. 2013). As an example, Figure 1 shows data for HD 115617 (61 Vir), where the debris disc is nearly
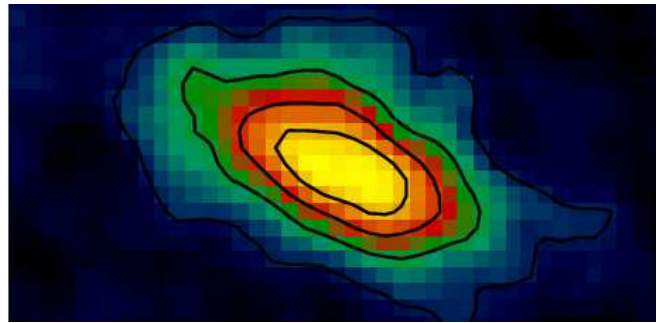
Figure 1. DEBRIS image of the HD 115617 (61 Vir) system at 70 μm, in a 40×20 arcsec RA, Dec. field with 5.6 arcsec beam, after subtracting stellar emission. For this 8th-closest G-dwarf to the Sun, 10 arcseconds corresponds to 85 AU. Image from Wyatt et al. (2012; Figure 2); see this paper for model details.

edge-on, and a less inclined disc would appear distinctly rounder. Implicitly, we assume that the discs have negligible vertical thickness and are circular; Greaves et al. (in prep.) discuss this in the context of highly resolved discs. HR 8799 (Herschel PI project; Matthews, in prep.) was added to the final sample; this interesting planet-host system was previously resolved by *Spitzer* at 70 μm (Su et al. 2009).

We fitted model discs to estimate inclinations with respect to the sky plane, so e.g. an $i_d = 0°$ disc is face-on (while an $i_* = 0°$ star is pole-on). The discs were analysed uniformly, with the two or three available wavebands fitted simultaneously, and least-squares minimisation was used to optimise the radius, position angle and inclination of a model thin annulus (see Wyatt et al. 2012 for description). Uncertainties in these i_d values were estimated by comparing alternate inclinations obtained from a thin-toroid grid-search algorithm (Booth et al. 2013) and from beam-deconvolved 2-D Gaussian fits to the discs. Comparison of the outcomes shows an average 7° discrepancy between methods. Here we adopt a conservative error of ±10° (at the upper end of measured differences), or the estimates from published detailed models. These include studies by Sibthorpe et al. (2010) for Vega, Wyatt et al. (2012) for 61 Vir, Broekhoven-Fiene et al. (2013) for γ Dor, Lestrade et al. (2012) for GJ 581, while Marshall et al. (in prep.) will further discuss HD 30495 and HD 110897. Models for Vega, 61 Vir and γ Dor showed that discrepancies between fits at different wavelengths are small, with inclination estimates varying by only ∼ 5°. As earlier spectral types tend to have better resolved discs (Booth et al. 2013; Eiroa et al. 2013), we subsequently order the systems by spectral type and then distance (Table 1; Figure 2), as a guide to the increasing difficulty of fitting inclinations.

2.2 Stellar Data

Inclinations of stars are difficult to determine. In principle, interferometry of features of the stellar surface could give full 3-D information on the angle at which we view the star, the same as obtained from resolved disc images. However, even with ultra-high resolution this technique is mainly applicable to giant stars. Here only Vega has i_* from interferometry; its apparent oblateness is sensitive to viewing angle because it is flattened by rapid rotation. Vega is very close to pole-on (Aufdenberg et al. 2006; Peterson et al. 2006;

Table 1. Debris disc systems observed by the *Herschel* Key Projects DEBRIS (γ Dor, HD 115617, GJ 581), DUNES (HD110897, HD 30495, HD 166, HD 17925, HD 131511) and in Guaranteed Time (Vega, ϵ Eri, AU Mic), plus HR 8799 observed separately. Stars are listed by most common name, and ordered by spectral type and distance (noted by 'UNS' identification where applicable; Phillips et al. 2010). Subsequent columns list system components, observed rotation periods P, projected rotation velocities $v \sin i_*$ and radii R_*. Derived stellar inclinations are given by i_*, and fitted disc inclinations by i_d ($0°$ = pole- or face-on). The Sun (for comparison) has angles with respect to the ecliptic plane. Absolute value of inclination differences $|\Delta i|$ are $|i_* - i_d|$, with an uncertainty from errors in i_d, i_* added in quadrature and adopting $(i_{*,min} + 90°)/2$ in lower-limit cases; $\sin^2 i_* + \cos^2 i_d$ is a measure of misalignment (see text). Stellar periods are from: [1] Simon & Fekel (1987); [2] Baliunas et al. (1996); [3] Gaidos et al. (2000); [4] Baliunas et al. (1983); [5] de Warf et al. (2010); [6] Donahue et al. (1996); [7] Bohigas et al. (1986); [8] Henry et al. (1995); [9] Vogt et al. (2010); [10] Messina et al. 2001; [11] Hebb et al. 2007.

system names (UNS id)	notes	P (days)	$v \sin i_*$ (km/s)	R_* ($R_\odot$)	i_* (°)	i_d (°)	$|\Delta i|$ (°)	$\sin^2 i_* + \cos^2 i_d$
Vega, HD 172167 (A003)	planet?; 2 belts	—	—	—	3–6	10 ± 2	5.5 ± 2.5	0.98 ± 0.01
HR 8799, HD 218396 (A—)	planets; 2 belts	—	—	—	$\gtrsim 40$	27 ± 10	$\gtrsim 3$	$\gtrsim 1.07$
10 CVn, HD 110897 (F050)		13 [1]	3.4 ± 1.4	0.99	$63 (\geqslant 33)$	56 ± 10	$7^{+29}_{(-7)}$	1.11 ± 0.65
γ Dor, HD 27290 (F085)	2 belts	—	—	—	63–80	69 ± 5	$3^{+10}_{(-3)}$	1.03 ± 0.11
Sun (G—)	*planets, 2 belts*	*—*	*—*	*—*	*7.3*	*1.7 ± 0.2*	*5.6 ± 0.2*	*1.02 ± 0.00*
61 Vir, HD 115617 (G008)	planets	29 [2]	1.6 ± 0.5	0.97	$68 (\geqslant 41)$	77 ± 4	$9^{+22}_{(-9)}$	0.91 ± 0.52
58 Eri, HD 30495 (G029)		11.3 [2,3,4]	3.4 ± 0.3	0.97	51 ± 6	51 ± 10	$0^{+12}_{(-0)}$	1.00 ± 0.20
V439 And, HD 166 (G030)	2 belts?	5.7 [3,5]	4.8 ± 0.7	0.87	39 ± 6	50 ± 10	$11^{+12}_{(-11)}$	0.81 ± 0.20
ϵ Eri, HD 22049 (K001)	planet(s); 2 belts	11.6 [6]	2.3 ± 0.3	0.74	46 ± 8	38 ± 10	$8^{+13}_{(-8)}$	1.14 ± 0.22
EP Eri, HD 17925 (K035)		6.9 [2,6,7]	5.8 ± 0.6	0.79	$88 (\geqslant 63)$	54 ± 10	34^{+10}_{-27}	1.34 ± 0.25
DE Boo, HD 131511 (K053)		10.4 [8]	4.5 ± 0.4	0.91	$\geqslant 70$	84 ± 10	$4^{+12}_{(-4)}$	1.06 ± 0.18
HO Lib, GJ 581 (M056)	planets	94 [9]	0.3 ± 0.3	0.30	$\geqslant 0$	50 ± 20	—	—
AU Mic, HD 197481 (M—)		4.9 [10,11]	8.5 ± 0.6	0.77	$\geqslant 81$	$\geqslant 80$	$1^{+7}_{(-1)}$	1.13 ± 0.16

Yoon et al. 2010; Monnier et al. 2012), which minimises apparent oblateness, while our analysis of four other DEBRIS A/F-stars (β Leo, α CrB, β UMa, η Crv) gave only weak lower limits to i_*. Stars seen nearly side-on are suggested when $v \sin i_*$ approaches the maximum value for the spectral type, but this also has poor accuracy and is subject to the assumption that stars of a given spectral type have a maximum spin rate. This method was used only to check inclinations. Estimates of i_* can also be made from models of asteroseismological data and/or rotation of spot patterns, as some surface features can only be seen in certain orientations. Here asteroseismology gives useful checks for HR 8799 (Wright et al. 2011), ϵ Eri (Croll et al. 2006, Fröhlich 2007) and γ Dor (Balona et al. 1996).

The primary method remains the classic approach of Campbell & Garrison (1985), yielding inclination of the stellar pole with respect to the line of sight when true rotation velocity can be compared to $v \sin i_*$. This gives

$$\sin i_* = 0.0198\, P\, v \sin i_* / R_*, \qquad (1)$$

where stellar rotation period P is in days, projected rotation velocity $v \sin i_*$ is in km/s and stellar radius R_* is in solar radii. Radii are from fitting optical and near-infrared fluxes for luminosity and effective temperature, with interferometric measurements for ϵ Eri and GJ 581 (Di Folco et al. 2004; von Braun et al. 2011). Checks on radii using surface-brightness relations (Kervella et al. 2004) show differences only at the 5 % level. Thus for radius and also period (see below), uncertainties usually contribute negligibly to the error estimate in inclination, and Table 1 only lists the uncertainty in i_* derived from that in $v \sin i_*$. Then by differentiation, $\delta i_* = \delta(\sin i_*)/\cos i_*$, with $\delta(\sin i_*) = 0.0198\, P\, \delta(v \sin i_*) / R_*$ from Eq. 1. In some cases, allowed

values of i_* range from a lower bound up to $90°$, and then the lower bound quoted is from $\sin i_*$ minus its error.

Projected rotational velocities of stars are found by fitting their spectral lines, with modest differences between methods and calibration systems that have been well characterised by Głębocki & Gnaciński (2005a). Here we compile values from Głębocki & Gnaciński (2005b) plus $v \sin i_*$ data from the subsequent literature, including a comprehensive study made for DUNES (Martínez-Arnáiz et al. 2010), thus adding up to 6 more measurements per star[1]. The Głębocki & Gnaciński (2005b) method of merging calibrations was not reproduced, but the weights w they attribute to different methods of line fitting were adopted. The weighted standard error on the mean is then $\sigma/\sqrt{N_{eff}}$, for an effective number of observations $N_{eff} = (\Sigma(w))^2/\Sigma(w^2)$. For values differing from the mean by δ, $\sigma = \sqrt{(\Sigma(w\delta)/\Sigma(w))}$. The number of velocities included is 5 to 14, with N_{eff} of 4.3–13.5, except for the very slow rotator GJ 581, whose $v \sin i_*$ (Marcy & Chen 1992) does not constrain the stellar inclination. Overall, some differences in $v \sin i_*$ between different catalogues were confirmed; omitting particular datasets shifts the means by up to $\approx 1.5\times$ the standard error.

Periods P are found from tracking variability associated with surface inhomogeneities, such as the data obtained under the long-running Mount Wilson Project. Such results are sparse, and limit our analysis to 9 nearby late-type (F9–M3) stars. Uncertainties and intrinsic variations in P are generally recorded as small, at $\sim$5 %. Hartman et al. (2011)

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[1] Data compiled from: Jenkins et al. (2011); Weise et al. (2010); Houdebine (2010, 2008); Schröder et al. (2009); Mishenina et al. (2008); Scholz et al. (2007); Desidera et al. (2006); Valenti & Fischer (2005); Santos et al. (2004); Nordstrom et al. (2004).
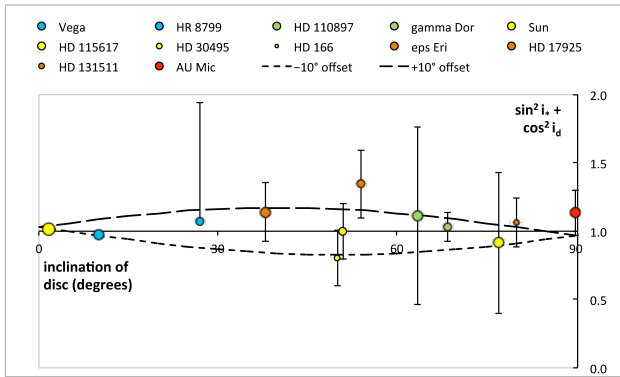
Figure 2. Plot of $sin^2i_* + cos^2i_d$ against disc inclination, where y-values $\neq 1$ indicate that the disc and star are misaligned. Symbols are ordered as in Table 1, with colours according to type (from blue for A to red for M) and smaller sizes for greater distances. X-axis error bars are omitted for clarity. The curves illustrate how $sin^2i_* + cos^2i_d$ varies with disc inclination, when the star has a *relative* tilt of $\pm 10°$.

investigated reliability of period extraction in a star survey including BY Dra rotational variables (including HD 166, HD 30495, ϵ Eri, GJ 581 and AU Mic here), and only the latter two M-stars have amplitudes in the 0.01-0.02 mag range that is of concern. Of these, only AU Mic rotates fast enough for useful analysis here, and the period was derived from a set of 10 light curves (Messina et al. 2001). More ambiguous periods could however arise in cases of differential surface rotation and/or temporal changes. The most extreme case noted here is HD 30495, where Baliunas et al. (1983) found a period of 7.6 days, in contrast to 10.5-11.5 days in more recent data (Gaidos et al. 2000). To illustrate this 'worst case' uncertainty, using the low period value and the lower bound in $v\ sin\ i_*$ would give a stellar inclination at the -2.3σ bound compared to the Table 1 solution.

Periods can be estimated from relations linking main-sequence spin-down to decline in chromospheric activity (e.g. Mamajek & Hillenbrand 2008). However, for more FGK discs resolved in DEBRIS/DUNES, this method showed a problem of $sin\ i_* > 1$ for 30 % of stars; Kennedy et al. (2013) discuss how i_* can be robust if it is small. An advantage of observed periods is that spin-down for Solar-type stars is rather well understood (Barnes 2007), and so 'gyrochronology' ages have be found (Vican et al. 2012); this confirmed the unbiased nature of our survey targets.

3   RESULTS

Results are listed in Table 1. Star-disc inclination differences Δi are typically close to zero, albeit with large errors where $v\ sin\ i_*$ is low. In the seven best-defined cases, the star-disc systems appear co-planar within $5°$ on average, with only the Vega system potentially misaligned (by $5.5\pm 2.5°$). This small tilt would be similar to the Sun's inclination versus the Kuiper belt, which for an external observer in an ecliptic co-ordinate frame would be $\Delta i = 5.6°$. A potentially misaligned system is the planet-host HR 8799, which has only a lower limit to i_* from asteroseismology and $\Delta i \gtrsim 3°$; if the star is far from pole-on it will not be co-planar with the disc.

The survey outcome is similar to the null result of Watson et al. (2011), from eight stars. The joint sample now covers 16 stars with useful Δi values, with three-quarters of these now observed uniformly by Herschel. Given the null results, no stellar property (Table 1) is noteworthy – unlike the situation for close-in planets, where e.g. a link with the proportion of the star that is convective has been suggested (Winn et al. 2010). For completeness, we note that a binary-star system is known with a highly misaligned (circumpolar) debris disc (Kennedy et al. 2012), but here our stars are single, except for the spectroscopic binary HD 131511.

To assess any *mean* tilt present, we use the measure $sin^2i_* + cos^2i_d$, which diverges from unity if the disc and star are misaligned. This is more statistically convenient than Δi, as measurement errors in $sin\ i_*$ and i_d can be assumed to be normally distributed. The errors can be written as $\delta(sin^2\ i_*) = 2\ sin\ i_*\ \delta(sin\ i_*)$ and $\delta(cos^2\ i_d) = 2\ cos\ i_d\ sin\ i_d\ \delta(i_d)$ and combined quadratically. The mean value of $sin^2i_* + cos^2i_d$ (excluding the Sun) is then 1.06 with a standard error of ± 0.04, consistent with no misalignment at the 1.5σ level. Figure 2 illustrates this by plotting $sin^2i_* + cos^2i_d$ for the whole sample. The value obtained for a particular star-disc tilt depends on viewing angle, and the over-plotted curves illustrate example relative tilts. These curves at $\pm 10°$ encompass all plotted stars within their errors, suggesting the mean tilt is within this range.

4   DISCUSSION

The generally good alignment of stars with their debris discs is in marked contrast to the situation for close-in planets. The cases can not be absolutely compared, because transit data yield inclination differences up to $180°$, versus a 0-90$°$ range for disc-star alignment, while neither method is fully 3-D (lacking the orientation of the stellar pole). However, approximately a third of Rossiter-McLaughlin detections have Δi of 30-150$°$, for example (Brown et al. 2012), while here there are no good candidates for this magnitude of misalignment. This suggests that dynamical effects near the star do not operate on the outer system planetesimals.

A few debris-host stars also have imaged planet-candidates, at semi-major axes of 15-180 AU. These systems suggest planet-disc co-planarity, as well as the star-disc alignments. HR 8799 b has an orbital plane inclined at 13–23$°$ (Lafrenière et al. 2009) versus our 17–37$°$ for the disc plane; Fomalhaut b's orbit is estimated at $17\pm 12°$ from the ring plane (Kalas et al. 2013); β Pic b (Lagrange et al. 2012) is thought to have perturbed the inner-disc plane to align close to its orbit; and ϵ Eri b (unconfirmed, at $\sim$3 AU) has a nominal astrometric orbit within $\sim 10°$ of the outer debris belt plane (Greaves et al., in prep.). This suggests different forces at work than on close-in planets, or binary stars, where orbits and spin axes tend to misalign at separations $\gtrsim 30 - 40$ AU (Hale 1994). The 'regime of coplanarity' is hard to define, though Figueira et al. (2012) have suggested that HARPS plus Kepler detection statistics may point to co-planarity of multiple planets out to about 0.3 AU.

To make further progress, it would help to discover transiting-planet-plus-disc systems (Hebb et al. 2007), as well as to resolve tilts within more multiple-belt systems like β Pic. Generally, models where external encounters affect

the alignment of outer components of the system (Bate et al. 2011; Thies et al. 2011) seem unlikely, as planets and discs at different radii should be differently perturbed, while here we find examples of stars aligned with both disc and planets over tens-of-AU scales. We note especially the case with the most 3-D information, the Fomalhaut system, where the orientation of the stellar pole is orthogonal to the disc plane (Le Bouquin et al. 2009), and Fomalhaut b's orbit is close to the plane of the debris ring (Kalas et al. 2013).

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