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ABSTRACT

An unbiased search for debris discs around nearby Sun-like stars is reported. Thirteen G-dwarfs at 12-15 parsecs distance were searched at 850 µm wavelength, and a disc is confirmed around HD 30495. The estimated dust mass is 0.008 M⊕ with a net limit ≲ 0.0025 M⊕ for the average disc of the other stars. The results suggest there is not a large missed population of substantial cold discs around Sun-like stars – HD 30495 is a bright rather than unusually cool disc, and may belong to a few hundred Myr-old population of greater dust luminosity. The far-infrared and millimetre survey data for Sun-like stars are well fitted by either steady state or stirred models, provided that typical comet belts are comparable in size to that in the Solar System.

Key words: circumstellar matter – planetary systems: formation

1 INTRODUCTION

Debris discs represent the fallout of collisions of comets or asteroids around main-sequence stars. Showers of dust particles are continually regenerated, and these orbiting grains produce thermal emission from the mid-infrared to the millimetre, depending on the distances of the particles from the host star and so their equilibrium temperatures. The Sun’s Kuiper Belt of comets would be a very faint example of the phenomenon if viewed externally, but much brighter exo-systems are known, which must be supported by belts of colliding bodies that are more populated and/or more perturbed.

A number of (sub)millimetre surveys have looked at nearby Solar analogues to see if massive belts of comets could be common [Wyatt et al. 2003; Holmes et al. 2003; Liu et al. 2003; Carpenter 2005; Najita & Williams 2005; Williams & Andrews 2006]. The debris is expected to be cool if these belts lie at tens of AU outwards and are heated by stars of ~ 1 L⊙, so long wavelength emission is expected. Discs were detected with moderate frequency for stars a few hundred Myr old, but no new detections were made for ages comparable to the Sun’s 4.5 Gyr. However, the sampling of mature stars is poor and the larger studies have only reached sensitivities of a few mJy around 1 mm [Matthews et al. 2007].

Thus, the prevalence of cool dust around Solar analogues remains unknown. Of particular interest are a few examples of discs of Sun-like stars with dust thought to be cooler than 40 K [Holmes et al. 2003; Najita & Williams 2003; Wyatt et al. 2003; Liseau et al. 2008]. These could have escaped detection in the recent Spitzer 24–70 µm surveys that have discovered new debris discs around Sun-like stars, as such cold dust has low contrast with the stellar photosphere. Large cool discs are interesting as they may still be evolving [Kenyon & Bromley 2008, Eq. 41] predict that for discs exceeding 200 AU in radius, 1000 km bodies would form later than the Sun’s present age of 4.5 Gyr, and these could create late debris showers by perturbing the comet belt. Debris is in fact seen in systems as old as 10 Gyr, in the nearby case of τ Ceti (Greaves et al. 2004).

We have thus searched a small sample of local Solar analogues to look for cold debris. This is the first such unbiased survey in the submillimetre – based only on distance, without pre-selection from stellar age, multiplicity, or evidence of far-infrared excess – and is a precursor to the SCUBA-2 Legacy Survey of nearby stars [Matthews et al. 2007]. Here we present the results on masses of cold dust around nearby G-dwarfs and make some comparisons with recent models.

2 SURVEY DATA

The SCUBA camera on the 15 m James Clerk Maxwell Telescope was used to survey G-dwarf (luminosity class V or IV-V) stars at distances of 10-15 pc. The initial selection was made from the NStars Spectra online catalogue1, yielding 29 stars. Eliminating 4 objects unsuitable for the JCMT...

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1 http://nstars.nau.edu/
Table 1. Star and disc properties. The mean and 1-σ error from 3σ-clipped photometry at 850 μm are quoted except for the summed flux of HD 30495. Dust masses and 3σ limits are for 60 K grains with emissivity of 1 cm²/g; HD 72905 is scaled from HD 30495 assuming the millimetre flux-ratio equals the 70 μm excess-flux ratio of 0.25 (Trilling et al. 2003). HD 172051 is background-contaminated (see text) so no mass is given. Spectral type and multiplicity information are from the NStars database, and metallicities (log-abundance of iron versus Solar) are from Valenti & Fischer (2005). Stellar ages are from Barnes (2007) or via the same gyrochronology method using B-V and estimated rotation periods from Wright et al. (2004); bracketed values of 0.5 Gyr are for candidate members of the UMa moving group (King et al. 2003).

| star (HD) | flux (mJy) | dust mass (M_⊙) | type | distance (pc) | age (Gyr) | [Fe/H] | notes |
|----------|------------|-----------------|------|--------------|----------|-------|-------|
| 30495    | 5.6 ± 1.7  | ≲ 0.008 G3 V    | 13.3 | 0.45         | +0.01 ISO & Spitzer disc |
| 34411    | +0.6 ± 2.2 | ≲ 0.009 G0 V    | 12.6 | 4            | +0.12 |
| 72905    | +1.7 ± 1.7 | ≲ 0.002* G1.5 V | 14.3 | 0.15(−0.5)   | —        | mV = 12 companion at 4" |
| 140538   | −1.1 ± 1.4 | ≲ 0.007 G5 V    | 14.7 | 4            | +0.08 |
| 141004   | +1.7 ± 2.4 | ≲ 0.008 G0 V    | 11.8 | 3–6          | +0.05 |
| 144579   | −1.8 ± 1.2 | ≲ 0.006 G8 V    | 14.4 | 6            | −0.09 |
| 146233   | −1.5 ± 2.1 | ≲ 0.010 G1 V    | 14.0 | 4            | +0.03 |
| 147513   | +0.8 ± 2.0 | ≲ 0.008 G3/5 V  | 12.9 | 0.5–0.6      | +0.09 |
| 157214   | −1.2 ± 1.2 | ≲ 0.006 G0 V    | 14.4 | 4            | −0.36 |
| 160269   | +0.8 ± 1.7 | ≲ 0.008 G0 V    | 14.1 | (0.5?)       | —      |
| 172051   | (+7.6 ± 2.1)| ≲ 0.008 G5 V    | 13.0 | 4            | −0.26 |
| 176051   | −0.7 ± 1.4 | ≲ 0.008 G0 V    | 15.0 | 2.5          | —      |
| 196761   | +1.5 ± 1.3 | ≲ 0.007 G8/KO V | 14.6 | 5            | −0.28 |
| 75732    | ~ 0 ± 0.4  | ≲ 0.002 G8 V    | 12.5 | 8            | +0.31 |

2 At closer distances, there are 12 further G-dwarfs, but these were omitted because any large discs would overwhelm the effective photometric beam. These stars include one known debris disc, HD 10700 (τ Ceti), and debris candidate HD 131156 (Holmes et al. 2003; Decin et al. 2003).

2.1 Observation methods

The stars were observed in extended photometry mode (Sheret et al. 2004), which is a compromise in observing speed between staring at one point and full mapping, for a detector array which undersamples the sky. The central SCUBA 850 μm bolometer observed a pattern of points around each star, at offsets of 1” and 7.5”. With the 15” (full-width half-maximum) diffraction-limited beam, this mode collects a significant fraction of the flux from a disc extending up to 15” from the star, i.e. up to approximately 200 AU radius for stars at 12–15 pc distance.

Integration times were 1.4–3.4 hours per star, summing to 36 hours and requiring nearly 70 hours at the telescope. The observing campaign ran from 2003 July to 2005 May, over 17 nights. All of the stars except two (HD 34411 and 146233) had observations on more than one night. Good to moderate conditions were used, with zenith sky opacities at 850 μm of 0.23 to 0.52. Data reduction was performed using the oracdr pipeline (Jenness et al. 2002) plus custom IDL routines (Wyatt et al. 2003), including extinction corrections from skydips on each night, and applying a flux conversion factor of 307 Jy/V per beam (with a 1σ spread of ±34 Jy/V per beam over the 13 nights with FCF measurements). This conversion factor was derived from point-like calibrator sources observed using the same extended photometry mode, and is higher than for normal on-source photometry, as two-thirds of the time is spent looking at the half-power points of the calibrator. For any extended discs, the true flux will be underestimated, but less so than for...
Figure 1. Disc image for HD 30495. Colour scale shows the mean of all measurements within 7′′ of the pixel, further smoothed by a 4′′ Gaussian. Black contours represent corresponding signal-to-noise at levels of 1, 2 and 3. The inner white circle delineates the beam of the central bolometer, and points from here to the outer circle are interpolations, as the first ring of bolometers samples only from this radius, i.e. ≥ 18″.

normal photometry because of the greater spatial coverage (Sheret et al. 2004, Table 3).

3 RESULTS

The fluxes are listed in Table 1, and each data set was also examined as an image to search for any disc-like structure. No new discoveries were made among the 13 stars observed, but the ISO and Spitzer excess of HD 30495 is confirmed as a debris disc by SCUBA (Figure 1). The total photometric flux is 5.6 ± 1.7 mJy (assuming a point-like morphology), to which the photosphere contributes a negligible ≈ 0.15 mJy. The disc is oriented at a position angle of approximately −12°, and adding up all data points in two quadrants around this major axis and within 10″ of the star gives a flux of 4.9 ± 1.2 mJy, compared to only 0.7 ± 1.2 mJy for the two minor-axis quadrants. We infer that the disc is seen rather edge-on, and is also marginally extended as the flux density at 7″ along the major axis is 4.8 ± 2.0 mJy/beam, similar to 4.3 ± 2.0 mJy/beam for the 1″ points. The under-sampled data (Figure 1) may not capture all the disc flux, but the estimate of 5.6 ± 1.7 mJy is roughly consistent with the flux pattern over the quadrants.

The interpolated image of HD 30495 suggests the major axis covers up to 25″ diameter, which after deconvolution from the 15″ beam implies dust extends out to about 10″ or 130 AU radius. In resolved images, r_{disc} ~ 100 − 150 AU is typical for F, G and K stars (Kalas et al. 2006, e.g.). The rather edge-on orientation is consistent with the estimated stellar inclination, assuming the star and disc are co-planar: from the stellar rotation period, radius and vsini (Gaidos et al. 2006; Valenti & Fischer 2005), the value of i is approximately 50 – 75°.

The spectral energy distribution for HD 30495 (Figure 2) implies dust at approximately 57 K, similar to the 70 K estimated by Zuckerman & Song (2004) based on the far-infrared SED. The disc is observed to be larger than the radius of 20 AU inferred for a blackbody SED (Zuckerman & Song 2004), suggesting some greybody emission where particles that are inefficient emitters lie further from the star at equivalent temperatures (Sheret et al. 2004, e.g.).

A positive signal was also found towards HD 172051 (Figure 3). However, the structure is not disc-like but more extended, and is approximately matched by a contour from Spitzer 70 μm data (Beichman et al. 2006a). In this larger image, widespread emission is seen that extends towards the Galactic Plane. Since this star is within 15 degrees of the Galactic Centre, the signal could be from molecular clouds, and there is no compelling evidence of a disc contribution to the flux at either wavelength.

All of our target stars have now been searched with Spitzer for debris discs, using MIPS at 24 and 70 μm wave-
lengths. (Archived data for HD 140538, 141004, 160269 and 176051 are not yet published but do not show any obvious cool excesses.) Of the twelve objects with SCUBA limits, one has a debris detection: HD 72905 has dust emission over wavelengths of at least 25 to 70 µm (Beichman et al. 2006; Bryden et al. 2006; Trilling et al. 2008). This has been interpreted as arising from warm and cool planetesimal belts, with the SCUBA upper limit suggesting $T > 40$ K for the cool dust.

### 3.1 Disc properties

The incidence of cool moderately-massive debris discs is not high, since we detect only one example among thirteen Sun-like stars ($\sim 8\%$). HD 30495 appears to be detectable in the submillimetre mainly because the disc is bright (e.g. 95 mJy at 70 µm versus 24 mJy for HD 72905) rather than because it has cold dust that is better matched to long wavelengths.

Table 1 lists the upper limits to debris masses, assuming an emissivity of 1 cm³/g and 60 K grains as for HD 30495 (adopting e.g. the 40 K lower limit from HD 72905 would increase the masses by 50 %). For the majority of the G-dwarfs, any debris must be below a level of about 0.01 M⊕ or about a lunar mass. Somewhat larger masses could exist in very distant cold dust belts without exceeding either SCUBA or Spitzer upper limits.

Lower mass limits can be reached by co-adding the data for ten fields without disc or background emission (Table 1), yielding a net 850 µm flux of $-0.3 \pm 0.5$ mJy. Thus, no dust (or photospheric emission) is found on average around these ten stars. The 3σ dust upper limit of 1.5 mJy implies that the mean disc around these stars comprises less than 0.0025 M⊕, for 60 K grains and representative distance $\approx 14$ pc. This limit is below the dust masses for nearly all the sub-mm-detected debris discs around Sun-like hosts (Wyatt et al. 2003), while the 0.008 M⊕ of material around HD 30495 is within the typical range of a few thousandths to a tenth of an Earth-mass of dust (Wyatt 2008, Fig. 3). There is a marginally positive signal of $+2.0 \pm 0.9$ mJy for all the four sub-Gyr sources averaged together, versus a null signal of $-0.6 \pm 0.6$ mJy for eight older objects, suggesting a possible decline of dustiness with age, as discussed further below.

The disc luminosities and limits here are similar to those from far-infrared data. Converting the 850 µm fluxes to fractional luminosities (Beichman et al. 2006a, Eq. 4), $L_{dust}/L_*$ is $4 \times 10^{-5}$ for HD 30495, similar to HD 72905 at $3 \times 10^{-5}$ (Beichman et al. 2006b), while the SCUBA limits for the older stars correspond to $\lesssim 2 - 6 \times 10^{-5}$. For the co-add of the ten blank SCUBA fields, $L_{dust}/L_*$ is $\lesssim 1 \times 10^{-5}$ for a typical stellar effective temperature of 5800 K.

### 4 DISCUSSION

The SCUBA survey has shown that the debris disc population can not be greatly boosted by previously missed cold discs of moderate mass. Only one disc was found in an unbiased sample of thirteen nearby Solar analogues, and the dust temperature of around 60 K is high enough to also yield prominent far-infrared excesses for this star (Habing et al. 2001; Trilling et al. 2008). Combining the new SCUBA results with earlier millimetre surveys for debris around FGK dwarfs (Wyatt et al. 2003; Holmes et al. 2003; Sheret et al. 2004; Najita & Williams 2005; Williams & Andrews 2006), in total 33 Sun-like stars $\geq 150$ Myr old have now been observed, spanning the epoch after terrestrial planet formation (e.g. the latest age of Earth completion, (Bouvier et al. 2007)) up to the end of the main-sequence. There are seven debris candidates and five also have confirmed far-infrared excesses. The far-infrared to millimetre fluxes have been fitted successfully with grain temperatures ranging from 50 to 100 K, so there is no indication of additional debris in very cold and distant comet belts for these stars. Thus although there are some systems with evidence of dust below 40 K (Wyatt et al. 2003, e.g.), this appears to be uncommon around Solar analogues.

Most millimetre detections have been made towards young stars. Dividing the 33 objects into two broad age bins of width 1 dex around 500 Myr and 5 Gyr (to reduce the effects of uncertain dating), there are up to 6 debris detections (2 tentative) out of 13 stars in the younger group, compared to only 1/20 in the older set. With Poisson counting errors, the detection rate then nominally declines from (30-45) ± (15-20) % to 5 ± 5 % for stars an order of magnitude older. However, the counts are skewed because some projects targeted more young stars and/or prior debris-candidates. Hence, the true incidences are likely to be lower, and the trend with time may be partly forced by deeper searches towards targets thought more likely to yield detections. For example, four of the seven young prior-debris candidates have possible millimetre detections, but these were also some of the deepest observations made in the respective surveys (Holmes et al. 2003; Sheret et al. 2004; Williams & Andrews 2006). In general, a decline of dustiness with age is plausible, especially as the fraction of prior debris candidates ($\approx 55\%$) happens to be the same in both the young and old samples, reducing one source of bias. Also, the oldest millimetre detection is HD 48682 at only $\sim 3$ Gyr, suggesting that stars several Gyr old may tend to be millimetre-faint.

One hypothesis is that high debris levels could be associated with an early epoch while lower levels of dust do not have such behaviour – e.g. Greaves & Wyatt (2003) noted that bright (IRAS-detected) debris is marginally more common among G-dwarfs under 1 Gyr old compared to older stars. To re-assess this hypothesis, we looked at far-infrared surveys of Sun-like stars and compiled literature results into the same broad age bins around 500 Myr and 5 Gyr (Figure 4). Earlier observations with ISO of stars in the 500 Myr-old UMa moving group (Spangler et al. 2000) were added to improve the statistics in the young bin; there are three far-infrared debris detections (for HD 125451, 139798, 184960) among fourteen additional Sun-like stars observed. Figure 4 confirms that dust luminosity derived from far-infrared excess is on average somewhat higher in the younger group. The millimetre-systems also appear to be representative of this luminous young group, with the four robust

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3 These stars are HD 8907, 30495, 38393, 48682, 109085, 131156 and 206893. HD 38393, 131156 and 206893 are only at $\approx 2.5 - 3\sigma$ confidence in the millimetre and the first two having ISO excesses not confirmed by Spitzer. Other Sun-like stars from individual studies also have millimetre debris detections: see Wyatt (2008) for a summary.
Debris discs around nearby Solar analogues

4.1 Comparison to models

In general the Sun-like stars observed in millimetre surveys do not show cold dust, nor are there debris detections later than about 3 Gyr. This suggests that large late-evolving comet belts are uncommon, such as those that could be stirred by formation of distant dwarf planets at several-Gyr ages (Kenyon & Bromley 2008). While there are examples of both very large discs (Williams et al. 2004; Liseau et al. 2008) and very old debris hosts (Greaves et al. 2004), neither appears to be the norm among Sun-like stars observed at millimetre wavelengths.

To determine typical disc properties, we compare recent (semi-)analytical models that predict the evolution of debris with time under various scenarios (Dominik & Decin 2003; Krivov et al. 2003; Löhne et al. 2007; Wyatt et al. 2007; Kenyon & Bromley 2008); see Wyatt (2008) for a summary.

- In steady state evolution, the fractional luminosity of debris declines slowly as the parent population of planetesimals is ground to dust that is blown out of the system. The dust is brightest early on and then fades after a time that is shortest in compact and/or massive discs, because of the greater planetesimal collision rates. Examples of models that fit the present data well (Wyatt 2008, Fig. 5) are discs of 30 AU radius with initial masses up to 1 M$_\odot$ in colliding bodies. If the majority are lower-mass systems (e.g. 0.1 M$_\odot$) then these are never detected as $L_{dust}/L_{star}$ is always below 10$^{-7}$, while the highest-mass discs have $L_{dust}/L_{star}$ of a few 10$^{-5}$ at around 500 Myr but declining to < 10$^{-5}$ after around 3 Gyr. These trends match most features of the data, including greater dust luminosity in the sub-Gyr stars.
- In contrast, in models where the planetesimals are stirred by gradually-forming larger bodies (from 1000 km sizes up to giant planets), debris can brighten from an early low state and then fade at a similar rate to steady-state models. These systems tend to be more luminous than we observe unless the initial disc mass is much less than in the Minimum Mass Solar Nebula (Wyatt 2008, Fig. 5). For millimetre and far-infrared debris detections to be made mainly for younger stars, discs should generally be compact, e.g. 70 AU in radius (Kenyon & Bromley 2008, Fig. 16), as larger discs will stay bright beyond 1 Gyr.
- Finally, in discs stirred by migration of giant planets, there can be an abrupt dust shower as these bodies cross an orbital resonance with the comet belt, and very little debris later as the belt is depleted (Gomes et al. 2003) find that the migration of Jupiter and Saturn could have stirred the Kuiper Belt thus causing the Late Heavy Bombardment of the Earth at around 0.7 Gyr, while Thonnnes et al. (2008) simulate this for different planetary system architectures and find equivalent events before ~ 0.3 Gyr. However, this is unlikely to be a general phenomenon as debris would not be seen at all at few-Gyr ages when the comet belts would be severely depleted. Further, the 70 µm excess is predicted to increase only slightly during such events and the dusty episode would last ≤ 20 Myr (Booth et al., submitted). Thus at most a few per cent of stars in the ~ 500 Myr bin should be undergoing heavy bombardment episodes when observed, and even fewer if only up to ~ 20 % of Sun-like stars host giant planets (Cumming et al. 2008).

4.2 Disc populations

In general, the low debris incidence at all ages and the mild decline in luminosity at a few Gyr require initial planetesimal discs of low mass, and of radius similar to the ≈ 50 AU of the Solar System. The stirred models have a distinctive brightening at early times (≈ 10$^{-7}$–8 yr) that the steady state models do not, and the somewhat raised incidence of 70 µm excesses among FEPS stars at 10$^{-7}$–8 years (Hillenbrand et al. 2008, ~ 20 %) could favour this class of interpretations. Bright debris systems undergoing resonance crossing in planetary migration are likely to be too few to be observed as a distinct subset among current surveys.

Resolved debris discs of Sun-like stars (Wyatt 2008; Kalas et al. 2006) are probably unusually large if most systems possess Solar System-sized comet belts. For five precise (G2 V) Solar analogues the fitted disc radii are ~ 100 – 200 AU (Krivov et al. 2008), also suggesting that the larger, more luminous, discs currently dominate the detected population. To place the Sun’s compact, low-dust, Kuiper Belt more accurately within the context of extrasolar debris systems requires deeper observations, and the results here are preliminary given the small sample size. The SCUBA survey was the first unbiased exploration of G-dwarfs in the submillimetre, and the upcoming SCUBA-2 survey (Matthews et al. 2007) will observe 100 G-dwarfs (as well as equal numbers of A, F, K and M stars), and address the models and evolutionary timescales in more detail.

Figure 4. Cumulative $L_{dust}/L_{star}$ from far-infrared data for Sun-like stars, in 1 dex-wide bins at 500 Myr and 5 Gyr containing 139 and 210 stars respectively. Data are from the age-selected FEPS project (Carpenter et al. 2008) and volume limited surveys (Trilling et al. 2008; Beichman et al. 2006a) with Spitzer plus an ISO search of the UMa moving group (see text). Some luminosities are lower limits (e.g. single-wavelength detection), and low values are incomplete, especially for ISO/FEPS at $< 10^{-5}$, contributing ≈ 80, 20 % of targets in the young, old bins respectively.

Detections with good dust temperature estimates yielding $L_{dust}/L_{star}$ ≈ 5 – 8 × 10$^{-5}$ from the millimetre fluxes.
5 CONCLUSIONS

This small unbiased survey for debris around Solar analogues suggests that cold bright dust-belts are rare, especially for stars of typical few-Gyr ages. The majority of stars should begin with insubstantial comet belts of dimensions similar to the Sun’s Kuiper Belt, with moderate dust luminosity only for about the first Gyr of main-sequence lifetime. If these systems fade slowly with time as predicted in models, counterparts of Sun-like age should be detectable in the far-infrared to submillimetre with near-future SCUBA-2 and Herschel observations.

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