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A search for debris disks 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 disks show that $\leqslant 5\%$ have gas giants inside a few AU — 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 disk — indicates that these phenomena are either not connected or are mutually exclusive. Comparison with an evolutionary model shows that debris masses should generally 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 disk 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 disks (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: protoplanetary discs – planetary systems: formation

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 disks of debris resulting from collisions of asteroids or comets orbiting at tens of AU. The dust particles in the primordial disks 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 regenerate 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 (Mayor & Queloz (1995); Marcy & Butler (1996); Vogt et al. (2003) and references therein), it is of interest to uncover the link, if any, between these planets and the dusty debris.

Two related observational questions are whether stars with disks also have planets, and whether stars with planets also have disks. It is not easy to simply 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, disks 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 disks also commonly had giant planets inside a few AU, this should now be apparent. However, many debris disk 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 ~ 3 AU, but the data

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have high intrinsic noise due to the active surface of the young (< 1 Gyr) star. Also, the inclinations of the star and disk are almost face-on which diminishes the amplitude of the velocity changes if the orbit of the planet is co-planar. 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 disk-and-planet systems should commonly be detectable.

The inverse question, of whether stars with known planets also have detectable disks, has been relatively little explored. This is mainly because there have been few space missions capable of detecting the far-infrared thermal disk emission since the discovery of radial-velocity planets. Also, sensitive submillimetre imaging that can detect cooler disks is a relatively new technique (Holland et al. 1999). ISO minimaps at 60 μm have probed the lowest dust masses, but the majority of the disk 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 disks detected coincide with systems where planets have so far been discovered.

We report here on a submillimetre-based search for debris disks around stars with known planets. Observations in this wavelength regime are sensitive to cold dust in large disks of about the size of the Sun's Kuiper Belt of comets. The targets were 8 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 SCUBA camera (Holland et al. 1999) on the James Clerk Maxwell Telescope, 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 due to better atmospheric transmission. We present only the 850 μm data here. The beamsize at this wavelength is 15″ full-width half-maximum, which is larger than the expected dust disk sizes. For example the Kuiper Belt with ∼ 90 AU diameter would subtend only 6″ at a distance of 15 pc. Disks 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 disks this large are known (Wyatt et al. 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 disk above levels of about 3 mJy/beam. There was also no disk-like structure seen in the first ring of detectors for any of the stars.

The standard chopped photometry mode uses 2″ 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 3-σ 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 flux conversion factor. This was within 8% of the standard value (Jenness et al. 2002) on average, with a standard deviation of ±14% from 37 measurements. A small amount of archival data from 1997–1999 were included for the stars 51 Peg and 47 UMa, and these have been corrected for the 15% 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 hours. The aim was to detect disks 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 co-ordinate transcription errors, which has 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″ pixels centred on the star, which mimics the pattern used in the photometry. For the other stars, the position observed was within 1.5″ of the correct point, less than typical 2″ pointing drifts; year-to-year corrections for proper motion were generally neglected as the largest value is 0.8″/year.

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 disks were detected in this small survey, with 2-sigma flux limits of about 2 mJy at 850 μm for 5 out of the 8 stars. Assuming a dust temperature of 35 K and a submillimetre dust opacity κ of 0.4 cm^2/g (Greaves et al. 1998), the 2-sigma 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 disks have a significant amount of dust hotter than 120 K, and in fact detected

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

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 2-σ 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 $\approx 3''$ (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 F7V is more consistent with the age than F6IV. Stellar ages are from Henry et al. (2000) and Lachaume et al. (1999). Planetary information is from online catalogs (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_{obs} (h)	Dust mass ($M_\oplus$) at 35 K:	at 120 K:	stellar type	stellar age (Gyr)	distance (pc)	planets: M, a (M_{Jup}, AU)
55 Cnc	HD 75732, ρ^1 Cnc	$1\sigma = 0.4$	7.1	$\leqslant$0.005	$\leqslant$0.001	G8V (+M4)	4–5	12.6	$\geqslant$ 0.8, 0.1 $\geqslant$ 0.2, 0.2 $\geqslant$ 4.1, 5.9
υ And	HD 9826, 50 And	$+0.5 \pm 0.9$	2.5	$\leqslant$0.012	$\leqslant$0.003	F8V (+M4.5)	2–4	13.6	$\geqslant$ 0.7, 0.06 $\geqslant$ 2.0, 0.8 $\geqslant$ 4.0, 2.6
47 Uma	HD 95128	0.0 ± 0.8	4.0	$\leqslant$0.012	$\leqslant$0.003	G1V	4–8	14.1	$\geqslant$ 2.5, 2.1 $\geqslant$ 0.8, 3.7
51 Peg	HD 217014	-0.6 ± 1.1	2.15	$\leqslant$0.021	$\leqslant$0.005	G2.5IV	3–8	15.4	$\geqslant$ 0.5; 0.05
τ Boo	HD 120136, 4 Boo	-1.3 ± 1.0	3.5	$\leqslant$0.019	$\leqslant$0.005	F6IV (+M2)	0.5–2	15.6	$\geqslant$ 4.1; 0.05
ρ CrB	HD 143761, 15 CrB	-1.5 ± 0.7	3.2	$\leqslant$0.016	$\leqslant$0.004	G0V	≈ 6	17.5	$\geqslant$ 1.1; 0.2
70 Vir	HD 117176	$+2.3 \pm 2.4$	1.95	$\leqslant$0.060	$\leqslant$0.015	G4V	7–8	18.1	$\geqslant$ 7.5; 0.5
16 Cyg B	HD 186427	-2.9 ± 3.3	1.5	$\leqslant$0.119	$\leqslant$0.029	G3V (+G1.5)	6–7	21.5	$\geqslant$ 1.6; 1.7
ϵ Eri	HD 22049	40 ± 3	12.1	0.016	—	K2V	0.5–1	3.2	$\geqslant$ 0.9; 3.4
Sun	—	—	—	$(0.6 - 4) \times 10^{-5}$		G2V	4.5	—	1.0, 5.2 0.3; 9.5 (etc.)

only disks 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, 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 with the 0.016 $M_\oplus$ *detected* around ϵ Eri with the same assumed dust parameters (35 K and 0.4 cm^2/g). For six of the eight stars, we can rule out with 95% confidence the presence of dust disks with masses similar to or slightly greater 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 hours of integration). This shows that if these stars *all* had disks like that of ϵ Eri, this would be detected at about the 4-σ 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 disks 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 was similar in statistical terms to the SCUBA results. These are complementary studies since they would be biased towards warm and cool disks 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 flux limit for Solar-type stars is about 400 mJy. This would have limited the detection of an ϵ Eri-like disk to within 6 pc of the Sun. Apart from ϵ Eri itself, only Gliese 876 lies within this distance and is known to have planets, and this M4V star has no IRAS data.

4 CORRELATION OF DISK AND PLANET SURVEYS

Having determined in this small survey that stars with inner-system planets do not commonly have debris moderate disks, we then re-examined the inverse question, of whether stars with known disks have planets. A database 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 disk' objects

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[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 2. Listing of stars with debris disks 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 the Sun's. 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 (G0V, 8.6, 3–11)	HD 30495 (G3V, 13.3, $\approx$ 0.1)
HD 1835 (G3V, 20.4, $\approx$ 0.6)	HD 32923 (G4V, 15.9, 4.5?)
HD 10647 (F8V, 17.4, $\leqslant$ 6)	HD 48682 (G0V, 16.5, 1–2)
HD 10700 (G8V, 3.6, 9–10)	HD 67199 (K1V, 17.3, 1.8–2.2)
HD 17925 (K1V, 10.4, $\approx$ 0.1)	HD 69830 (K0V, 12.6, 0.6–2)
HD 20010 (F8V, 14.1, 4.5?)	HD 74576 (K2V, 11.1, $\approx$ 0.1)
HD 20794 (G8V, 6.1, 4–13)	HD 196378 (F7V, 24.2, 4.5?)
HD 20807 (G2V, 12.1, 4–12)	HD 207129 (G0V, 15.6, 4–8)
HD 22049 (K2V, 3.2, 0.5–1)	HD 214953 (G0V, 23.5, 4.5?)
HD 22484 (F8V, 13.7, 4–6)	HD 221354 (K2V, 16.9, 0.5–2.5)
Young stars (low priority)	
HD 10800 (G1/2V)	HD 53143 (K1V)
HD 35296 (F8V)	HD 128400 (G5V)
HD 41700 (F8/G0V)	
Binary systems (low priority)	
HD 41824 (G6V)	HD 73752 (G3/5V)
HD 53246 (G6V)	
Stars fainter or bluer than survey limits (not observed)	
HD 38393 (F7V)	HD 95241 (F9V)
HD 82189 (F7V)	HD 203608 (F7V)
Stars with possible giant classifications (not observed)	
HD 23937 (M5V?)	HD 152306 (G2V?)
HD 42137 (K3/4V?)	HD 223075 (F8/G0V?)

are all taken from classes IV-V and V and there are around 220 in the current database. Further comparison of the catalogued position of the star with the IRAS source position, and then comparing the offset with the IRAS positional uncertainty (error ellipse), also enables us to remove stars with nearby unassociated far-infrared sources.

Within the database we find 36 stars with disks (Table 2; see also information on fluxes etc. at http://www.roe.ac.uk/atc/research/) 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 (Cumming et al. (1999); Udry et al. (2000); 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 disk-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 disks, we would expect to see radial velocity signatures towards most of the 20 disk-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% 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 disk-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 disks 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 (Habing et al. 2001; Decin et al. 2000), where we measure the excess by the 60 μ flux normalised to a constant distance and divided by stellar luminosity. Many more stars were observed but not detected, however, so low-mass disks 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 disk 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.

– Assuming that planetesimals are present at all, their numbers can not 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 ~ 0.3 M$_\oplus$ (Backman et al. 1984), there is $\lesssim 4 \times 10^{-5}$ M$_\oplus$ of dust (Moro-Martín & Malhotra 2003) which would produce an 850 μm flux < 0.1 mJy.

– 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.

– 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

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[3] The disk star HD196378 was also suggested to have a planet (Kürster et al. 2000), but Butler et al. (2001) did not confirm the velocity signature in recent low-noise data.

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 focussing 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 timescale is proportional to the orbital period and disk density profile, hence $\propto a^3/\sqrt{M_*}$, and also inversely proportional to the initial disk mass. Their results for a 3 $M_\odot$ star and 100 M_{oplus} particle disk extending out to 150 AU can thus readily be scaled to the Solar-type stars considered here.

At the stellar ages relevant here, typically 2–8 Gyr (Table 1), this scaling indicates that the particle disks of 100 M_{oplus} would have to exceed 100–200 AU in radius for planetesimals to still 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 disks 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 disk beyond 30 AU.) Limits will also differ if the disks are Kuiper Belt-sized but of different initial mass: in this case disks 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 disk properties.

5.2 Planetary systems within debris disks

The lack of dusty debris in most mature planetary systems is not surprising in the light of the timescales discussed above. Dust would only be predicted to be seen in systems where the belts of planetesimals evolve slowly, either because they are 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 dust to be detectable with SCUBA. An estimate based on the dust-to-solid-body mass ratio of the Kuiper Belt (Moro-Martín & Malhotra 2003; Backman et al. 1984) implies that $>$ 100 Earth masses in comets or asteroids would be required. This is substantial (equivalent to about Saturn's mass) and is very large compared to the ~ 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, paper in prep.), 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 disks. 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* 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-infared excess and this implies the existence of a central cavity in the dust disk, 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 are Solar-type stars; warm dust near these stars must therefore be rare. The maximum number of warm-dust detections is $\approx 20\%$, from the 4 stars of the 20 listed in Table 2 that IRAS detected at 25 μm. These mid-IR 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% 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 (due to 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 disks (Sasselov & Lecar 2000). If sublimation is important, temperatures of ~ 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 grain mantles could therefore create a cavity around the star of dimensions comparable to those we infer. However, dust with a range of temperatures up to ~ 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 disks, 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 disks around Solar-type stars.

5.3 Planetary systems and migration

These results show that among the debris stars, $\gtrsim 80\%$ 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 disks. However, $\leqslant 5\%$ 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 timescales 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 disk (although other properties can also change the timescales). Thommes et al. (2003) have also found that the growth timescale for planet cores is a strong function of disk surface density. Observations show a mass range of nearly two orders of magnitude exists in young disks, estimated from submillimetre flux measurements (Wyatt et al. 2003), or from millimetre interferometry, for example, Natta et al. (2000) measure 0.02–1.1 $M_\odot$ around luminous stars. Therefore, a wide range of initial masses suggests a wide dispersion in evolutionary timescales. If a core forms slowly, the gas in the disk 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 et al. (2003).

In systems with massive disks, where cores grow fast, we would expect gas giants to be produced rapidly, and because the disk is still gas-rich for the first several Myr, these planets will migrate inwards (e.g. Nelson et al. (2000)). In the outer disk 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 which generate the dust, and the dust itself is removed by drag forces, Dent et al. (2000).) These systems will therefore have planets detectable by radial velocity methods but very little dust. In contrast, systems with low mass disks at the start will grow planetary cores slowly, and these will not have accreted much gas at the time when the gas disk 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 disks of debris.

Other properties of the disk may also affect the evolutionary timescales, as discussed by Kenyon & Bromley (2002). The disk mass dependence is the stongest, following a $t \propto M_0^{-1}$ 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 means larger cross-sections so the planetesimals grow faster), and speed up evolution where weaker planetesimals disrupt at low speeds, (although this changes timescales by only about 10–30%). The evolution is more affected by stocastic 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 disk so large bodies grow more slowly (Kenyon & Bromley, in prep.). None of these properties can presently be measured for extrasolar disks, 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 disk masses, which is demonstrably wide, and this is also the property that has the strongest global effect on timescales.

This hypothesis of inwards versus outwards migration as a function of initial disk 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 disks (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% have radial velocity detections and 15% have debris (**?**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.

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[4] Planetary systems could be missed if the inclination is 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 $\sim 25^\circ$ from the plane of the sky based on the disk morphology (Greaves et al. 1998).

6 CONCLUSIONS

A small survey of stars with known giant-planet companions has shown that associated debris disks are uncommon, at 2-σ 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 than the Solar System, or any significant perturbing effect by stellar companions. In an inverse survey, the stars with known debris disks are found to rarely 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 disk masses, which affects the timescale to grow solid cores of gas giants, with respect to the time at which the gas disk is dispersed. Although qualitative and not including other properties of the planetesimal disks, this hypothesis does match the observations.

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APPENDIX A: BIAS EFFECTS

The counts of systems with both inner planets and debris disks can be biased in two ways. The first occurs if the two sets of target stars differ. The second is if the phenomena of disks 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.

Firstly, the choices of stellar targets are found to be similar for both radial velocity and debris disk experiments, once only late-type stars are considered. For example, both the AAPS radial velocity program (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 disks in the ISOPHOT 60 μm experiments (Habing et al. 2001; Decin et al. 2000). The number of these now known have planets is eight, so the detection rate of 9% is very similar to that in the general stellar population observed in radial velocity programs. The number of targets with disk detections is ten, hence a detection rate of 12% 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 disk database, appear to be intrinsically biased against the detection of joint disk-and-planet systems.

Secondly, the disk 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 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% of the sky, so 60 μm constraints exist for very nearly all nearby stars. The effects of sensitivity to disk mass are briefly considered below.

Thirdly, debris disks 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 disks have been detected with ISO out to 50 pc (Decin et al. 2000), with more massive IRAS-detected disks well beyond this. A plot of detected numbers versus distance (Figure 1) does flatten off more rapidly beyond about 20 pc for disks than for planets, in particular for disks around cooler stars. This suggests that the volume within 20 pc of the Sun may be regarded as having similar completeness in both the disk and planet surveys.

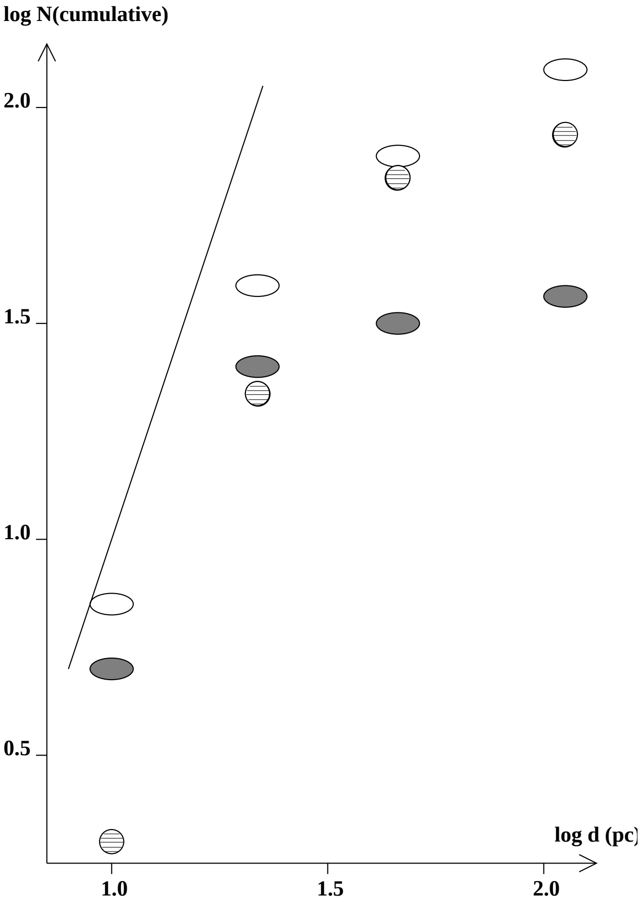

Figure A1. Plot of cumulative numbers of detected planets and disks versus distance, on log scales. Complete results would yield a slope of 3 (solid line, at an arbitrary vertical offset) as the volume increases with the cube of the distance. Striped symbols denote radial velocity planets, unfilled ellipses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

Stellar age can be a cause of bias if the disk 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 ≈ 1 Gyr (Gonzalez et al. 2001; Suchkov & Schultz 2001; Song et al. 2000) among the ≈ 100 currently known, consistent with an expected fraction ∼ 10% 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

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[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.

influence. The planet stars could be too old to possess detectable disks, 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 disk detection rates for Solar-type stars younger and older than 0.8 Gyr; the rates are respectively 18% and 5%, 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 Disk), then four to nine stars should fall in each bin assuming 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 2, 2 and 5 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 disk-and-planet systems. However, it is certainly not the case that we see only disks or only planets because the two sets of stars have no age overlap.

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

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[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.