THE DUST PROPERTIES OF EIGHT DEBRIS DISK CANDIDATES AS DETERMINED BY SUBMILLIMETER PHOTOMETRY

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ABSTRACT

The nature of far-infrared dust emission toward main-sequence stars, whether interstellar or circumstellar, can be deduced from submillimeter photometry. We present JCMT/SCUBA flux measurements at 850 μm toward eight stars with large photospheric excesses at 60–100 μm. Five sources were detected at 3 σ or greater significance and one was marginally detected at 2.5 σ. The inferred dust masses and temperatures range from 0.033 to 0.24 M⊙ and 43–65 K, respectively. The frequency behavior of the opacity, τν ∝ νβ, is relatively shallow, β < 1. These dust properties are characteristic of circumstellar material, most likely the debris from planetesimal collisions. The two nondetections have lower temperatures, 35–8 K, and steeper opacity indices, β > 1.5, that are more typical of interstellar cirrus. The confirmed disks all have inferred diameters ≥2″, most lie near the upper envelope of the debris disk mass distribution, and four are bright enough to be feasible for high-resolution imaging.

Subject headings: circumstellar matter — planetary systems: formation — planetary systems: protoplanetary disks — submillimeter

1. INTRODUCTION

Dust around main-sequence stars with ages ≥10 Myr must have been formed in situ due to the short timescales for collisional destruction and radiative dispersal (Artymowicz 1988). The micron- and submicron-sized particles that are detected in infrared images of scattered light (e.g., Liu 2004) and emission (e.g., Su et al. 2005) are created from the collisions of larger particles, possibly from the late stages of planet formation. The study of such debris disks therefore constrain planet formation models (Kenyon & Bromley 2004) and new detections can mark good targets for imaging of extrasolar planets (Zuckerman & Song 2004).

The faint emission from the cold dust is generally only apparent above the stellar photosphere at wavelengths longer than about 20 μm. The IRAS All Sky Survey has been the primary resource for debris disk searches, subsequently augmented with more targeted surveys by Infrared Space Observatory (ISO; see de Muizon 2005) and most recently by Spitzer (Meyer et al. 2004; Rieke et al. 2005). These instruments are able to define the spectral energy distribution (SED) of the dust out to near its peak at about 100 μm, but photometry at longer wavelengths, where the emission is optically thin, is an essential complement by providing a measure of the dust mass. Moreover, by constraining the Rayleigh-Jeans side of the SED, the disk temperature and luminosity and the the power-law index of the dust opacity can be determined. These are significantly different in debris disks and the interstellar medium, and thus submillimeter observations can confirm or reject debris disk candidates that are based solely on unresolved far-infrared excesses.

Observations of debris disks at long wavelengths are difficult due to the intrinsic weakness of the emission and the poor transparency of the atmosphere. The Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) has been the workhorse instrument to date (e.g., Holland et al. 1998), but still has had limited success: less than 20 systems have been detected at submillimeter wavelengths. Consequently, the evolution of mass and inner radius, derived from the dust temperature, is not well understood (Najita & Williams 2005).

Far-infrared surveys provide a good starting point to define a target list for submillimeter observations, although the coldest disks may be missed (Wyatt et al. 2003; Najita & Williams 2005). A recent list of 58 nearby (<100 pc) debris disk candidates was published by Zuckerman & Song (2004) based on an extensive search of the IRAS Faint Source Catalog by Silverstone (2000). Most of their candidates have not been observed beyond 100 μm, but many have large excesses, and their SEDs extrapolate to detectable fluxes in the submillimeter regime.

A program to obtain 850 μm photometry of stars in the Zuckerman & Song (2004) catalog began in 2004 Spring with the intent to survey as many sources with large predicted fluxes as possible. The unfortunate retirement of SCUBA in the summer of 2005 ended the project after only eight sources had been observed. Nevertheless, the truncated survey yielded a very high (75%) detection rate and significant constraints on the nature of the dust toward the two other sources. This short paper describes the observations in § 2, the spectral energy distributions of the eight candidate debris disks in § 3, discusses the results and implications in § 4, and concludes in § 5.

2. OBSERVATIONS

Photometry observations were conducted using the SCUBA bolometer at the JCMT on Mauna Kea, Hawaii between 2004 March and 2005 July. For most of the data presented here, the precipitable water vapor level was between 1 to 2 mm, corresponding to zenith optical depths at 850 μm between about 0.2 to 0.3. The optical depth at 450 μm was generally greater than 1 so high-sensitivity measurements were not possible with the short-wavelength bolometers.

We took the position of each source from the Two Micron All Sky Survey (2MASS) Point Source Catalog, was observed for between 50 and 70 minutes with the exception of HD 206893, which was observed for 140 minutes. The pointing was checked via observations of bright quasars near each source after each major slew, and the focus was adjusted every 3 hr on average, more frequently at times near sunrise and sunset. Calibration was performed by observations of Uranus, Mars, and standard sources CRL 618, CRL 2688, IRC +10216. Based on the agreement of
the measured fluxes with those predicted for these calibrators, we estimate that the photometry is accurate to within 10% at 850 μm.

CO(3–2) emission was detected toward HD 218396 using the B3 dual-polarization receiver on the JCMT during observations in 2005 June. The emission was relatively strong, and a small map was made in the vicinity of the source to measure its extent. The map was made by scanning across the field alternately in right ascension and declination with a fixed “off” position 3° east of the map center. The system temperatures decreased from 620 to 430 K as the source rose from 37° to 64°. First-order baselines were removed and the data gridded and coadded to produce a fully sampled map with size 70′′ × 70′′ and rms 0.2 K per 0.15 km s⁻¹ channel. Due to the time taken to make this map, none of the other sources were observed with the heterodyne receivers.

3. RESULTS

3.1. Spectral Energy Distributions

The eight sources that were observed with SCUBA are listed in Table 1. The age estimates are from a recent reevaluation by Moór et al. (2006), whose target list of 60 debris disk candidates with high fractional luminosity overlap with six of the sources here. The ages for the two sources not in Moór et al., HD 14055 and HD 56099, are taken from Zuckerman & Song (2004). Distances are derived from Hipparcos parallaxes. The SCUBA flux measurements and 1σ statistical uncertainty are listed in the last column of the table. A 10% calibration uncertainty applies to both the flux and error.

Five of the eight sources, HD 14055, HD 15115, HD 21997, HD 127821, and HD 219396, were detected at 850 μm at 3σ significance or higher. An additional source, HD 206893, was detected with a signal-to-noise ratio of 2.5. It was observed on two consecutive days with consistent (∼2σ) results and is considered a marginal detection. The SEDs of these six sources are shown in Figure 1. The Hipparcos and 2MASS catalogs were used to obtain the photometry at BV and JHK bands, respectively, and Kurucz models appropriate for each stellar type are shown normalized to the near-infrared data. Fluxes at mid- and far-infrared wavelengths are from the IRAS Faint Source Catalog, color-corrected for the temperature of the star at 12 and 25 μm and for the temperature of the dust at 60 and 100 μm where appropriate. Since the corrections change the SED fit slightly, they are determined iteratively along with the dust temperature. Additional data points from ISO and Spitzer observations at 10–90 μm from Chen et al. (2006) and Moór et al. (2006) were added where available.

We model the excess dust emission above the stellar photosphere with a single-temperature greybody, \( F_\nu = B_\nu(T_{\text{dust}}) \times (1 - e^{-\tau_\nu}) \Delta \Omega \). Here \( B_\nu \) is the Planck function, \( \tau_\nu = (\nu/\nu_0)^k = (\lambda_0/\lambda_0)^{-\beta} \) is the optical depth with power-law index \( \beta \) and \( \Delta \Omega \) is the solid angle. Because the dust is only detected at 3–6 wavelengths in each source, we apply an additional constraint, \( \lambda_0 \lesssim 100 \mu m \). This is based on similar fits to better sampled SEDs of other debris disks (Dent et al. 2000) and is also justified a posteriori from the fitted disk parameters below.

The dust excesses were then fit to determine \( \beta \), \( T_{\text{dust}} \), and \( \Delta \Omega \) for a range of values of \( \lambda_0 \). The results are shown for a representative source, HD 15115, in Figure 2. Fits to the SEDs of the other sources show a similar behavior: \( \beta \) and \( T_{\text{dust}} \) decrease slightly as \( \lambda_0 \) decreases but \( \Delta \Omega \) increases rapidly. This is due to the fact that the dust is cold, \( \sim 50 \text{K} \), so the mid- and far-infrared data points all lie on the Wien side of the graybody, where the frequency dependence is dominated by the exponential term. The optical depth dependence produces only a slight change to the shape of the fit and, if less than 1, mainly affects the flux scale.

The different fits for the different values of \( \lambda_0 \) are almost indistinguishable in terms of the least-squares difference and the plotted SED, shown in Figure 1. Consequently, these data are unable to give an accurate measure of \( \lambda_0 \) and therefore also of \( \Delta \Omega \). Because \( \beta \) and \( T_{\text{dust}} \) are only weakly dependent on \( \lambda_0 \), however, they are well determined. The one SCUBA data point is critical in this regard because it lies on the Rayleigh-Jeans side of the distribution, where the emission is both optically thin (so \( \lambda_0 \) is only a scaling factor), and the frequency dependence is due to a power law and therefore strongly dependent on \( \beta \).

The remaining two sources in the observed sample, HD 56099 and HD 78702, were not detected. Both stars have strong infrared excesses, but the low limit on the 850 μm flux from the SCUBA observations implies a significantly steeper submillimeter spectral index, or equivalently a higher value for \( \beta \), than determined for the detected sources. The best three-parameter fit to the observed IRAS and SCUBA fluxes requires \( \beta \gtrsim 2 \) for all values of \( \lambda_0 \). Mie theory, laboratory measurements, and ISM observations suggest an upper limit of \( \beta = 2 \) (Pollack et al. 1994; Draine 2006). The lowest value of \( \beta \) consistent with the data is obtained by fitting the SED with an 850 μm flux equal to the 3σ SCUBA upper limit. The best-fit SED is shown for each source in Figure 3, and the allowable fits consistent with the upper limits are overlaid in gray scale.

Table 1 lists the best-fit parameters, \( T_{\text{dust}} \) and \( \beta \), and their full range, including errors, for \( \lambda_0 = 3–100 \mu m \). The derived dust mass and fractional luminosity are listed in columns (4) and (5), respectively. The dust mass is calculated from the 850 μm flux in the standard way and assumes a dust mass absorption coefficient \( k_{850} = 1.7 \text{ cm}^2 \text{ g}^{-1} \), for ease of comparison with other studies. There is considerable uncertainty over this number, and the masses of the submillimeter emitting particles may be underestimated by a factor of 3–5 (see discussion in Najita & Williams 2005). This uncertainty dominates that due to the linear dependence of mass on \( T_{\text{dust}} \). The ratio of dust to stellar luminosity is a measure of the fraction of the starlight absorbed by the dust and is a good indicator of the likelihood of detecting scattered light (see §4). This value is independent of \( \lambda_0 \), as the plotted best-fit SEDs are almost indistinguishable. The fact that a single temperature characterizes the emission very well for each SCUBA detection shows that the mass surface density jumps at a specific distance from the star.\(^1\) A minimum radius of this inner

| Source | HIP | SpT | Age (Myr) | \( d \) (pc) | \( F_{\text{850}} \) (mJy) |
|--------|-----|-----|----------|------|----------------|
| HD 14055  | 10670 | A1 V | 1007 | 36.1 | 5.5 ± 1.8 |
| HD 15115  | 11360 | F2 | 12 5 | 44.8 | 4.9 ± 1.6 |
| HD 21997  | 16449 | A3 IV/V | 20 10 | 73.8 | 8.3 ± 2.3 |
| HD 56099  | 35457 | F8 | >5007 | 86.8 | 1.4 ± 1.9 |
| HD 78702  | 44923 | A0/A1 V | 220 10 | 79.9 | 0.3 ± 2.3 |
| HD 127821 | 70952 | F4 IV | [200, 3400] | 31.7 | 13.2 ± 3.7 |
| HD 206893 | 107412 | F5 V | <2800 | 38.9 | 3.8 ± 1.5 |
| HD 218396 | 114189 | A5 V | [20–150] | 39.9 | 10.3 ± 1.8 |

\(^1\) There may still be a significant amount of dust, as measured by area, in very small dust grains closer to the star. Scattered light images need not, therefore, show a central hole (Wahhaj et al. 2005).
hole, $R_{\text{dust}} = 7.8 \times 10^4$ AU $(L_{\text{star}}/L_\odot)^{0.5} T_{\text{dust}}^{-2}$, is obtained by bounding the dust luminosity by a blackbody, and is listed in column (6) of Table 2.

The low masses and large radii that we have determined allow us to justify, a posteriori, our initial assumption in the SED fits. Even if the dust were concentrated in a narrow annulus of width $\Delta R_{\text{dust}} = 1$ AU at a radius $R_{\text{dust}}$ from the star, the inferred surface densities for each source are very small, $\Sigma_{\text{dust}} = M_{\text{dust}}/2\pi R_{\text{dust}} \Delta R_{\text{dust}} \simeq 10^{-3} - 10^{-2}$ g cm$^{-2}$. Since $\tau_{\lambda} \propto \lambda^{-\beta}$, the wavelength where the disks become optically thin is $\lambda_0 = 850$ $\mu$m $(\kappa_{850} \Sigma_{\text{dust}})^{1/\beta} \simeq 1$–10 $\mu$m. If the dust were more spread out, or the inner hole larger than the minimum estimate in Table 2, the inferred value of $\lambda_0$ would be even smaller.

The five detections and one marginal detection have dust temperatures ranging from 43 to 65 K and dust opacity index $\beta = 0.6$–1.0. These are typical values for debris around main-sequence
stars (Dent et al. 2000; Najita & Williams 2005) and differ from the diffuse interstellar medium, where $T_{\text{dust}} \approx 20$ K and $\beta \approx 2$ (Boulanger et al. 1996). Thus, these SCUBA observations help to confirm the disk nature of the far-infrared emission around these stars.

On the other hand, the possible fits to the two nondetections have lower temperatures, $T_{\text{dust}} = 36-38$ K, and steeper dust opacity indices, $\beta > 1.5$, than the other sources in the sample. These values suggest that the IRAS emission is warm interstellar cirrus (Low et al. 1984), and we conclude that these two sources are probably not debris disks.

3.2. Molecular Gas along the Line of Sight to HD 218396

A CO 3–2 spectrum was taken toward HD 218396 and surprisingly strong emission was detected. CO disk emission rapidly decreases as the infrared excess decreases (Dent et al. 2005). No star with such a small excess has been detected in CO before, and the measured integrated intensity, $I_{\text{CO}} = 1.6$ K km s$^{-1}$, is more typical of protostellar, rather than debris, disks.

In fact, it seems unlikely that the CO comes from a disk around the star. The radial velocity of the gas, $v_{\text{CO}} = -5.0$ km s$^{-1}$, and star, $v_{\star} = -12.6$ km s$^{-1}$ (Moór et al. 2006), are significantly different, and there is no indication that the star is a spectroscopic binary (Royer et al. 2002). No significant emission to a 3 $\sigma$ limit of 0.54 K per 0.15 km s$^{-1}$ channel is detected at the stellar radial velocity. We also mapped the emission and found it to be extended (Fig. 4). The CO line probably arises from an unrelated background high-latitude ($b = 35^\circ$ N) cloud along the line of sight, about 1° north and perhaps an extension of cloud 54 in the catalog of Magnani et al. (1985). The filling factor of high-latitude molecular gas is small, $\approx 3\%$, in the southern hemisphere (Magnani et al. 2000), but not negligible.

The mid-infrared emission is compact in the Spitzer Infrared Spectrograph (IRS) SL slit, at 6$''$ resolution, but it may possess some extended emission, containing approximately half the total flux, in the wings of the point-spread function (PSF) in the LL2 slit (C. Chen 2006, private communication). At the much lower IRAS resolution, $\approx 1''$, there is no evidence for extended emission. The SCUBA detection of HD 218396 has the highest signal-to-noise ratio of our sample, $\approx 6$. There is no emission in the neighboring bolometers, however, showing that the 850 $\mu$m flux is concentrated within about 20$''$.

Any extended background emission would imply that the measured fluxes overestimate the disk emission. A uniform scaling would not change the inferred values of $T_{\text{dust}}$ and $\beta$. The shallow submillimeter slope, in particular, is strong evidence that the dust
The stellar ages of the six detected sources range from (Liu et al. 2004) and stellar activity (Najita & Williams 2005). Massive stars (Wyatt et al. 2003), or moving group membership surveys based solely on young stellar ages, either via association with this is a far higher success rate than other submillimeter surveys. Carpenter et al. (2005) showed that the mass of dust particles traced by millimeter measurements is smaller in debris disks around main-sequence stars than in protostellar disks. Liu et al. (2004) and Najita & Williams (2005) define an upper envelope to the debris disk mass distribution that decreases inversely with age. The new detections here and the revised age estimates in Moór et al. (2006) do not greatly alter these conclusions (Fig. 5). Four of the six new detections here lie near the upper boundary of the mass distribution, and two, HD 127821 and HD 206893, add to the statistics in the poorly characterized region where stellar ages are greater than 300 Myr.

We have also reexamined the dependence of dust temperature and minimum inferred radius on the stellar luminosity and age with the addition of the six new sources here. As in Najita & Williams (2005), no obvious correlations were found.

The double peak in the SEDs shows that the dust is physically separated from the stars but the far-infrared and submillimeter observations discussed here are unable to resolve the disks. Higher resolution studies are important for measuring disk sizes and characterizing asymmetries that may point to planetary companions. Minimum radii based on the fitted dust temperatures are given in Table 2 and range from 1″ to 2″ in angular size. These are

![Fig. 4.—Contours of CO 3–2 emission toward HD 218396. The integration range is −6 to −4 km s⁻¹, and the contour levels are 0.25 K km s⁻¹. The inset shows the spectrum toward the star, and the arrow marks its radial velocity where any disk emission should be seen.](image)

![Fig. 5.—Dust mass in debris disks vs. stellar age. These points represent the known SCUBA 850 μm debris disk detections in the literature (Wyatt et al. 2003, 2005; Sherr et al. 2004; Liu et al. 2004; Greaves et al. 2004; Najita & Williams 2005, Williams et al. 2004). They have been converted to a disk mass for the same mass absorption coefficient, κ_{850} = 1.7 cm² g⁻¹, and dust temperature given in the SCUBA detection paper. The error bars in the masses include the stated statistical uncertainty plus an assumed 10% calibration uncertainty. The error bars in the stellar ages are from Moor et al. (2006) where available, or else from the discovery paper. If no error was given, a minimum and maximum age spanning a factor of 2 and centered on the stated age is plotted. The six new measurements presented in this paper are shown with an outer ring around the central dot.](image)

emission is disklike in nature. Even if the SCUBA flux were a factor of 2 lower and the infrared data unchanged, the best fit, β = 1, is significantly less than ISM dust.

Based on the above, we conclude that HD 218396 is surrounded by a debris disk that is detected in the continuum from 30 to 850 μm, but not in the CO 3–2 line.

4. DISCUSSION

The eight sources here were selected based on the extrapolation of far-infrared SEDs to submillimeter wavelengths. Six of the eight were detected, although one only at 2.5 σ significance. This is a far higher success rate than other submillimeter surveys based solely on young stellar ages, either via association with massive stars (Wyatt et al. 2003), or moving group membership (Liu et al. 2004) and stellar activity (Najita & Williams 2005). The stellar age of the six detected sources range from ~10 to ~200 Myr and possibly as large as 3 Gyr. Rieke et al. (2005) suggest that age is not the only factor in either disk occurrence or dust mass and that there may be a significant stochastic influence due to rare collisions of large objects (see also Song et al. 2005).

| Source        | T_{dust} | β    | M_{dust} | L_{dust}/L_{star} | R_{dust} | Notes               | Notes |
|---------------|----------|------|----------|------------------|----------|---------------------|-------|
| HD 14055      | 65 ± 10  | 0.98 ± 0.17 | 0.033     | 1.0              | 84       |                     |       |
| HD 15115      | 62 ± 5   | 0.73 ± 0.16 | 0.047     | 5.8              | 34       |                     |       |
| HD 21997      | 56 ± 6   | 0.86 ± 0.14 | 0.24      | 7.1              | 75       |                     |       |
| HD 56099      | 38 ± 5   | 2.00 ± 0.51 | <0.091    | ~11              | ...      | interstellar cirrus?|       |
| HD 78702      | 36 ± 7   | 2.00 ± 0.19 | <0.018    | ~2.6             | ...      | interstellar cirrus?|       |
| HD 127821     | 43 ± 11  | 0.64 ± 0.44 | 0.096     | 3.0              | 67       |                     |       |
| HD 206893     | 53 ± 10  | 0.82 ± 0.25 | 0.033     | 2.8              | 42       | marginal detection  |       |
| HD 218396     | 50 ± 3   | 0.71 ± 0.21 | 0.10      | 2.8              | 66       | CO detection        |       |

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well within the range of optical and infrared observations, and the issue of detectability is one of contrast. Two systems, HD 15115 and HD 21997, have reasonably high fractional luminosities, $L_{\text{dust}}/L_{\text{star}} = 6-7 \times 10^{-4}$, that are comparable to AU Mic and therefore might be detectable in scattered light either via ground-based coronagraphy (Kalas et al. 2004; Liu 2004) or direct imaging with the Hubble Space Telescope (e.g., Krist et al. 2005).

Interferometric imaging at (sub)millimeter wavelengths is an important alternative means to investigate disk structure (e.g., Wilner et al. 2002). The millimeter-sized particles that are revealed in such observations are less affected by radiative forces than the micron-sized particles seen in scattered light. Consequently, resolved millimeter-wavelength images are a more reliable measure of the gravitational potential of a system and of any dynamical resonances that might be induced by a planet (Kuchner & Holman 2003; Wyatt 2003). The two systems here, HD 127821 and HD 218396, with 850 mJy fluxes greater than 10 mJy, and diameters $\geq 3''-4''$, are just accessible to the current generation of interferometers for high-resolution mapping.

5. CONCLUSIONS

We have carried out 850 $\mu$m photometry of eight nearby stars to search for thermal emission from cold circumstellar dust. With one exception, the rms noise levels of these SCUBA observations lie between $\sigma = 1.5$ and 2.3 mJy. Five sources were detected at $3 \sigma$ significance or higher and an additional one at $2.5 \sigma$. The high detection rate is attributable to their selection based on high IRAS 60 and 100 $\mu$m excesses.

These six sources are a significant addition to the small number of debris disks detected at submillimeter wavelengths. The inferred dust masses range from 0.033 to 0.23 $M_\odot$. Several are some of the most massive disks known for their age and show that even the upper end of the disk mass distribution may not have been fully explored. Dust temperatures range from 43 to 65 K, and are similar to other debris disks. There is no correlation of either temperature of equivalent blackbody radius with stellar luminosity or age.

Far-infrared and submillimeter observations are generally unable to resolve the emission from the cold dust. Flux measurements, or even sensitive upper limits, on the Rayleigh-Jeans side of the SED regime constrain the dust opacity index and are important for distinguishing between a disk or interstellar (most likely cirrus) origin. The former applies for the six detections that have $\beta < 1$, and the latter for the two nondetections where the combination of high far-infrared and low submillimeter fluxes constrain $\beta > 1.5$.

The photospheric excesses are well fit by single temperature graybodies, implying that the bulk of the dust, as measured by mass, lies far from the star, ranging from 42 to 84 AU for each source or about $1''-2''$ in angular size. Two of the confirmed disks have high fractional luminosities and may be detectable in scattered light. An additional two are strong enough to image with the current generation of (sub)millimeter interferometers. Such high-resolution observations may show clumping in the disk due to planetary induced resonances.

There are undoubtedly more sources in the Zuckerman & Song (2004) catalog, and perhaps others in the plethora of new Spitzer results (e.g., Bryden et al. 2006), which would be detectable if SCUBA were available. Its successor, SCUBA-2, will be about 3 times more sensitive for photometry and far quicker for mapping (Holland et al. 2003). It will be able to distinguish between circumstellar and interstellar emission and provide mass measurements and dust opacities for perhaps as many as an order of magnitude more debris disks.

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