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Stellar multiplicity and debris discs: an unbiased sample

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ABSTRACT

Circumstellar dust discs have been observed around many nearby stars. However, many stars are part of binary or multiple stellar systems. A natural question arises regarding the presence and properties of such discs in systems with more than one star. To address this, we consider a sample of 449 systems (spectral types A–M) observed with the *Herschel Space Observatory* as part of the DEBRIS (Disc Emission via a Bias-free Reconnaissance in the Infrared/Submillimetre) programme. We have examined the stellar multiplicity of this sample by gathering information from the literature and performing an adaptive optics imaging survey at Lick Observatory. Five new companions were revealed with our programme. In total, we identify 188 (42 per cent) binary or multiple star systems. The multiplicity of the sample is examined with regards to the detection of circumstellar discs for stars of spectral types AFGK. In general, discs are less commonly detected around binaries than single stars, though the disc frequency is comparable among A stars regardless of multiplicity. However, this sample reveals the period distribution of disc-bearing binaries is consistent with that of non-disc binaries and with comparison field samples. We find that the properties of discs in binary systems are not statistically different from those around single stars. Although the frequency of disc-bearing FGK binaries may be lower than in single star systems, the processes behind disc formation and the characteristics of these discs are comparable among both populations.

Key words: binaries: general – infrared: planetary systems – infrared: stars.

1 INTRODUCTION

Discs rich in gas and dust around young stars are sites of planet formation. Jovian-class planets need to form rapidly, as gas within the discs dissipates over a period of a few million years (Zuckerman, Forveille & Kastner 1995; Pascucci et al. 2006). The dust in the system is also removed eventually, either through accretion on to larger objects, stellar winds, or radiative processes (Haisch, Lada & Lada 2001; Uzpen, Kobulnicky & Kinemuchi 2009). However, collisions between any planetesimals in the disc can generate a second population of dust. These second-generation systems are known as debris discs and generally contain very little gas (Zuckerman 2001; Wyatt 2008, and references therein). Our own Solar system's Kuiper belt may be analogous to these debris discs (e.g. Luu & Jewitt 2002, and references therein). The study of discs, from the gas-rich protoplanetary discs to the gas-poor debris discs, is necessary for a more complete understanding of the formation and evolution of planetary systems.

Approximately half of all stars are in binary or multiple star systems (Duquennoy & Mayor 1991; Eggleton & Tokovinin 2008; Raghavan et al. 2010; Duchêne & Kraus 2013). Given how common binary stars are, it is important to address the properties of planet formation in such systems. About 20 per cent of known extra solar planets reside in wide binaries with separations of the order of 100s of AU (Raghavan et al. 2006; Eggenberger et al. 2007). The *Kepler* satellite has also revealed several planets orbiting pairs of close binary systems (e.g. Doyle et al. 2011; Orosz et al. 2012a,b;

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Welsh et al. 2012; Schwamb et al. 2013; Kostov et al. 2014). Earlier work with eclipse timing variations have suggested planets around the binaries HW Virginis, CM Draconis, and NN Serpentis (a post-common envelope binary; Deeg et al. 2008; Lee et al. 2009; Beuermann et al. 2010).

Circumstellar discs can be used as indirect evidence of planets in binary systems. For example, the close (3.4-d) main-sequence binary BD +20 307 displays a large amount of warm dust in the terrestrial planet zone (Song et al. 2005), which can be interpreted as the result of a planetary-scale collision in this ∼1 Gyr old binary system (Zuckerman et al. 2008; Weinberger et al. 2011). Disc studies among young pre-main-sequence systems have shown that the presence of a nearby companion star can readily truncate and disperse discs (Jensen, Mathieu & Fuller 1996; Bouwman et al. 2006; Cieza et al. 2009; Andrews et al. 2010; Kraus et al. 2012), in good agreement with what is expected from numerical simulations (Artymowicz & Lubow 1994; Lubow & Artymowicz 2000). Older debris disc binary systems also show a similar behaviour (Trilling et al. 2007; Rodriguez & Zuckerman 2012). Studying circumstellar and circumbinary discs is then a complementary way to explore the properties of planet formation in binary star systems.

The *Herschel Space Observatory*[1] (Pilbratt et al. 2010) offers the best opportunity to date of performing a large-scale volume-limited survey for debris discs, the ideal approach to systematically analyse the interplay between debris discs and stellar multiplicity. The DEBRIS (Disc Emission via a Bias-free Reconnaissance in the Infrared/Submillimetre; Matthews et al. 2010) programme has explored nearby star systems to search for infrared excesses indicative of discs at wavelengths longwards of 70µm. Prior work on the multiplicity of debris disc stars has been limited by small samples with strong biases; for example, considering only debris disc systems (Rodriguez & Zuckerman 2012) or only binary and multiple star systems (Trilling et al. 2007). The DEBRIS sample has observed stars regardless of prior known discs or stellar multiplicity and thus provides a better sample in which to explore the relationships between these two phenomena. Several DEBRIS binaries/multiples with discs have been individually explored in detail (Kennedy et al. 2012a,b, 2014). In this paper, we explore the multiplicity statistics of the DEBRIS sample and its role in the detection of circumstellar and circumbinary discs.

2 MULTIPLICITY IN THE DEBRIS SAMPLE

The DEBRIS sample consists of 451 stars, of which 2 are not primaries (Fomalhaut B & C; see Mamajek et al. 2013; Kennedy et al. 2014), and includes the 5 systems observed by the *Herschel* Guaranteed Time (GT) discs programme (PI: Olofsson). The majority of the stars were observed by *Herschel* as part of the DEBRIS programme, with some observations coming from the DUNES programme (Eiroa et al. 2010). The sample of 449 primaries is roughly equally divided in spectral types A through M and is volume-limited for each individual spectral type, where the limit is 45.5, 23.6, 21.3, 15.6, and 8.6 pc for A, F, G, K, and M spectral types, respectively (Phillips et al. 2010). *Herschel* observations with PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) have been performed for the DEBRIS sample in order to search for and characterize far-IR emission from circumstellar (or circumbinary) dust. Except for cases in which a companion fell within the field of view, we did not explicitly aim to observe companions with exception of Fomalhaut's companions, of which companionship was unknown until recently (see Mamajek et al. 2013; Kennedy et al. 2014). Thus, we may be missing some circumsecondary discs and thus focus on circumprimary or circumbinary discs only. Simultaneously to these *Herschel* observations, we have gathered literature data and adaptive optics (AO) observations (see Section 3) in order to characterize the multiplicity of stars in this sample.

Given that the majority of the stars in the DEBRIS sample are close to Earth and well studied in the literature, published data concerning stellar multiplicity exists for a large fraction of the sample. Our AO observations complement this literature search (see Section 3). We present the full list of stars and multiplicity information in Table 1. Some systems have tentative evidence of being astrometric binaries, but no additional information exists to confirm this. These systems are treated as single stars for this study. Binaries and higher multiples are listed with more details in Table 2. In general, we only have measurements of the period of spectroscopic binaries and projected separation for visual binaries. We derive the remaining quantities (i.e. period or semimajor axis) assuming the measured separation is the orbital semimajor axis, orbits are circular, and adopting main-sequence masses from Baraffe et al. (1998) and Siess, Dufour & Forestini (2000). Which quantity is derived is indicated in Table 2. While clearly not all orbits are circular and projection effects have not been incorporated in our analysis (corrections for these are small, of the order of ∼10 per cent; see Dupuy & Liu 2011), this nevertheless provides useful information in a statistical manner.

The sample has 188 (42 per cent) star systems where two or more stars are present. As previously mentioned, we calculate or adopt literature values for parameters of the system, such as the orbital period and semimajor axis. In Fig. 1, we show the period distribution for all multiples in the sample, including those determined from our AO observations (Section 3). This includes all periods, so, for example, triples have two periods counted. Also shown is the period distributions from Raghavan et al. (2010) and Eggleton & Tokovinin (2008) normalized to the same number of periods. These two latter distributions sample solar-type stars and bright systems and are representative of what we would expect for our sample. The distributions are remarkably similar to each other suggesting that our multiplicity survey is not biased against any particular range of periods.

The multiplicity fraction among A–K stars in our sample is 40–50 per cent, consistent with some prior studies (Duquennoy & Mayor 1991; Eggleton & Tokovinin 2008). However, Duchêne & Kraus (2013) estimate a lower limit to the multiple star fraction among A-type stars 50 per cent suggesting we may still be missing some A-star binaries. Among M-dwarfs, we find a multiplicity fraction of 26 per cent, in agreement with the multiplicity fraction listed in Duchêne & Kraus (2013). However, we note that these faint stars have not been as intensely studied for binarity as more massive stars in the DEBRIS sample. Furthermore, the DEBRIS *Herschel* sensitivity towards discs around M-dwarfs is also low (see fig. 2 in Matthews et al. 2014). The combination of low detection rates (multiplicity or debris discs) results in small number statistics whose robustness is too limited for a detailed analysis. Therefore, we primarily focus on the A–K sample in this article. We summarize the multiplicity statistics, divided by spectral type, in Table 3.

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

Table 1. DEBRIS sample.

Name	UNS ID[a]	Multiple?	Notes	References
HD 38	K050	Y	(8.2K6+9.9M2; 6.041 arcsec)	HIP, SHA11
HD 166	G030	N	optical double; LAF07: background source 10.23 arcsec away	WDS, LAF07, KIY08
HD 693	F069	N	F7V	ET08, TAN10
HD 739	F096	N	F4V	ET08
HD 1237	G070	Y	(G6+M4; 3.857 arcsec)	CHA06
HD 1326	M011	Y	(8.31M2V+11.36M6V; 2600y, 41.15 arcsec) WDS: AC pair ruled out; TAN10: companions to A & B found, but no common motion	WDS, VB6, TAN10
HD 1404	A103	Y	A2V, proper motion companion found in Lick AO images	ET08, ThisWork
HD 1581	F005	N	F9V	ET08
HD 1835	G118	N	Optical double, different proper motions	WDS, RAG10
HD 2262	A021	N	A7V	ET08
HD 3196	F092	Y	(5.61(F8V + ?; 2.082d) + 6.90G0V; 6.89 yr e=0.76)	ET08
HD 3443	G044	Y	(6.37G8V + 6.57G9V; 25.09 yr e=0.24)	ET08
HD 3651	K045	Y	(4.55+16.87T7.5; 42.9 arcsec) WDS: AB optical, AC common proper motion	WDS, KIY08, LUH07
HD 4391	G041	Y	(5.8G1V + (13.5; 16.6 251 au) + (14M5; 49 742 au)); ET08 incorrectly lists as single, WDS entries somewhat contradictory	WDS, RAG10
HD 4628	K016	N	K2V	ET08
HD 4676	F124	Y	((F8V + F8V; 13.82d e=0.24) + ?; 0.25 arcsec)	ET08
HD 4747	G089	Y	(?+?; 6832d e=0.64)	SB9
HD 4813	F038	N	F7IV–V	ET08, TAN10
HD 4967	K127	Y	(8.16K5+15.2M5.5; 16.8 arcsec)	WDS, POV94, HAW97, GOU04
HD 5133	K089	N	No stellar companion	RAG10
HD 5448	A090	N	A5V	ET08

Notes. Systems in the DEBRIS sample. The notation follows that of Eggleton & Tokovining (2008). The full table is available online. Details on binary and multiple systems are listed in Table 2. Systems with multiplicity flag 'A' have some indication that they are astrometric binaries, yet no other information is available.
[a]Unbiased nearby stars from Phillips et al. (2010)
Table references as follows: HIP : Hipparcos Catalog (ESA 1997), SB9 : The ninth catalogue of spectroscopic binary orbits (Pourbaix et al. 2004), VB6 : Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf, Mason & Worley 2001), WDS : Washington Double Star Catalog (Mason et al. 2001), BAI10 : Baines et al. (2010), BAR09 : Bartlett, Ianna & Begam (2009), BER10 : Bergfors et al. (2010), CAB07 : Caballero (2007), CAR05 : Carson et al. (2005), CAR11 : Carson et al. (2011), CHA06 : Chauvin et al. (2006), CLO07 : Close et al. (2007), DEL99 : Delfosse et al. (1999), DER11 : De Rosa et al. (2011), DER12 : De Rosa et al. (2012), DM91 : Duquennoy & Mayor (1991), EGG07 : Eggenberger et al. (2007), EHR10 : Ehrenreich et al. (2010), EIS07 : Eisenbeiss et al. (2007), EKE08 : Eker et al. (2008), ET08 : Eggleton & Tokovinin (2008), FRA07 : Frankowski, Jancart & Jorissen (2007), FUH14 : Fuhrmann et al. (2014), GOL06 : Goldin & Makarov (2006), GOL07 : Goldin & Makarov (2007), GOU04 : Gould & Chanamé (2004), HAR12 : Hartkopf, Tokovinin & Mason (2012), HAW97 : Reid, Hawley & Gizis (1995), HIN02 : Hinz et al. (2002), HIN10 : Hinkley et al. (2010), JAO03 : Jao et al. (2003), KIY08 : Kiyaeva, Kiselev & Izmailov (2008), KOH12 : Köhler, Ratzka & Leinert (2012), KON10 : Konopacky et al. (2010), LAF07 : Lafrenière et al. (2007), LAG06 : Lagrange et al. (2006), LAW08 : Law, Hodgkin & Mackay (2008), LEC10 : Leconte et al. (2010), LEI01 : Leinert et al. (2001), LEI97 : Leinert et al. (1997), LEP07 : Lépine & Bongiorno (2007), LUH07 : Luhman et al. (2007), MAK05 : Makarov & Kaplan (2005), MAM10 : Mamajek et al. (2010), MAM13 : Mamajek et al. (2013), MAR14 : Marion et al. (2014), MAS98 : Mason et al. (1998), MCA93 : McAlister et al. (1993), MCC04 : McCarthy & Zuckerman (2004), MET09 : Metchev & Hillenbrand (2009), NAK94 : Nakajima et al. (1994), NAK95 : Nakajima et al. (1995), NID02 : Nidever et al. (2002), NIE10 : Nielsen & Close (2010), OPP01 : Oppenheimer et al. (2001), PHI10 : Phillips et al. (2010), POT02 : Potter et al. (2002), POV94 : Poveda et al. (1994), RAG10 : Raghavan et al. (2010), ROB11 : Roberts et al. (2011), SCH07 : Schröder & Schmitt (2007), SCH11 : Schneider et al. (2011), SEG00 : Ségransan et al. (2000), SHA11 : Shaya & Olling (2011), TAN10 : Tanner, Gelino & Law (2010), TOK08 : Tokovinin (2008), TOK10 : Tokovinin, Mason & Hartkopf (2010), TOK11 : Tokovinin (2011), TOK92 : Tokovinin (1992), WIL01 : Wilson et al. (2001).

3 AO SEARCH FOR COMPANIONS

3.1 Survey setup and observations

We have utilized the AO camera IRCAL (Lloyd et al. 2000; Perrin, Graham & Lloyd 2008) at Lick Observatory to search for companions separated from the primary by ∼10–1000 au. The NIR camera offers a ≈0.077 pixel arcsec scale (which provides Nyquist sampling for diffraction-limited observations at 2.2 micron on the Shane 3 m telescope) and a 20 arcsec FOV. Precise pixel scale (including the known slight anamorphism of the camera) and orientation was determined by observations of multiple known binaries. The precision is estimated to be 1 per cent for the pixel scale and 0°.7 for the absolute orientation. The dither pattern typically used was a 5 arcsec-on-the-side square, giving us full coverage out to 12.5 arcsec from the primary, and we only consider companions within this radius in the survey. Tables 4 and 5 list our observations and measured parameters for binary and single stars, respectively.

We carried out our observations on various nights in 2009 June & October, 2010 August, and 2012 March & September. A total of 221 DEBRIS targets were observed over this time period. This corresponds to 75 per cent of all targets with declinations larger than –10°. For our observations, we used a dithered sequence to remove artefacts and cosmic rays and observed with either the *Ks* or Br-γ filters. Objects that had a close companion or appeared extended were subsequently observed at *J* and either *H* or Fe II in

Table 2. DEBRIS multiples.

Name	Component	Period (d)	Sep (au)	Eccentricity	Derived[a]	Dust R (au)
HD 38	AB	1.95E+05	68.2		P	
HD 1237	AB	1.91E+05	67.5		P	
HD 1326	AB	9.50E+05	147.3		N	
HD 1404	AB	1.10E+06	272		P	26.4
HD 3196	AB	2.082	0.035		a	
	AB–C	2.52E+03	3.95	0.76	a	
HD 3443	AB	9.16E+03	8.93	0.24	a	
HD 3651	AB	3.72E+06	474		P	
HD 4391	AB	1.23E+06	252		P	
	AC	6.26E+06	743		P	
HD 4676	AB	13.82	0.126	0.24	a	
	AB–C	4.40E+03	5.86		P	
HD 4747	AB	6.83E+03	7.23	0.64	a	
HD 4967	AB	1.72E+06	262		P	
HD 7439	AB	9.13E+06	1162		P	

Notes. Measurements of components of binaries and multiples in the DEBRIS sample. The location of blackbody dust grains for dusty systems is also listed. For HD 216956, dust R is listed first for A, then C. For HD 223352, the AC pair's dust is located around the C component. The full table is available online. For clarity, we have rounded periods to 1 d when larger than 100 d. Similarly, separations in au are rounded to 0.1 au when larger than 20 au and to 1 au when larger than 200 au. We refer readers to the references listed in Table 1 for the most exact values.
[a]Quantity derived: P, period; a, semimajor axis; N, none. See Section 2 for details.

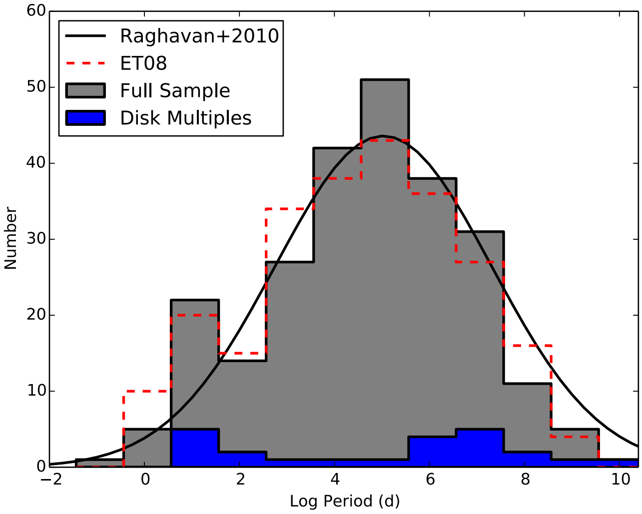

Figure 1. Distribution of calculated and measured orbital periods for multiples (grey histogram). Triples and higher order multiples have more than one period per system. The dashed line is the period distribution from Eggleton & Tokovinin (2008) and the solid curve is from Raghavan et al. (2010). Both are normalized to the number of periods in the DEBRIS sample. The blue shaded histogram shows the distribution of periods for disc-bearing multiples in our sample.

order to estimate colours and spectral types. The choice of Fe II and Br-γ over *H* and *Ks* was due to saturation on bright targets. The Fe II and Br-γ filters have central wavelengths of 1.644 and 2.167 Å with bandwidth FWHM of 0.016 and 0.020 Å, respectively. We assume the flux ratio between the primary and any companion at Br-γ is comparable to that in *Ks* (and similarly for Fe II and H). To confirm companions, we either obtained a second epoch and tested for common motion, or estimated the spectral type of the companion with our colour information and verified that the photometric distance agrees with that of the primary. We achieve a typical contrast of 6 mag (5σ) at separations >1 arcsec (see Fig. 2).

Table 3. Multiplicity fractions.

Sp. Type	Number	This work	From RZ12	From ET08	Others
B	–	–	83^{+6}_{-23}	–	–
A	35/86	41 ± 5	26^{+7}_{-5}	46.0	>50
F	50/94	53 ± 5	12^{+7}_{-3}	47.4	–
G	43/90	48 ± 5	33^{+15}_{-10}	45.0	44
K	37/91	41 ± 5	40^{+21}_{-16}	29.1	–
M	23/88	26^{+5}_{-4}	–	–	26
All	188/449	42 ± 4	25 ± 4	42.8	

Notes. Fraction of multiple stars (all as percentages) broken down by spectral type of the primary star with comparisons from the literature (RZ12: Rodriguez & Zuckerman 2012; ET08: Eggleton & Tokovinin 2008; Raghavan et al. 2010, Duchêne & Kraus 2013). Note that the Rodriguez & Zuckerman (2012) sample only contains disc-bearing systems. Errors are binomial errors estimated as described by Burgasser et al. (2003).

The Siess et al. (2000) models, for ages up to 1 Gyr, predict a flux ratio of 9–9.5 mag between A0 stars (2.5–3 $M_\odot$, depending on age) and 0.1 $M_\odot$ stars at *K* band. Our median detection limit beyond ~2 arcsec is 8 mag suggesting we are close to being complete for stellar mass companions. While a few lower mass companions may remain to be found, particularly around the later spectral types, we do not anticipate that these would significantly change the results. Our AO results are incorporated in Fig. 1 in which we see no strong bias or incompleteness against any particular range of orbital periods.

3.2 Newly identified companions

Most targets observed either had no detected companion or were binaries previously known in the literature. However, we have identified five new companions. We discuss each new system below.

HD 1404: this is an A2 star located 41 pc from Earth. We detect a companion 6.7 mag fainter at *Ks* and Br-γ that over a 3 yr period has remained at a projected separation of 6.6 arcsec with position angle

Table 4. IRCAL companion measurements.

Name	Filter	Sep (arcsec)	PA (deg)	Δ*m* (mag)	UT date	Depth (mag)
HD 38	*Ks*	5.62	5.87	0.071	2009-10-28	8.47
HD 1404	*Ks*	6.60	144.40	6.682	2009-10-28	8.59
	BrG	6.56	144.23	6.746	2012-09-28	
HD 3196	*Ks*	0.26	248.43	0.770	2010-08-03	7.97
HD 16160	BrG	1.73	318.49	5.142	2010-08-05	9.13
HD 16765	*Ks*	3.82	300.81	1.880	2010-08-04	9.06
HD 16970	*Ks*	2.21	297.83	1.312	2010-08-04	8.93
HD 19994	BrG	2.12	203.15	2.830	2009-10-28	8.36
HD 56537	BrG	9.29	35.72	3.953	2009-10-28	8.42
HD 56986	BrG	5.35	228.90	3.117	2009-10-28	8.7
HD 76943	BrG	0.50	233.34	1.161	2012-03-10	9.34
HD 78154	BrG	4.02	348.12	2.337	2012-03-10	9.63
HD 82328	BrG	2.59	145.18	5.777	2012-03-10	10.37
HD 82885	BrG	6.65	61.00	3.753	2012-03-10	9.03
HD 98231	BrG	1.50	196.14	0.271	2012-03-10	9.48
HD 100180	*Ks*	14.66	329.39	1.439	2012-03-10	10.32
HD 101177	*Ks*	8.79	248.08	0.879	2012-03-10	10.12

Notes. A sample of measurements of companions detected in the IRCAL FOV. The depth is the 5σ limit reached at 4–5 arcsec range, where the contrast is highest. The full table is available online.

Table 5. Single stars observed with IRCAL.

Name	Filter	UT date	Depth (mag)
HD 166	BrG	2009-10-28	9.12
HD 693	*Ks*	2010-08-03	8.29
HD 1326	*Ks*	2009-10-28	8.75
HD 1835	*Ks*	2010-08-05	9.07
HD 3651	BrG	2009-10-28	7.96
HD 4628	*Ks*	2010-08-03	8.69
HD 4676	BrG	2009-10-28	7.9
HD 4813	BrG	2010-08-05	8.95
HD 5448	BrG	2009-10-28	8.89
HD 7439	BrG	2010-08-05	9.28
HD 10307	BrG	2009-10-28	8.23
HD 10476	BrG	2010-08-05	8.99
HD 11171	BrG	2010-08-05	8.21
HD 11636	BrG	2010-08-05	9.02
HD 13161	BrG	2009-10-28	9.2
HD 13974	BrG	2009-10-28	8.69
HD 14055	BrG	2009-10-28	8.72
HD 16673	BrG	2010-08-05	9.04
HD 17093	*Ks*	2009-10-28	8.61

Notes. Lick IRCAL observations with no companions detected. The depth is the 5σ limit reached at 4–5 arcsec range, where the contrast is highest. The full table is available online.

(PA) of 144°. The companion has $Ks \sim 11.2$, or $M_{Ks} \sim 8.1$. At an age of 450 Myr (Vican 2012), the Baraffe et al. (1998) models suggest a mass of ∼0.17 M$_\odot$ and effective temperature of ∼3200 K (spectral type M4) for this companion. This A+M binary is separated by 271 au and hosts a debris disc of radius 22 au around the primary A star (Thureau et al. 2014).

HD 168151: this system is an F star situated 32 pc from Earth. We detect a companion 3.3 arcsec from the primary in observations carried out in 2010 and 2012. The companion is 6 mag fainter than the primary suggesting an absolute $M_{\mathrm{Br}\gamma}$ magnitude of 7.4. The system's age is estimated to be 1.3 Gyr (Vican 2012). At that age, the Baraffe et al. (1998) models predict a $T \sim 3400$ K and 0.3 M$_\odot$ (∼M3) dwarf would have that absolute magnitude.

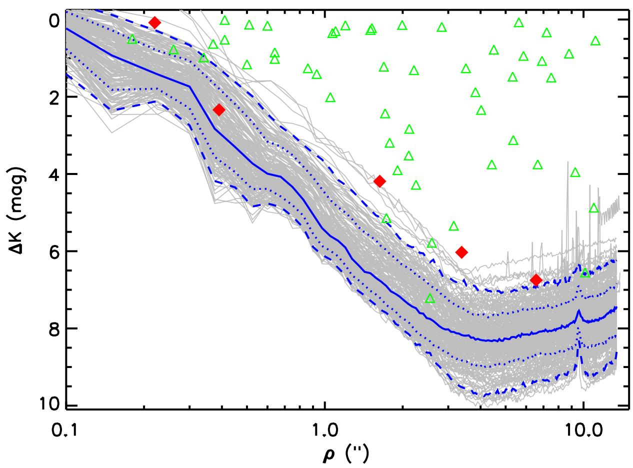

Figure 2. IRCAL 5σ detection limits for the sample including detected known systems (green triangles) and new companions (red diamonds). In blue, we show the median 5σ sensitivity of our survey, along with the ±1 and ±2σ ranges.

HD 140538: this G-star had a previously known companion at a projected separation of 4.2 arcsec (Eggleton & Tokovinin 2008). With our Lick survey, we have resolved the companion into two equal brightness components separated by 0.22 arcsec. At a distance of 15 pc, this separation corresponds to just over 3 au. We estimate J, Fe II, and Br-γ magnitudes of 8.5, 7.9, and 8.1 for the pair, with one component being ∼0.1 mag fainter than the other. The system has various age estimates, but as suggested by Vican (2012), we adopt the chromospheric age estimate of 3.6 Gyr. The Baraffe et al. (1998) models suggest a mass of 0.25–0.3 M$_\odot$ (∼M3) for each resolved component.

HIP 42220: this is a late-K star 17 pc away that has been previously suggested to be an astrometric binary (Makarov & Kaplan 2005). We detect a companion 0.4 arcsec from the primary with Δmag of 2.3–2.4 across *J*, *H*, and *Ks*. The *JHKs* magnitudes of the companion are 8.7, 8.2, and 7.9, respectively. The *J*–*Ks* colour (0.8) is suggestive of an early to mid-M-dwarf. No age estimate is available for HIP 42220 (Vican 2012), but K-stars in our sample have median ages of 2 Gyr and dispersion of 2.9 Gyr. From the absolute *Ks* magnitude (6.7) and an age range of 100 Myr–5 Gyr, we estimate the mass of the companion lies roughly in the range 0.3–0.35 M$_\odot$. The information listed in Makarov & Kaplan (2005) can be used with their equation (2) to derive a limiting mass ratio for the unseen astrometric companion. In this case, assuming a circular orbit, total system mass of 0.9–1 M$_\odot$, and minimum projection effects, we find our detected companion is massive enough to be consistent with the astrometric signature observed by Makarov & Kaplan (2005).

HD 110833: this system is a K3+K3 binary 15 pc away. Raghavan et al. (2010) list this as an equal mass spectroscopic binary with a 271-d period. Vican (2012) estimates an age of 2.2 Gyr for this system. Our AO work reveals another star 1.6 arcsec from the primary with Δmag of 4.2–4.4 across *J*, *H*, and *Ks*. This projected separation amounts to ∼24 au. The absolute *JHKs* magnitudes of the companion are approximately 8.7, 8.4, 8.1, and the Baraffe et al. (1998) models suggest effective temperatures of ∼3200 K and mass ∼0.17 M$_\odot$ for that age. The detected companion thus constitutes a mid-M dwarf in the system.

4 DEBRIS DISCS AND MULTIPLICITY

Systems in the DEBRIS sample have been observed with the *Herschel* spacecraft with PACS (100 and 160 μm; Poglitsch et al. 2010) and in some cases with SPIRE (250, 350, 500 μm; Griffin et al. 2010) and/or additionally at 70/160 μm with PACS. Furthermore, most also have observations with *IRAS*, *Spitzer*-MIPS (Rieke et al. 2004), AKARI (Murakami et al. 2007), and WISE (Wright et al. 2010). Hence, the spectral energy distribution (SED) of these objects can be sampled in a broad wavelength range and any IR excess emission can be characterized and studied in detail. Full descriptions on the observation strategy, source extraction, SED modelling, and selected results can be found in Matthews et al. (2010) and other DEBRIS publications (e.g. Lestrade et al. 2012, Booth et al. 2013, Thureau et al. 2014, Matthews et al., in preparation; and references therein). To summarize, stellar atmosphere models are first fit to data shortward of about 10 μm to determine the photospheric flux. These predictions are then compared to the mid to far-IR photometry to look for the excesses indicative of emission from cool dust. Disc systems are those with at least one photometric 3σ excess. To characterize the disc properties, a blackbody is fit to the star-subtracted SED and modified by a factor $(\lambda_0/\lambda)^\beta$ for wavelengths longer than λ_0 to account for inefficient grain emission at long wavelengths. For most cases, λ_0 is left as a free parameter, though in cases with limited photometry it is fixed (see details in Matthews et al, in preparation). We note, however, that a number of systems have poorly constrained temperatures or are required to have cold discs ($T_{\rm dust} \leq$ 20 K), which could instead be a result of contamination from extragalactic sources (Krivov et al. 2013; Sibthorpe et al. 2013; Gáspár & Rieke 2014). For purposes of this paper, we include these ∼8–10 systems as part of our statistical analysis. Among the DEBRIS sample, we find 76 systems with IR excess emission suggestive of circumstellar (or circumbinary) discs. In two cases (Fomalhaut and HD 223352), two stars in the same system each show IR excess which implies 78 discs among individual components in the sample (see Section 4.4).

4.1 Global statistics

Among the DEBRIS sample, there are 21 multiple systems which host circumstellar discs. There are several ways to approach the statistics of stellar multiplicity and disc incidence in our sample. We first consider the disc detection frequency among both single and multiple stars by spectral type. We note that our ability to detect a disc, or, more accurately, detect an infrared excess, will depend on the spectral type because our survey is flux-limited. The distribution of distances for single and multiple star systems is similar so no distance biases are introduced. We note that multiple systems, regardless of the number of components, are counted only once. Considering the entirety of our 449-star sample, the 76 disc systems identified suggest an overall detection frequency of 17 ± 2 per cent. For single stars, this is 55/261 = 21 ± 3 per cent and for multiples, 21/188 = 11 ± 3 per cent. Fig. 3 summarizes the disc detection frequency in the DEBRIS sample as a function of spectral type and binarity. The detection of discs around A-stars is comparable regardless of multiplicity (35^{+7}_{-6} per cent for singles and 29^{+9}_{-6} per cent for multiples; see also Thureau et al. 2014). Among the lower mass stars, multiples host fewer discs than single star systems. For the FGK sample, we find single stars have a disc detection frequency of 25^{+4}_{-3} per cent while multiple systems have 8^{+3}_{-2} per cent. A two-sided Fisher test for the A-stars reveals a *p*-value of 0.64, which implies any different in detected disc frequency is not statistically significant. In contrast, for the FGK sample the Fisher test returns a *p*-value of 3.5 × 10^{-4} implying a statistically significant difference in the detected disc frequency between single and multiple star systems.

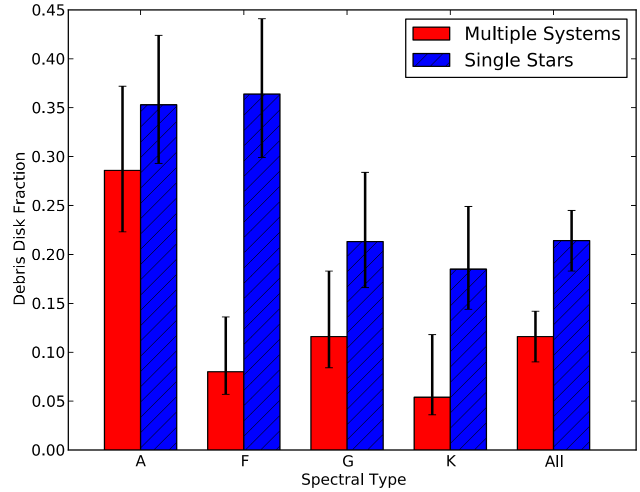

Figure 3. Disc detection frequency among the DEBRIS sample, divided by spectral type and binarity.

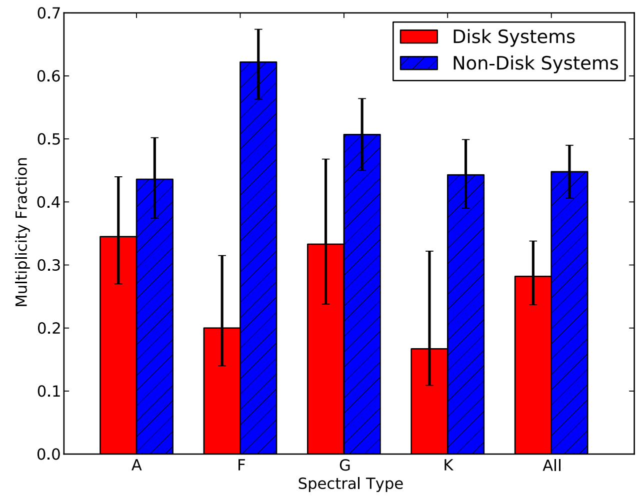

Figure 4. Multiplicity fraction among the DEBRIS sample, divided by spectral type and presence or absence of detected discs.

An equivalent way of examining the frequency of discs around multiple-star systems is to consider the multiplicity fraction around dusty stars and those not bearing discs. This fraction is the ratio of the number of binary or multiple systems compared to the total number of systems in the disc or discless samples; that is, the individual components within a multiple system are not considered. Fig. 4 illustrates the multiplicity fraction as a function of spectral type. Again, A-stars show similar multiplicity fractions regardless of whether we consider the disc and non-disc sample. Disc-bearing stars among the lower mass stars, however, have lower multiplicities. That is, it is rarer to find an FGK disc-bearing system that is also a binary or multiple.

In addition to the incidence of infrared excesses among the DEBRIS sample, we examine properties of the disc, namely the distribution of dust temperature and the disc luminosity divided by the stellar luminosity ($L_{\rm IR}/L_{\rm bol}$; or fractional luminosity), to see if any differences or trends are evident in the sample. A KS test reveals no difference between single and multiple stars in terms of dust temperature ($p = 0.9$) or L_{IR}/L_{bol} ($p = 0.5$), as was also demonstrated for A stars by Thureau et al. (2014). This holds regardless of whether we consider the full sample or break it as A or FGK stars: for dust temperatures we find $p = 0.3$ for A singles versus multiples and similarly $p = 0.9$ for FGK systems. For L_{IR}/L_{bol}, we find $p = 0.3$ and 0.4 for A and FGK systems, respectively. For systems with detected discs, the basic properties of these discs do not appear to be correlated with the multiplicity of the system.

4.2 Disc frequency around A and FGK stars

The frequency of discs around A stars, as well as their properties, is the same regardless of multiplicity. The situation is different for FGK stars in that while the disc properties are similar, the frequency of discs is lower among the multiple systems.

The dynamical effects of a second star can serve to disrupt the disc, accelerating its dispersal. As such, the disc detection frequency among multiples should be lower, or equivalently, disc-bearing systems should more likely be single stars. The discrepancy between the A-star and FGK sample, however, could be a result of a selection bias due to their ages. Examining ages from Vican (2012), we find dusty A-stars in the DEBRIS sample have a median age of about ∼0.3 Gyr, whereas the dusty FGK-stars are older, at a median age of ∼4 Gyr. On the other hand, the binary fraction of disc-bearing systems for <1 Gyr and >1 Gyr FGK stars is 29^{+14}_{-9} and 21^{+9}_{-6} per cent, respectively. While we expect older FGK stars to be less likely to host discs, the multiplicity difference we observe is not statistically significant.

We also considered the age distribution of A, F, G, and K stars for both single and multiple stars regardless of the presence of discs. If the ages were different as a function of multiplicity, these could account for the observed difference in the disc frequency. However, both single and multiple star distributions look very similar (see Fig. 5). The KS test does not show evidence that singles and binaries of any spectral type are drawn from separate age distributions.

As a further test to ascertain the difference between A and FGK binaries with discs, we constructed samples of systems eliminating either very wide binaries (>500 au) or very close binaries (<1 au). In both cases, these companions tend to be more common for A stars than lower mass stars and could contribute to the discrepancy (see fig. 2 in Duchêne & Kraus 2013). These systems have little effect on the discs *Herschel* is sensitive to. However, in our sample there are only a handful of these wide or close systems and as such the statistics do not appreciably change when eliminating these. In fact, the distribution of periods or semimajor axes between A and FGK multiples among this sample is not appreciably different.

The discrepancy between A and FGK disc-bearing binaries does not appear to be a result of binary properties or an age bias in our sample. A possible explanation is that we are missing a significant number of companions among A-stars, as suggested by the higher multiplicity fraction (>50 per cent) in Duchêne & Kraus (2013). However, the A-stars in the DEBRIS sample are generally well studied and we would require 6–7 additional binaries, all without detected discs, to yield a comparable difference between disc-bearing and non-disc bearing systems as observed among the FGK stars.

4.3 Discs in binary and multiple systems

As previously mentioned, the binary period distribution of the full DEBRIS sample is consistent with prior studies of stellar multiplicity (Eggleton & Tokovinin 2008; Duquennoy & Mayor 1991; Raghavan et al. 2010). Fig. 1 highlights the period distribution of disc-bearing systems, which appears flat in comparison to the full sample. Fig. 6 shows the cumulative distribution of periods for the non-disc and disc binaries compared to the distribution of Raghavan et al. (2010) and a flat distribution across all periods. At a glance, among the relatively low number of disc-bearing binaries there appear to be fewer of these with periods between 10^3 and 10^5 d. However, the period distribution of disc-bearing DEBRIS systems does not differ significantly from that of the non-disc sample. A KS test returns a p-value of 0.09 when comparing these two distributions. For us to assert that the two samples to be drawn from different distributions we require a p-value of 0.05 or lower. Hence, we cannot claim that the distribution of disc and non-disc binaries differ from each other or from the general distribution of Raghavan et al. (2010) or from a flat, uniform distribution. While the various distributions look tantalizingly different at first glance, we cannot

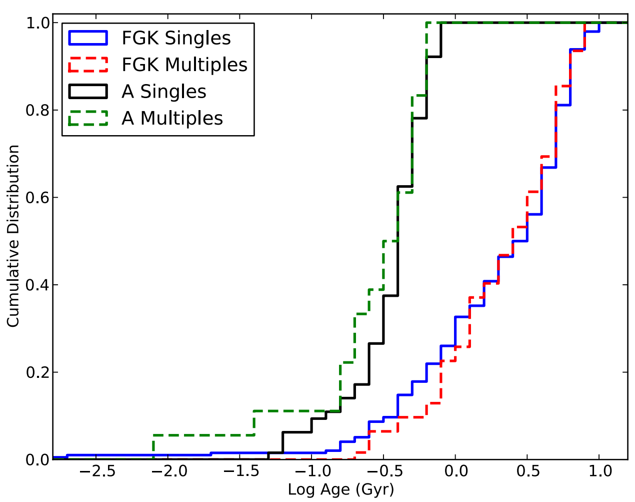

Figure 5. Cumulative age distribution for A and FGK stars in both single and multiple star systems.

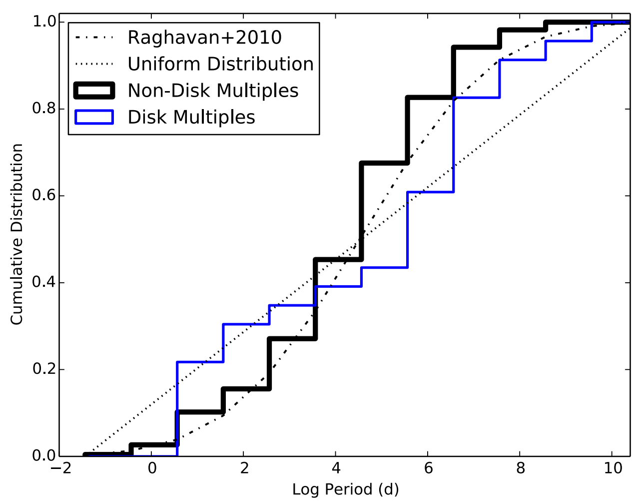

Figure 6. Cumulative distribution of calculated and measured orbital periods for multiples. Black shows the full sample, while blue are disc-bearing binaries. The Raghavan et al. (2010) distribution is shown as a dashed line and a flat distribution is shown with the dotted line.

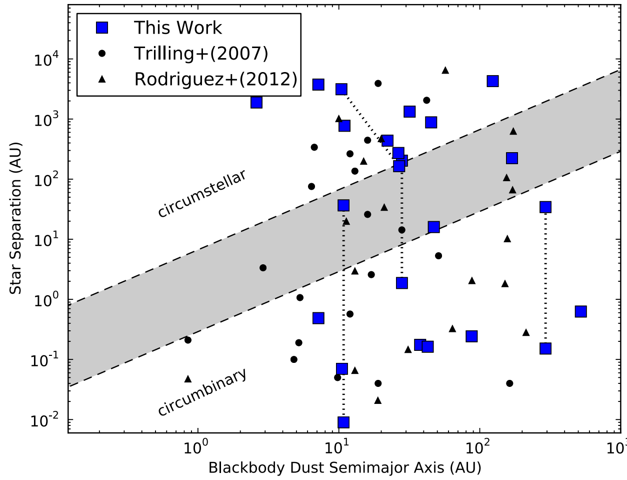

Figure 7. Stellar separation versus blackbody dust semimajor axes for the dusty multiple systems in the DEBRIS sample and from other surveys in the literature. The grey denotes the approximate region at which gravitational effects can perturb the disc. Triples where the dust lies between the AB and C pair are connected with a dotted line. HD 223352 is the system with the slanted line as the system hosts two separate debris discs. With stellar separations exceeding 150 kau, the three components of HD 216956 (Fomalhaut) are beyond the plot range in this figure.

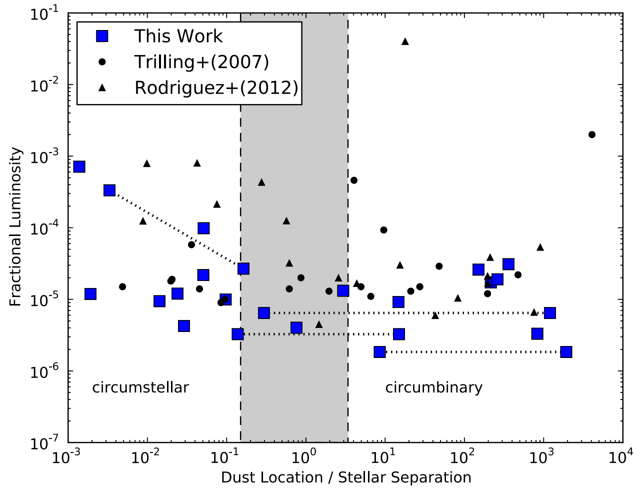

Figure 8. Ratio of dust to stellar separation compared with L_{IR}/L_* for dusty multiple systems. The grey denotes the approximate region at which gravitational effects can perturb the disc. As before, triples are connected and HD 223352 is the system connected with a slanted line as two separate debris discs are present in the system. HD 216956 (Fomalhaut) has a ratio $<10^{-3}$ and is not shown in this figure. The system with fractional luminosity ∼4 per cent is BD+20 307.

rule out they are drawn from the same underlying distribution with the limited statistics offered by this survey.

Another way to examine the disc-bearing binaries is by examining the stellar separation. Fig. 7 shows the stellar separation compared to the location of the dust in the system for multiples in this work, as well as others from Rodriguez & Zuckerman (2012) and Trilling et al. (2007). For the dust, we plot the semimajor axis of the dust assuming it is composed of large, blackbody grains. Some discs are spatially resolved and discussed elsewhere (e.g. Kennedy et al. 2012a,b; Booth et al. 2013). For A-stars, the disc location for resolved systems tends to be a factor of ∼1–2.5 times that estimated by the assumption of blackbody grains; FGK discs may be larger (see Pawellek et al. 2014). As such, some of the systems may be shifted rightwards in the plot. For clarity and consistency, we use only the dust semimajor axis as derived from the SED rather than any resolved radius. Some systems may be shifted upwards because of projection effects (or downwards if observed near periastron) in the plot, but this tends to be a small correction (e.g. Dupuy & Liu 2011). Some multiples are connected by dotted lines corresponding to the stellar separations. For example, a triple may consist of a close binary surrounded by a dust disc and a more distant stellar companion. Both the separation of the close binary and the more distant companion would be plotted and connected in Fig. 7.

Fig. 7 also shows a grey region representing the area where the gravitational influence of a companion would disrupt the disc. This is done by computing the critical semimajor axis using the relationships in Holman & Wiegert (1999). This is the distance at which a test particle would survive for less than 10^4 times the binary orbital period. For these relationships, we adopt 0.5 for the mass ratio and 0.4 for the eccentricity and derive critical semimajor axes values of 0.15 and 3.4 times the stellar semimajor axis (see tables 3 and 7 in Holman & Wiegert 1999 for values for other mass ratios and eccentricities). Systems located in this region would have their discs quickly cleared out by the stellar companion. Of the 26 DEBRIS components plotted, 4 (HD 223352, 99 Her, HIP 14954, HIP 73695) lie in this unstable region, or 15^{+10}_{-5} per cent. If we generate a random sample populating the diagram, either with a uniform distribution or a distribution following the period distribution of Duquennoy & Mayor (1991) and with a disc population uniformly spread between disc radii of 0.12 to 1000 au, we find that ∼20 per cent of components lie in the unstable area. Errors due to unknown inclinations or dust grains deviating from blackbodies were not included in this simulation, but their effects are expected to be minor (see above and Dupuy & Liu 2011). This suggests the location of the dust in the system may not be strongly correlated with the location of the stellar companion.

As previously mentioned, the fractional luminosity, L_{IR}/L_{bol}, of multiples with detected discs is not significantly different from that of single stars within the DEBRIS sample. Fig. 8 compares this fractional luminosity against the ratio of the dust semimajor axis and the stellar separation. Systems located towards the left of the plot are circumstellar in nature where the dust orbits a single star, yet there is a distant stellar companion in the system. Systems towards the right are circumbinary in nature in that the dust surrounds a pair of stars. Again, the unstable zone is highlighted as discussed above. The spread in fractional luminosity is comparable between the circumstellar discs (dust location/stellar separation ratio <0.1) and the circumbinary discs (ratio >3). Combined with the results of Figs 6 and 7, this suggests the properties of discs around disc-bearing binary stars do not, in general, depend strongly on the orbital properties of the binary.

4.4 Individual binary debris disc systems

In this section, we highlight a handful of discs around binary or multiple star systems. These stand out in our sample as we describe below.

HD 223352: as detailed in Phillips (2011), HD 223352 is a quadruple system in which two components, A and C (HD 223340), host circumstellar discs. The AB pair is separated by 3.9 arcsec (164 au) and the C component is much farther away at 74 arcsec (3100 au). Recent observations have resolved the B component as two separate stars (De Rosa et al. 2011). The two discs in the system are located around the A and C stars, with estimated blackbody dust locations of 27 and 10 au. The ratio of the dust to stellar separation for the AB pair is $27/164 = 0.16$ placing it just inside the unstable region in Figs 7 and 8, whose upper bound is set at a ratio of 0.15. For Figs 7 and 8, we have taken care to connect the two disc-bearing components together as each disc is associated with a different star separation within the system.

Very few debris disc systems are known in which two stars host individual discs. Disregarding ∼10–20 Myr-old (and younger) systems whose discs may be primordial in nature (see, e.g. Rodriguez et al. 2014, and references therein), the only other multiple system known to host two discs is that of Fomalhaut, also part of this survey (see Kennedy et al. 2014). As a member of AB Dor (Zuckerman et al. 2011; Malo et al. 2013), HD 223352 has an age of ∼100 Myr and represents a rare opportunity to study the development and evolution of discs around a pair of co-eval stars.

HD 165908: commonly known as 99 Her, this system has been described in detail in Kennedy et al. (2012a). With a stellar separation of ∼16 au and a blackbody disc dust location of ∼47 au, it is one of the unstable disc systems in our study. However, the disc has been resolved by *Herschel* to be located ∼120 au from the binary pair, which places the system beyond the grey unstable zone in Fig. 7. A more detailed discussion of the disc and its interaction with the binary can be found in Kennedy et al. (2012a).

HIP 14954: an F8 primary orbited by a widely separated M star at ∼223 au. Like 99 Her above, HIP 14954 appears to have dust located in an unstable configuration given the blackbody dust location of ∼164 au is comparable to the stellar separation. Roberts et al. (2011) provides orbital parameters for this system: a period of 2029 yr, a semimajor axis of 9.87 arcsec (223 au), and eccentricity of 0.26. Using these orbital elements, the relationships of Holman & Wiegert (1999) predict critical semimajor axes of 59 and 708 au. That is, orbits whose semimajor axis is smaller than 59 au (or larger than 708 au) are stable on time-scales longer than 10^4 times the stellar period (∼20 million years in this case). The fact that the dust is located beyond 59 au suggests it should have been quickly disrupted or instead has been recently produced. However, this system shows possible confusion in the *Herschel* data and the infrared excess could be originating from a background source.

HIP 73695: a triple system in which the primary is orbited by a 0.3-d binary. The binary orbits the primary with a period of 206 yr and eccentricity 0.55 (Eggleton & Tokovinin 2008); this amounts to a semimajor axis of about 37 au. The dust is around the primary at a blackbody dust location of ∼11 au. The location of the dust is uncertain as the infrared excess is detected only at 70 μm. With the binary properties listed in Eggleton & Tokovinin (2008), we estimate critical semimajor axes of 4 and 138 au. As with HIP 14954, the dust appears to be located beyond the inner critical semimajor axis. Additional information would be needed to make a definitive statement on the stability of the disc in the system.

5 CONCLUSIONS

The DEBRIS sample consists of 449 AFGKM systems observed with *Herschel* to search for circumstellar discs. In this study, we have examined these stars for signatures of stellar multiplicity. In this sample, 42 per cent of the targets are binary and higher order stellar multiples, as noted by others in the literature and our own AO observations (Table 3). This sample allows us to examine the influence of stellar multiplicity on the incidence and properties of debris discs.

Disc systems among the sample are summarized in Matthews et al. (in preparation), Thureau et al. (2014), and Sibthorpe et al. (in preparation) . Despite the large number of systems considered, the number of disc-bearing systems (78 across all spectral types) is lower than considered in Rodriguez & Zuckerman (2012). This is a result of the way these two samples were constructed. Nevertheless, an advantage to this study is that it allows us to consider both the disc frequency (as in Trilling et al. 2007) and the binary/multiple frequency (as in Rodriguez & Zuckerman 2012) simultaneously for the same sample. Our results are, at a glance, similar to both prior studies. However, an examination of the period distribution of the multiples in the sample shows no statistically significant difference with regards to whether or not these systems host debris discs and instead follows more closely the distribution previously reported for stellar multiples in general (e.g. Duquennoy & Mayor 1991; Raghavan et al. 2010).

Unlike prior studies, the larger sample allows us to break up the results as a function of spectral type. Among A-type stars, as primarily examined in Trilling et al. (2007), Rodriguez & Zuckerman (2012), and Thureau et al. (2014), discs are detected just as frequently among single stars as in multiple star systems. Equivalently, disc and non-disc A-star systems show comparable multiplicity. The results for FGK stars, however, differ substantially from the A stars. In FGK stars, the presence of a second star reduces the likelihood to find a circumstellar or circumbinary disc in the system. We have ruled out potential biases due to age or binary properties, but have been unable to find a convincing mechanism for this difference compared to A stars. Having a significant number of missing binaries among A-stars remains a plausible explanation. A larger sample of well-characterized FGK stars may be needed to further examine the disc detection frequency as a function of stellar multiplicity.

Among the disc-bearing multiples, both circumstellar and circumbinary disc systems exist. The basic properties of detected discs in binary systems, namely the temperature of the dust and the fractional luminosity, are comparable to those in single star systems. There are a few systems (described in more detail in Section 4.4) in which the stellar separation and the location of the dust (assuming large blackbody grains) are comparable to each other. This would result in an unstable scenario in which the gravity of the stellar companion would readily disrupt the disc. However, limitations in our knowledge of the orbital parameters, namely the projection on the sky, as well as the possibility of inefficient grain emission in the disc, can conspire to make a system appear to have an unstable configuration when it does not.

We interpret these results as follows. Any sample of binary stars dominated by FGK stars (as is this one) will in general demonstrate the period distribution of stellar multiples of Duquennoy & Mayor (1991) and Raghavan et al. (2010). The distribution of such a sample will not vary significantly between systems with detected dust discs and the general population. A binary star hosting a circumstellar or circumbinary disc will exhibit properties consistent with other (non-disc-bearing) binaries and the dust properties in the system will be comparable to those of single stars with discs. However, the gravitational influence of the companion star(s) will accelerate the collisional evolution of the disc. As such, a sample of binary stars will have a detectable excess for a shorter period of time. Hence, discs will be less readily detected among a sample of old binary or multiple stars than single stars of comparable spectral types and ages. However, given the stochastic nature of debris disc formation as a function of time, this signature is diminished among samples dominated by stars with ages larger than a few hundred million years.

The increasing number of planets found orbiting pairs of stars shows that planet formation in binary systems is not an uncommon product of planetary evolution. Binary and multiple star systems are plentiful and our work suggests that the processes behind disc and planet formation are similar between single and multiple star systems.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. DEBRIS sample.
Table 2. DEBRIS multiples.
Table 4. IRCAL companion measurements.
Table 5. Single stars observed with IRCAL.
(http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stv483/-/DC1).

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