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A search for debris discs around stars with giant planets

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ABSTRACT

Eight nearby stars with known giant planets have been searched for thermal emission in the submillimetre arising from dust debris. The null results imply quantities of dust typically less than 0.02 Earth masses per star. Conversely, literature data for 20 Sun-like stars with debris discs show that $\leqslant 5$ per cent have gas giants inside a few astronomical units – but the dust distribution suggests that nearly all have more distant planets. The lack of overlap in these systems – i.e. few stars possess both inner planets and a disc – indicates that these phenomena either are not connected or are mutually exclusive. Comparison with an evolutionary model shows that debris masses are predicted to be low by the stellar ages of 2–8 Gyr (unless the colliding parent bodies are quite distant, located beyond 100–200 au), but it remains to be explained why stars that *do* have debris should preferentially only have distant planets. A simple idea is proposed that could produce these largely different systems, invoking a difference in the primordial disc mass. Large masses promote fast gas giant growth and inwards migration, whereas small masses imply slow evolution, low-mass gas giants and outwards migration that increases the collision rate of Kuiper Belt-like objects. This explanation neglects other sources of diversity between discs (such as density and planetesimal composition and orbits), but it does have the merit of matching the observational results.

Key words: circumstellar matter – planetary systems: formation – planetary systems: protoplanetary discs – submillimetre.

1 INTRODUCTION

Far-infrared flux excesses were discovered around normal main-sequence stars nearly two decades ago (Aumann et al. 1984), and are interpreted as discs of debris resulting from collisions of asteroids or comets orbiting at tens of astronomical units (au). The dust particles in the primordial discs must have been dispersed quite early [generally $\ll 1$ Gyr (Dent et al. 2000)], by forces including radiation pressure, transverse light drag (the Poynting–Robertson effect) and interstellar erosion. Thus detections of dust at later main-sequence ages are an indication that bodies at least as large as planetesimals formed in these systems, and are still present to re-generate the observed dust. The Solar system has small quantities of dust beyond the orbit of Saturn (Landgraf et al. 2002), and this is believed to have a similar origin in the collision of comets in the Kuiper Belt. Given the more recent discoveries of giant planets orbiting within a few au of main-sequence stars – see Mayor & Queloz (1995), Marcy & Butler (1996) and Vogt et al. (2002), and references therein – it is of interest to uncover the link, if any, between these planets and the dusty debris.

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Two related observational questions are whether stars with discs also have planets, and whether stars with planets also have discs. It is not easy simply to take a large sample of nearby stars and search for both phenomena, as the detection constraints are different. In particular, the radial-velocity technique that traces the stellar 'wobble' if a giant planet is present can only be used if the appropriate stellar lines are strong, which occurs mainly for stars of spectral type F7 and later (Butler et al. 2001). On the other hand, discs are hotter and brighter if more strongly illuminated by the stars, so debris around stars of type A is the easiest to detect and cool stars such as K-types have only weakly emitting dust (Greaves et al. 1998).

Planet searches using the radial-velocity technique have been ongoing for nearly a decade, so if solar-type stars with discs also commonly had giant planets inside a few au, this should now be apparent. However, many debris disc stars have been identified (largely from the *IRAS* survey), and so far only ϵ Eridani has tentative evidence for a planet (Hatzes et al. 2000). Fits to the radial-velocity data suggested a planet of about two Jupiter masses with a very eccentric orbit at a mean distance of $\sim$3 au, but the data have high intrinsic noise due to the active surface of the young ($<$1 Gyr) star. Also, the inclinations of the star and disc are almost face-on which diminishes the amplitude of the velocity changes if the orbit of the planet is coplanar. ϵ Eri is also unusual in being extremely close (3.2 pc), so effects such as sensitivity need to be taken into account to determine if disc-and-planet systems should commonly be detectable.

The inverse question, of whether stars with known planets also have detectable discs, has been relatively little explored. This is mainly because there have been few space missions capable of detecting the far-infrared thermal disc emission since the discovery of radial-velocity planets. Also, sensitive submillimetre imaging that can detect cooler discs is a relatively new technique (Holland et al. 1999). *ISO* mini-maps at 60 μm have probed the lowest dust masses, but most of the disc survey time was used for unbiased and age-based samples (Habing et al. 2001; Spangler et al. 2001). Decin et al. (2000) used *ISO* to observe a sample of 30 G dwarfs taken from the CORALIE radial-velocity catalogue, but none of the five discs detected coincides with a system where planets have so far been discovered.

We report here on a submillimetre-based search for debris discs around stars with known planets. Observations in this wavelength regime are sensitive to cold dust in large discs of about the size of the Sun's Kuiper Belt of comets. The targets were eight stars with secure radial-velocity detections, which at the time of the initial observations comprised the majority of the extrasolar planetary systems then known. The stellar distances lie in the range 12 to 22 pc, and the number of planet-stars within this range has now increased to about 25, so larger sensitive surveys are possible in the future. The null result for dust around the closest star, 55 Cnc, has already been reported by Jayawardhana et al. (2002).

2 OBSERVATIONS

We used the Submillimetre Common-User Bolometer Array (SCUBA) camera (Holland et al. 1999) on the James Clerk Maxwell Telescope (JCMT), obtaining data between 1999 and 2002. The observations were made in photometry mode and were simultaneous at 850 and 450 μm, but the former wavelength generally yields lower mass constraints owing to better atmospheric transmission. We present only the 850-μm data here. The beamsize at this wavelength is 15 arcsec full width to half-maximum, which is larger than the expected dust disc sizes. For example, the Kuiper Belt with ∼90-au diameter would subtend only 6 arcsec at a distance of 15 pc. Discs would escape detection only if large and seen face-on, so that the emission fell entirely between the central and first ring of detectors (Holland et al. 1999); this would imply dust restricted to radii between 100 and 350 au, depending on the stellar distance. A few discs this large are known (Wyatt, Dent & Greaves 2003; Holland et al. 2003), but any one at random is unlikely to be face-on. In a test map of 47 UMa, we found no evidence for such a very large disc above levels of about 3 mJy beam^{-1}. There was also no disc-like structure seen in the first ring of detectors for any of the stars.

The standard chopped photometry mode uses 2-arcsec steps of a single bolometer in a 3 × 3 mini-map centred on the star (Holland et al. 1999). Residual sky noise was subtracted using the signals seen by the other 36 bolometers, in three concentric rings covering a field of view 2.3 arcmin in diameter. A 3σ clip of the data stream was then adopted to eliminate outlying photometry points. Skydips were used to measure the zenith optical depth, which ranged from 0.11 to 0.37 (with a mean of 0.23), and Mars, Uranus and a number of secondary calibrators were observed to obtain the Jy V^{-1} flux conversion factor. This was within 8 per cent of the standard value (Jenness et al. 2002) on average, with a standard deviation of ±14 per cent from 37 measurements. A small number of archival data from 1997–99 were included for the stars 51 Peg and 47 UMa, and these have been corrected for the 15 per cent lower throughput of the older filter used.

Integration times were varied as the observations were flexibly scheduled and done as conditions became suitable, but ranged from 1.5 to 4 h. The aim was to detect discs of about 0.01 $M_\oplus$ [the approximate amount of dust towards ϵ Eri reported by Greaves et al. (1998)], with corresponding 850-μm fluxes of about 1–3 mJy at the distances of the target stars (assuming the same dust temperature). Some periods of observing were affected by coordinate transcription errors, which have affected the sensitivity as the detector array undersamples the sky (Holland et al. 1999) and so the actual stellar location may not be close to a detector. In these cases (ρ CrB, 70 Vir and 16 Cyg B), the data were reconstructed as a map (Jenness et al. 2000), and the mean and standard deviation were measured for a 3 × 3 box of 2-arcsec pixels centred on the star, which mimics the pattern used in the photometry. For the other stars, the position observed was within 1.5 arcsec of the correct point, less than typical 2-arcsec pointing drifts; year-to-year corrections for proper motion were generally neglected as the largest value is 0.8 arcsec yr^{-1}.

For 70 Vir and 16 Cyg B, the stellar position was not well sampled so the final noise level is increased. The rms achieved is generally about 1 mJy, while Jayawardhana et al. (2002) reached a 0.4-mJy limit in a longer observation of 55 Cnc.[1] After co-adding all the data, the results for each source are as given in Table 1.

3 RESULTS

No discs were detected in this small survey, with 2σ flux limits of about 2 mJy at 850 μm for five out of the eight stars. Assuming a dust temperature of 35 K and a submillimetre dust opacity κ of 0.4 cm^2 g^{-1} (Greaves et al. 1998), the 2σ limits correspond to $\leqslant 0.02$ $M_\oplus$ of dust per star. If the dust is warmer, the mass limits are mostly less than 0.005 $M_\oplus$ for a temperature of 120 K. These temperatures were chosen so that the lower value corresponds with the observed dust temperature around the K2 star ϵ Eri (Dent et al. 2000), and the higher value with the limit set by the 25-μm ISOPHOT survey by Laureijs et al. (2002). This study found that very few debris discs have a significant amount of dust hotter than 120 K, and in fact detected only discs around luminous stars rather than the late-type stars observed in our sample. Hence it is unlikely that these stars heat any dust above 120 K.[2] Our derived dust mass limits are further reduced if the opacity is higher [e.g. κ up to 1.7 cm^2 g^{-1} (Holland et al. 1998)]. The only massive component that could have been missed is a population of very large ($\gg$ cm-sized) grains which emit inefficiently in the submillimetre and so are hard to account for (Wyatt & Dent 2002).

Thus we find that dust masses are very unlikely to exceed 0.02 $M_\oplus$ per star, a limit comparable to the 0.016 $M_\oplus$ *detected* around ϵ Eri with the same assumed dust parameters (35 K and 0.4 cm^2 g^{-1}). For six of the eight stars, we can rule out with 95 per cent confidence the presence of dust discs with masses similar to or slightly greater

[1] This is an effective limit to submillimetre surveys: ∼30 per cent of 15-arcsec-beam sized areas will contain a background dusty galaxy with an 850-μm flux of 0.5 mJy (R. Ivison, private communication). Disc detections at this flux level will therefore be debatable without better spatial resolution. This limits surveys for discs similar to those of the ϵ Eri prototype to distances less than about 30 pc.

[2] More stringent limits on a warm dust component are in fact supplied by 25-μm observations of five of our stars; depending on assumed grain size there is less than a few × 10^{-5} to a few × 10^{-4} $M_\oplus$ of warm dust close to the star (Laureijs et al. 2002).

Table 1. 850-μm results, with the stars listed in order of distance and by most commonly used name. Comparative values for ϵ Eri and the Solar system are given in the last two lines of the table (Greaves et al. 1998; Moro-Martín & Malhotra 2003); the two temperatures listed do not necessarily apply to the Solar system. The photometric mean flux and standard deviation are listed; the 55 Cnc result has been previously published by Jayawardhana et al. (2002). Dust masses are 2σ limits from the 850-μm data, using the parameters described in the text. The systems with stellar companions are all wide binaries and the second object lies outside the JCMT beam except for τ Boo where the projected separation is currently ≈3 arcsec (Fischer et al. 2001; Patience et al. 2002). Stellar types are from SIMBAD: literature values vary by about one sub-class, and in the case of τ Boo the alternative type of F7 V is more consistent with the age than F6 IV. Stellar ages are from Henry et al. (2000) and Lachaume et al. (1999). Planetary information is from online catalogues (http://www.obspm.fr/encycl/encycl.html and http://exoplanets.org); masses M derived from the radial-velocity technique are all lower limits and a is the orbital semi-major axis.

Star	Other names	850-μm flux (mJy)	$t_{\rm obs}$ (h)	Dust mass ($M_\oplus$) at 35 K	at 120 K	Stellar type	Stellar age (Gyr)	Distance (pc)	Planets: M, a ($M_{\rm Jup}$, au)
55 Cnc	HD 75732, ρ^1 Cnc	$1\sigma = 0.4$	7.1	⩽0.005	⩽0.001	G8 V (+M4)	4–5	12.6	⩾0.8, 0.1 ⩾0.2, 0.2 ⩾4.1, 5.9
υ And	HD 9826, 50 And	+0.5 ± 0.9	2.5	⩽0.012	⩽0.003	F8 V (+M4.5)	2–4	13.6	⩾0.7, 0.06 ⩾2.0, 0.8 ⩾4.0, 2.6
47 UMa	HD 95128	0.0 ± 0.8	4.0	⩽0.012	⩽0.003	G1 V	4–8	14.1	⩾2.5, 2.1 ⩾0.8, 3.7
51 Peg	HD 217014	−0.6 ± 1.1	2.15	⩽0.021	⩽0.005	G2.5 IV	3–8	15.4	⩾0.5, 0.05
τ Boo	HD 120136, 4 Boo	−1.3 ± 1.0	3.5	⩽0.019	⩽0.005	F6 IV (+M2)	0.5–2	15.6	⩾4.1, 0.05
ρ CrB	HD 143761, 15 CrB	−1.5 ± 0.7	3.2	⩽0.016	⩽0.004	G0 V	≈ 6	17.5	⩾1.1, 0.2
70 Vir	HD 117176	+2.3 ± 2.4	1.95	⩽0.060	⩽0.015	G4 V	7–8	18.1	⩾7.5, 0.5
16 Cyg B	HD 186427	−2.9 ± 3.3	1.5	⩽0.119	⩽0.029	G3 V (+G1.5)	6–7	21.5	⩾1.6, 1.7
ϵ Eri	HD 22049	40 ± 3	12.1	0.016	–	K2 V	0.5–1	3.2	⩾0.9, 3.4
Sun	–	–	–	$(0.6–4) \times 10^{-5}$		G2 V	4.5	–	1.0, 5.2 0.3, 9.5 (etc.)

than this nearby prototype. (Less stringent flux limits were obtained for the other two stars.) In case the flux limits reached were not quite deep enough, we have co-added the data for four stars where all the observations were correctly pointed (υ And, 47 UMa, 51 Peg and τ Boo, totalling 12 h of integration). This shows that if these stars *all* had discs like that of ϵ Eri, this would be detected at about the 4σ level. Instead the mean signal measured is -0.6 ± 0.5 mJy, which is consistent with the 0.1–0.2 mJy expected from the stellar photospheres alone. These photospheric values were estimated from the spectral energy distributions of similar stars plotted by Jayawardhana et al. (2000) and Sylvester & Mannings (2000).

Far-infrared missions have not yet searched effectively for debris discs around stars with planets. The *ISO* 60-μm surveys of nearby stars have included eight stars now known to have planetary companions (see Appendix), so were similar in statistical terms to the SCUBA results. These are complementary studies since they would be biased towards warm and cool discs respectively. The only experiment to include more stars is the *IRAS* survey with nearly all-sky coverage, and, as noted by Decin et al. (2000), the typical 60-μm flux limit for solar-type stars is about 400 mJy. This would have limited the detection of an ϵ Eri-like disc to within 6 pc of the Sun; in fact even the photospheres of nearby cool stars were difficult for *IRAS* to detect. (For example, there are fewer than 50 G-dwarf systems with *IRAS* detections at 25 μm or longwards, as listed in the 'NStars' catalogue of stars within 25 pc at http://nstars.arc.nasa.gov.) Apart from ϵ Eri itself, only Gliese 876 lies within 6 pc of the Sun and is known to have planets, and this M4 V star has no *IRAS* data.

4 CORRELATION OF DISC AND PLANET SURVEYS

Having determined in this small survey that stars with inner system planets do not commonly have moderate debris discs, we then re-examined the inverse question, of whether stars with known discs have planets. A data base has been compiled from the literature, with the aim of including all stars known to have *IRAS* excesses above the stellar photosphere. Checking luminosity classes then allows us to eliminate stars with other reasons for such excesses, such as dusty giant stars; the remaining 'debris disc' objects are all taken from classes IV–V and V and there are around 220 in the current data base. Further comparison of the catalogued position of the star with the *IRAS* source position, and then comparison of the offset with the *IRAS* positional uncertainty (error ellipse), also enables us to remove stars with nearby unassociated far-infrared sources.

Within the data base we find 36 stars with discs (Table 2; see also information on fluxes etc. at http://www.roe.ac.uk/atc/research/ddd/) that fit the criteria for searches for planets using the radial-velocity technique. These criteria are typically that spectral types should be F7 or later (Butler et al. 2001) and V magnitudes $\lesssim 8$. We then verified that 20 of these stars are actually being searched for planets – see Cumming, Marcy & Butler (1999), Udry et al. (2000) and Nidever et al. (2002), and the online source list at http://www.aao.gov.au/local/www/cgt/planet/aat.html. The remaining 16 stars fall into three groups: stars just outside magnitude or colour limits of the various surveys; candidate giant stars (either pulsators or with possibly larger distances and hence higher luminosities); and systems with non-planetary effects which modulate the velocities of the stellar lines (close binaries, or young stars with active chromospheres or fast rotation). The CORALIE survey (Udry et al. 2000) includes fast rotators and binaries as low-priority targets, so more of these stars may eventually be observed.

Of the 20 disc-stars being observed for radial velocity shifts, only one[3] in fact has a candidate planet, ϵ Eri. If there exist associated processes that produce inner system planets and debris discs, we would expect to see radial-velocity signatures towards most of the

[3] The disc star HD 196378 was also suggested to have a planet (Kürster et al. 1999), but Butler et al. (2001) did not confirm the velocity signature in recent low-noise data.

Table 2. Listing of stars with debris discs suitable for radial-velocity surveys (see text). In brackets after each star are listed the spectral type, distance in pc and approximate age taken from the literature (Greaves et al. 1998; Queloz et al. 1998; Lachaume et al. 1999; Decin et al. 2000; Song et al. 2000; Butler et al. 2001; Endl et al. 2002; Messina & Guinan 2002; Pijpers et al. 2003). Ages are in Gyr and '4.5?' denotes an age estimated to be near that of the Sun. HD 22049 is ϵ Eri which has a candidate planet (Hatzes et al. 2000). HD 155826 and HD 75732 (55 Cnc) are omitted because the far-infared 'excess' appears to come from background sources (Lisse et al. 2002; Jayawardhana et al. 2002). Stars listed in the second to fifth table sections are not being actively searched for planets and fewer details are given for brevity.

Stars included in surveys	
HD 1581 (G0 V, 8.6, 3–11)	HD 30495 (G3 V, 13.3, $\approx$ 0.1)
HD 1835 (G3 V, 20.4, $\approx$ 0.6)	HD 32923 (G4 V, 15.9, 4.5?)
HD 10647 (F8 V, 17.4, $\leqslant$ 6)	HD 48682 (G0 V, 16.5, 1–2)
HD 10700 (G8 V, 3.6, 9–10)	HD 67199 (K1 V, 17.3, 1.8–2.2)
HD 17925 (K1 V, 10.4, $\approx$ 0.1)	HD 69830 (K0 V, 12.6, 0.6–2)
HD 20010 (F8 V, 14.1, 4.5?)	HD 74576 (K2 V, 11.1, $\approx$ 0.1)
HD 20794 (G8 V, 6.1, 4–13)	HD 196378 (F7 V, 24.2, 4.5?)
HD 20807 (G2 V, 12.1, 4–12)	HD 207129 (G0 V, 15.6, 4–8)
HD 22049 (K2 V, 3.2, 0.5–1)	HD 214953 (G0 V, 23.5, 4.5?)
HD 22484 (F8 V, 13.7, 4–6)	HD 221354 (K2 V, 16.9, 0.5–2.5)
Young stars (low priority)	
HD 10800 (G1/2 V)	HD 53143 (K1 V)
HD 35296 (F8 V)	HD 128400 (G5 V)
HD 41700 (F8/G0 V)	
Binary systems (low priority)	
HD 41824 (G6 V)	HD 73752 (G3/5 V)
HD 53246 (G6 V)	
Stars fainter or bluer than survey limits (not observed)	
HD 38393 (F7 V)	HD 95241 (F9 V)
HD 82189 (F7 V)	HD 203608 (F7 V)
Stars with possible giant classifications (not observed)	
HD 23937 (M5 V?)	HD 152306 (G2 V?)
HD 42137 (K3/4 V?)	HD 223075 (F8/G0 V?)

20 disc-stars and this is not the case. On the other hand, if the processes are mutually exclusive we would expect no coincidences, and if they are unrelated processes we would expect the same frequency of planet detections as in the general late-type stellar population ($\approx$10 per cent and hence $\approx$2 planets). Given the small-number statistics, the detection of only one possible planet is consistent with either of these two latter scenarios.

Bias effects that could prevent the detection of joint disc-and-inner-planet systems are discussed in the Appendix, but for nearby stars no strong biases have been identified; it is, however, noted that cool low-mass discs would be very hard to detect beyond a few parsecs. To put our dust target mass in context, the fractional excess of ϵ Eri is about the median of 10 detections around late-type stars made with *ISO* (Decin et al. 2000; Habing et al. 2001), where we measure the excess by the 60-μm flux normalized to a constant distance and divided by stellar luminosity. Many more stars were observed but not detected, however, so low-mass discs could be escaping our notice unless very close. More importantly, there is no reason why a planet should not be detected with radial-velocity techniques where a disc has already been identified.

5 DISCUSSION

The SCUBA null results rule out some hypotheses, in particular moderate dust masses that could be generated by random collisions of planetesimals, or by enhanced collision rates in perturbed systems.

(i) Assuming that planetesimals are present at all, their numbers cannot be sufficiently great that random collisions generate detectable amounts of dust. This would be true of the Solar system if viewed at a distance of a few parsecs: although the mass of orbiting objects in the Kuiper Belt is $\sim$0.3 $M_\oplus$ (Backman, Dasgupta & Stencel 1995), there is $\lesssim 1.4 \times 10^{-5}$ $M_\oplus$ of dust (Moro-Martín & Malhotra 2003) which would produce an 850-μm flux < 0.1 mJy.

(ii) The presence of moderately close stellar companions [inside 100 au for τ Boo (Patience et al. 2002)] evidently does not perturb the planetesimal population to the point where collisionally generated dust is detected in the four multiple-star systems.

(iii) The planetary companions apparently do not perturb the planetesimals orbiting outside them enough to boost the collision rate. This result is reasonable because the planets all have semi-major axes of less than 6 au, whereas any dust cooler than 120 K orbits at a minimum of 20 au (Laureijs et al. 2002). Strongly perturbed regions such as resonances generally lie within three times the distance of the planetary orbit (e.g. Moro-Martín & Malhotra 2002).

5.1 Theory of dust evolution

Kenyon & Bromley (2002) have modelled the generation of dust in relation to the formation of planetary cores. After a short runaway growth phase, cores grow slowly to sizes of 1000 km and above, then becoming sufficiently massive for gravitational focusing to increase the collision rate among nearby smaller (km-sized) bodies. This can produce dust rings at large radii at ages exceeding a Gyr. The formation time-scale is proportional to the orbital period (Kenyon & Luu 1998) and disc density scaling with radius, hence $\propto a^3/\sqrt{M_*}$ (where a is the semi-major axis and M_* the stellar mass), and also inversely proportional to the initial disc mass. Kenyon & Bromley (2002)'s results for a 3-$M_\odot$ star and 100-$M_\oplus$ particle disc extending out to 150 au can thus readily be scaled to the solar-type stars considered here.

At the stellar ages relevant here, typically from 2 to 8 Gyr (Table 1), this scaling indicates that particle discs initially of 100 $M_\oplus$ would have to exceed between 100 and 200 au in radius for planetesimals still to be slowly forming at the outer edge and generating detectable dust. If the systems are smaller then the era of forming a large body has already passed, and the dust will have decayed since by collisional grinding. The null SCUBA results therefore suggest that any Kuiper Belt-like zone must be smaller than 100–200 au. This is not a very strong constraint on the sizes of planetary systems – debris discs as large as 200 au are known (e.g. Holland et al. 2003), while the outer radius of the main Kuiper Belt is around 50 au. [The radial constraint could be tighter for the youngest star, τ Boo, but this is a binary system, and Patience et al. (2002) argue that the close stellar companion would in any case truncate a circumprimary disc beyond 30 au.] Limits will also differ if the discs are Kuiper Belt-sized but of different initial mass: in this case discs must exceed a few Earth masses for the dust generation era to be prolonged but still over at the present ages of the stars. This is also not a strong constraint on possible disc properties.

5.2 Planetary systems within debris discs

The lack of dusty debris in most mature planetary systems is not surprising in the light of the time-scales discussed above. Dust would only be predicted to be seen in systems where the belts of planetesimals evolve slowly, because they are either quite large (radii > 100–200 au) or of initial mass much lower than the minimum-mass solar nebula. If dust is instead generated only by random collisions (planet growth is complete), then the belts would have to be very massive for them to be sufficiently dusty to be detectable with SCUBA. An estimate based on the dust-to-solid-body mass ratio of the Kuiper Belt (Backman et al. 1995; Moro-Martín & Malhotra 2003) implies that > 100 Earth masses in comets or asteroids would be required. This is substantial (equivalent to about the mass of Saturn), and is very large compared with the $\sim$0.3 $M_{\oplus}$ in comets around the Sun. There is evidence of diversity, since several stars of Sun-like age are known to have debris [e.g. τ Ceti, recently imaged in the submillimetre (Greaves et al., in preparation)], so there must be a range of initial conditions. However, the planet-bearing stars do not seem to be among the late-age dusty minority.

These are relatively weak limits on the scales and initial masses of the planetary systems, but much more significant results can be obtained from the inverse survey of stars with known discs. Table 2 shows that only one of the debris systems around solar-type stars has a possible detection of a radial-velocity planet. However, there is evidence that nearly *all* of these systems have planets on larger orbits (i.e. with long periods not yet accessible to radial-velocity techniques). Very few of the stars have a mid-infrared excess, and this implies the existence of a central cavity in the dust disc (e.g. Aumann et al. 1984; Chini et al. 1991) that is most naturally explained by clearing by massive planets. If there is no planet, a cavity might instead be produced by melting of icy grain mantles: this reduces the grain size and hence the thermal emission. To discriminate between these two possibilities, the far-infrared data have been examined to establish the radii where the dust emission arises.

Strong constraints come from the 25-μm band observed by both *ISO* and *IRAS*. Very few of the ISOPHOT target stars have dust excesses at 25 μm (Laureijs et al. 2002), and none of these is a solar-type star; warm dust near these stars must therefore be rare. The maximum number of warm-dust detections is $\approx$20 per cent, from the four stars of the 20 listed in Table 2 that *IRAS* detected at 25 μm. These mid-infrared signals require confirmation since the apparent excess may arise from other sources in the beam (Aumann & Probst 1991).

Among the solar-like stars that were observed more recently with ISOPHOT (Laureijs et al. 2002), there are three that were *not* detected at 25 μm but that do have excesses at 60–170 μm (Habing et al. 2001). This allows the dust temperature to be constrained: the spectral energy distributions are well-fitted by blackbody grains at 50–70 K, which corresponds to 15–30 au in thermal equilibrium with the stars. There can be little dust inside these distances without exceeding the 25-μm limit: for example for HD 10700 (τ Ceti) less than 10 per cent of the dust mass can be warmer than 80 K, i.e. lie within 9 au of the star. If the grains are instead greybodies, they will orbit at larger distances for the same temperature (because of inefficient re-emission) and so the inferred cavity size would be greater.

Alternatively, if the cavities are created by the melting of icy grain mantles, the temperatures required are around 170 K. This 'snow-line' effect occurs at small distances: about 2.7 au for a Sun-like star and less for young stars with substantial discs (Sasselov & Lecar 2000). If sublimation is important, temperatures of $\sim$100 K may suffice, and pure ice grains of sizes less than 10 μm would sublime inside 15 au (Moro-Martín & Malhotra 2002). Removal of icy grain mantles could therefore create a cavity around the star of dimensions comparable to those that we infer. However, dust with a range of temperatures up to $\sim$100 K would be expected, and this is not observed: 70 K is about the maximum temperature seen, with no 120-K grains detected around Sun-like stars (Laureijs et al. 2002).

The best explanation for these cavities is then a giant planet at Jupiter- or Saturn-like distances or beyond. Simulations of the Solar system by Liou & Zook (1999) show a deep cavity in the dust distribution extending just beyond the orbit of Jupiter, the main perturber. Such planets would typically escape radial-velocity detection except in the longest duration experiments: only one planet has so far been detected with a semi-major axis exceeeding that of Jupiter (5 au). Present techniques are not sensitive to planets on Saturn- to Neptune-like orbits ($\approx$10–30 au), but there is strong evidence for a planetary population at 40 au and beyond, from the perturbations of debris discs (e.g. Greaves et al. 1998; Holland et al. 1998). It is therefore not unreasonable to suggest that planets exist on orbits intermediate between 5 and 40 au that can clear the observed cavities in the debris discs around solar-type stars.

5.3 Planetary systems and migration

These results show that, among the debris stars, $\gtrsim$ 80 per cent must have a cavity-clearing planet on a moderately large orbit; the lower percentage applies if all the *IRAS* 25-μm excesses are actually from debris discs. However, $\leqslant$ 5 per cent of these 20 stars can have a planet on a *small* orbit (period of days up to a few years), since only ϵ Eri among the 20 stars listed in Table 2 has a possible radial-velocity detection.[4] The evolution of these dusty systems with inferred long-period planets must have been very different from the eight stars of Table 1, which have planets inside 6 au but no detectable dust emission.

One hypothesis which could explain the difference is that the time-scales to form giant planets vary from star to star. This is plausible given that Kenyon & Bromley (2002) have found that the core accretion time is inversely proportional to the initial mass of solids in the disc (although other properties can also change the time-scales). Thommes, Duncan & Levison (2003) have also found that the growth time-scale for planet cores is a strong function of disc surface density. Observations show that a mass range of nearly two orders of magnitude exists in young discs, estimated from submillimetre flux measurements (Wyatt et al. 2003), or from millimetre interferometry: for example, Natta, Grinin & Mannings (2000) measure 0.02–1 $M_{\odot}$ around luminous stars. Therefore a wide range of initial masses suggests that a wide dispersion in evolutionary time-scales is possible. Then, if a core forms slowly, the gas in the disc may be dispersed before the core is massive enough to accrete a gaseous envelope and grow to gas-giant size. The critical point in this process is the time at which the gas disperses, thought to be roughly 10 Myr (e.g. Thi et al. 2001; Bary, Weintraub & Kastner 2003).

In systems with massive discs, where cores grow fast, we would expect gas giants to be produced rapidly, and, because the disc is still gas-rich for the first several Myr, these planets will migrate inwards (e.g. Nelson et al. 2000). In the outer disc where the density is lower, smaller Pluto-like bodies will also form relatively rapidly, and trigger dust cascades that will be over before the time at which we observe the star. [Collisional grinding has removed the bodies that generate the dust, and the dust itself is removed by drag forces (Dent

[4] Planetary systems could be missed if the inclination were very unfavourable for radial-velocity observations, with orbits almost in the plane of the sky, but this should have a minor impact. A readily detectable signal of 19 m s^{-1} (Hatzes et al. 2000) was measured for the ϵ Eri system, the plane of which lies at only $\sim$25° from the plane of the sky based on the disc morphology (Greaves et al. 1998).

et al. 2000).] These systems will therefore have planets detectable by radial-velocity methods but very little dust. In contrast, systems with low-mass discs at the start will grow planetary cores slowly, and these will not have accreted much gas at the time when the gas disc as a whole disperses. Interaction with smaller planetesimals in larger orbits will then cause these incomplete planets to migrate *outwards*: angular momentum exchange moves the planet to larger orbits, and consequently the resonance positions sweep outwards collecting planetesimals and increasing their collision rate (Hahn & Malhotra 1999). With predominantly outwards motion, the result could be planets on large orbits that clear partially dust-free cavities (Liou & Zook 1999) within discs of debris. This scenario may also explain the clumpiness of debris discs, since the distribution of resonant planetesimals is clumpy (Wyatt 2003).

Other properties of the disc may also affect the evolutionary time-scales, as discussed by Kenyon & Bromley (2002). The disc mass dependence is the strongest, following a $t \propto M^{-1}{}_0$ function, but the planetesimal eccentricities, densities and tensile strength also enter. These factors, respectively, delay runaway growth in proportion to $(e_0/10^{-5})^{1/2}$; change the evolutionary times by $t \propto \rho^{-2/3}$ (smaller densities mean larger cross-sections so the planetesimals grow more quickly); and speed up evolution where weaker planetesimals disrupt at low speeds (although this changes time-scales by only about 10–30 per cent). The evolution is more affected by stochastic events, for example the formation of a single large body that stirs the dust and enhances dust production, or a 'fly-by' of another star that can perturb the disc so that large bodies grow more slowly (Kenyon & Bromley 2004). None of these physical properties can presently be measured for extrasolar discs, although in a few cases it may be possible to detect narrow dust rings associated with forming planets, or identify stars involved in a fly-by. The only property quantified at present is the range of initial disc masses, which is demonstrably wide, and this is also the property that has the strongest global effect on time-scales.

This hypothesis of inwards versus outwards migration as a function of initial disc mass – while qualitative – could explain the results of Tables 1 and 2. The debris systems and the stars with radial-velocity planets would then represent the opposite ends of the mass range of the primordial discs (low and high mass, respectively). The remaining question is how the intermediate systems would evolve – these include about three-quarters of nearby stars, given that approximately 10 per cent have radial-velocity detections and 15 per cent have debris (Plets & Vynckier 1999; Decin et al. 2000), with very little overlap between these two groups. The Solar system must fall somewhere within this largest group of stars, since the giant planets have long periods and the dust emission from the Kuiper Belt would be very difficult to detect externally. Longer duration radial-velocity experiments or high-precision astrometry, combined with sensitive far-infared space missions capable of detecting low dust masses (such as *SIRTF*), may in future be able to detect these systems analogous to our own.

6 CONCLUSIONS

A small survey of stars with known giant planet companions has shown that associated debris discs are uncommon, at 2σ limits of $\sim$2 mJy at 850 μm or about 0.01–0.02 $M_\oplus$ of cold dust. This rules out some processes that would generate debris, including still-evolving Kuiper Belt-like zones substantially larger or less massive than the Solar system, or any significant perturbing effect by stellar companions. In an inverse survey, the stars with known debris discs are found rarely to have short-period planets detectable by radial-velocity techniques, but the majority are inferred to have cavity-clearing planets on large orbits. Thus there appear to be two stellar groups with different planet locations. We suggest that this may be explained by a range of primordial disc masses, which affects the time-scale to grow solid cores of gas giants, with respect to the time at which the gas disc is dispersed. Although qualitative and not including other properties of the planetesimal discs, this hypothesis does match the observations.

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APPENDIX A: BIAS EFFECTS

The counts of systems with both inner planets and debris discs can be biased in two ways. The first occurs if the two sets of target stars differ. The second is if the phenomena of discs and planets co-exist but are not always equally detectable. We therefore compare the two lists of targets and the properties of the detected systems to see if bias effects are important.

First, the choices of stellar targets are found to be similar for both radial-velocity and debris disc experiments, once only late-type stars are considered. For example, both the Anglo-Australian Planet Search (AAPS) radial-velocity programme (Tinney et al. 2001) and the unbiased *ISO* 60-μm survey (Habing et al. 2001) include stars down to a magnitude of $V = 7.5$ and reject most binaries. The best test that there is no intrinsic selection bias is to examine the outcome of the searches. In total, 85 target stars of type F7 or later were searched for dust discs in the ISOPHOT 60-μm experiments (Decin et al. 2000; Habing et al. 2001). The number of these now known to have planets is eight, so the detection rate of 9 per cent is very similar to that in the general stellar population observed in radial-velocity programmes. The number of targets with disc detections is 10, hence a detection rate of 12 per cent that is again consistent with general values (Habing et al. 2001). In general, neither the ISOPHOT targets, nor the stars in our SCUBA mini-survey nor the stars of F7 or later in the disc data base appear to be intrinsically biased against the detection of joint disc-and-planet systems.

Secondly, the disc surveys and the planet surveys could be observing stars of similar type, but not actually the same stars. The ISOPHOT unbiased survey, for example, had distance limits of 10–25 pc depending on spectral type (Habing et al. 2001) and not all stars were visible within the mission scheduling, hence there will be cases of local stars with identified planets that have no ISOPHOT 60-μm observation. However, *IRAS* observed 96 per cent of the sky, so 60-μm constraints exist for very nearly all nearby stars. The effects of sensitivity to disc mass are briefly considered below.

Thirdly, debris discs and planets could co-exist but not always both be detectable. Examples of this include critical distance limits (i.e. if searches are sensitivity-limited) and changes with age. It can be shown that distance is not a major factor and in fact the distance limits of the two kinds of experiment are broadly similar. Nearly all of the stars with radial-velocity detections lie within 70 pc, and discs have been detected with *ISO* out to 50 pc (Decin et al. 2000), with more massive *IRAS*-detected discs well beyond this. A plot of

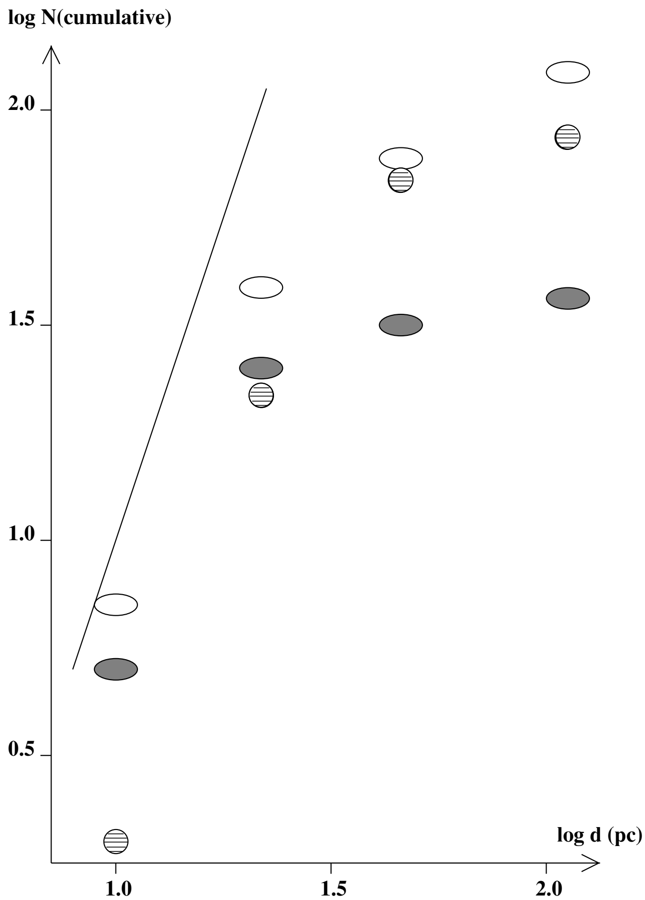

Figure A1. Plot of cumulative numbers of detected planets and discs versus distance, on log scales. Complete results would yield a slope of 3 (solid line, at an arbitrary vertical offset) as the volume increases with the cube of the distance. Hatched symbols denote radial velocity planets, unfilled ellipses are for discs, and shaded ellipses are for discs around stars meeting the planet search criterion of type F7 and later.

detected numbers versus distance (Fig. A1) does flatten off more rapidly beyond about 20 pc for discs than for planets, in particular for discs around cooler stars. This suggests that the volume within 20 pc of the Sun may be regarded as having similar completeness in both the disc and planet surveys.

Stellar age can be a cause of bias if the disc masses decline with time [as expected with collisions breaking up bodies into smaller and smaller fragments until the particles are small enough to be blown out by stellar radiation pressure (Wyatt & Dent 2002)]. In contrast, the planets and the star will change very little during the main-sequence lifetime, and this is borne out by the number of planet detections. There are around 11 planetary systems thought to be younger than $\approx$1 Gyr (Song et al. 2000; Gonzalez et al. 2001; Suchkov & Schultz 2001) among the $\approx$100 currently known, consistent with an expected fraction $\sim$10 per cent if 10 Gyr is a typical main-sequence lifetime.[5] The fractional increase in stellar luminosity of a Sun-like star during the main sequence is also not sufficient to make any dust significantly brighter, leaving the mass decline as the most important influence. The planet-stars could be too old to possess detectable discs, introducing an apparent lack of joint systems.

The ages listed in Table 2 show that the debris stars are not very young on average. Greaves & Wyatt (2003) have compared the disc detection rates for solar-type stars younger and older than 0.8 Gyr; the rates are respectively 18 and 5 per cent, with small-number statistics but implying that the mass decline with time must be shallow, $\propto t^{-0.5}$ or flatter.[6] This moderate decline in detection rates may be reflected in the statistics of Table 2. For example, dividing the stars into age bins of 0–3, 3–6 and $\geqslant$ 6 Gyr (9 Gyr is a likely upper bound, being the approximate age of the Galactic disc), then four to nine stars should fall in each bin assuming that birth times are random and statistics are Poissonian. The actual counts are nine, six and four respectively, so any decline is within the uncertainties. Following the same age division for the nine extrasolar planetary systems in Table 1, one to five stars should be in each bin and the counts are two, two and five with increasing age. Thus the slight trend to older stars in the planet sample (average of 5 Gyr versus 3.5 Gyr for the debris stars) may mean there is a small bias against detecting older disc-and-planet systems. However, it is certainly not the case that we see only discs or only planets because the two sets of stars have no age overlap.

Therefore we find no serious cause of bias that would prevent disc-stars being found with planets, or planet-stars being found with discs, provided that suitable late-type stars within about 20 pc are observed. An exception is that we may be detecting only the most massive debris discs, i.e. the completeness limit could be $\ll$ 20 pc for more typical masses. The number of disc detections within 10 pc, for example, is too small to determine if the statistics are skewed in disc mass. Future deep far-infrared surveys, such as those planned with *SIRTF*, could discover these systems and correlate them with the radial-velocity searches.

[5] Some recent surveys (e.g. Tinney et al. 2001) do not examine stars younger than about 3 Gyr for planets because of higher surface activity; this appears not to produce a bias because the more recent surveys contribute fewer of the planet discoveries.

[6] The steep dust-mass declines inferred previously (Spangler et al. 2001) refer to times $\leqslant$ 1 Gyr (hence to primordial dust in some cases), and in part to more luminous stars with intrinsically short main-sequence lifetimes.

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