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DUST IN THE 55 CANCRI PLANETARY SYSTEM

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ABSTRACT

The presence of debris disks around ~1 Gyr old main-sequence stars suggests that an appreciable amount of dust may persist even in mature planetary systems. Here we report the detection of dust emission from 55 Cancri, a star with one, or possibly two, planetary companions detected through radial velocity measurements. Our observations at 850 and 450 μm imply a dust mass of 0.0008–0.005 Earth masses, somewhat higher than that in the Kuiper Belt of our solar system. The estimated temperature of the dust grains and a simple model fit both indicate a central disk hole of at least 10 AU in radius. Thus, the region in which the planets are detected is likely to be significantly depleted of dust. Our results suggest that far-infrared and submillimeter observations are powerful tools for probing the outer regions of extrasolar planetary systems.

Subject headings: circumstellar matter — planetary systems — stars: individual (55 Cancri)

1. INTRODUCTION

Planetary systems are born in dusty circumstellar disks. Once planets form, the circumstellar dust is thought to be continually replenished by collisions and sublimation (and subsequent condensation) of larger bodies such as asteroids, comets, and Kuiper Belt objects (Nakano 1988; Backman & Paresce 1993). Such debris disks have now been directly imaged around several nearby main-sequence stars: β Pictoris, HR 4796A, Vega, Fomalhaut, and ϵ Eridani (Holland et al. 1998; Jayawardhana et al. 1998; Koerner et al. 1998; Greaves et al. 1998). The presence of debris disks around stars that, in some cases, may be 2×10^8–10^9 yr old suggests that an appreciable amount—perhaps tens of lunar masses—of dust may be present even in mature planetary systems. The ring of dust recently imaged at 850 μm around the nearby K2V star ϵ Eridani is also spatially analogous to the Kuiper Belt of our own solar system (Greaves et al. 1998).

The G8V star 55 Cancri, at a distance of 13 pc, is unique in having planets as well as a substantial dust disk. It contains one planet of about 2 Jupiter masses in an orbit with a semimajor axis of 0.11 AU (Butler et al. 1997) and evidence for a second planet at several AU in the form of a residual drift in the stellar velocity over the past 10 years (Marcy & Butler 1998). The dust disk, first inferred by Dominik et al. (1998) using *Infrared Space Observatory* (*ISO*) observations at 25 and 60 μm, is much larger, with a radius of ~50 AU. Recent near-infrared coronagraphic observations by Trilling & Brown (1998) have resolved the 55 Cancri dust disk and confirm that it extends to at least 40 AU (3$''$.24) from the star.

We have recently commenced a minisurvey of the parent stars of known extrasolar planets using the Submillimeter Common User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT). Our program is to obtain 850 and 450 μm flux measurements in the photometry mode since the expected disk sizes are too small to be spatially resolved at present. Our goals are to explore the kinship between circumstellar dust and planets and to provide significant constraints on the nature and amount of dust associated with the Kuiper Belts of these extrasolar planetary systems. Here we report the detection of submillimeter emission from 55 Cnc during the first observing shift of our survey program.

2. OBSERVATIONS AND RESULTS

We observed 55 Cnc with the SCUBA instrument (Holland et al. 1999) on the JCMT on Mauna Kea, Hawaii. The data were obtained on 1999 February 4–9 UT using the SCUBA photometry mode. Although SCUBA operates at 450 and 850 μm simultaneously, the observing conditions are generally poorer at the shorter wavelength. Zenith atmospheric opacities were exceptionally good at 850 μm, ranging from 0.10 to 0.15. Observations of Uranus were used for calibrations. Pointing accuracy was 2$''$, which is small compared with the beam size of 15$''$ at 850 μm (FWHM) and 8$''$ at 450 μm. The data were reduced using the SCUBA User Reduction Facility (Jenness & Lightfoot 1998).

We also obtained mid-infrared observations of 55 Cnc on 1999 May 3 UT using the OSCIR instrument on the Keck II telescope. OSCIR is a mid-infrared imager/spectrometer built at the University of Florida,[7] using a 128×128 Si:As

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[7] Additional information on OSCIR is available on the Internet at www.astro.ufl.edu/iag/.

TABLE 1

MEASURED FLUX DENSITIES FOR 55 CANCRI

λ (μm)	F_ν (mJy)	Source
10.8......	1000 ± 100	OSCIR/Keck
12........	981	*IRAS*
18.2......	280 ± 28	OSCIR/Keck
24........	170 ± 20	*ISO*
25........	241	*IRAS*
60........	<400	*IRAS*
61........	170 ± 30	*ISO*
95........	<90	*ISO*
100	<1000	*IRAS*
161	<780	*ISO*
185	<750	*ISO*
450	7.9 ± 4.2	SCUBA/JCMT
850	2.8 ± 0.5	SCUBA/JCMT

Blocked Impurity Band (BIB) detector developed by Boeing. On Keck II, OSCIR has a plate scale of 0.″062 pixel^{-1}, providing a 7.″9 × 7.″9 field of view. We used a chop frequency of 4 Hz and a throw of 8″. Images were obtained in N (10.8 μm) and IHW18 (18.2 μm) filters, with on-source integration times of 120 and 300 s, respectively. The standard stars μ UMa and α Boo were used for flux calibration.

In the submillimeter, we measure 2.8 ± 0.5 mJy at 850 μm and 7.9 ± 4.2 mJy at 450 μm from 55 Cnc, presumably because of thermal emission of dust in a Kuiper Belt–like population. In the mid-infrared, where the emission is dominated by the stellar photosphere, we measure 1.0 ± 0.1 Jy at 10.8 μm and 280 ± 28 mJy at 18.2 μm. The mid-infrared images do not show any evidence for spatial extension. This is not surprising given that 55 Cnc has little or no excess above the photosphere at these wavelengths. Table 1 lists all available mid-infrared to submillimeter flux measurements and limits from our observations, *IRAS*, and *ISO*.

3. DISCUSSION

Following Backman & Gillett (1987), we can write the fractional luminosity of dust as $\tau = L_d/L_*$, where L_d and L_* are the luminosities of the dust debris and the star, respectively. For 55 Cnc, based on its far-infrared excesses, $\tau \approx 7 \times 10^{-5}$, some 2 orders of magnitude lower than that of the debris disk prototype β Pictoris.

Figure 1 shows that a single-temperature blackbody can match the far-infrared and submillimeter flux measurements of 55 Cnc quite well. If one assumes that the emission at $\lambda \leq 25$ μm is primarily due to the stellar photosphere, a $T = 100$ K blackbody fits the *ISO* 60 μm measurement and the SCUBA 450 and 850 μm detections. It is also roughly consistent with the *ISO* 90 μm limit. Figure 1 also includes a modified blackbody fit with $T = 60$ K and $\beta = 0.5$, where $F_\nu \propto \nu^{2+\beta}$, for comparison. This can fit the 60 μm and submillimeter points well, but does not meet the *ISO* 90 μm constraint.

A blackbody temperature of 100 K for the grains suggests that the dust disk around 55 Cnc has a central disk hole with a minimum radius of 13 AU. If the dust temperature is closer to 60 K, the hole could be as large as 35 AU. This would not conflict significantly with the coronagraph image of Trilling & Brown (1998), in which reliably detected emission begins at ~27 AU from the star. Thus, the 55 Cnc dust disk is likely to be well outside the orbits of the two known planets in the system. Since $\beta = 0$ corresponds to large grains and $\beta = 1$ to small grains for optically thin emission, our best fit to the data in Figure 1 would imply a population of grains with $a \sim 100$ μm.

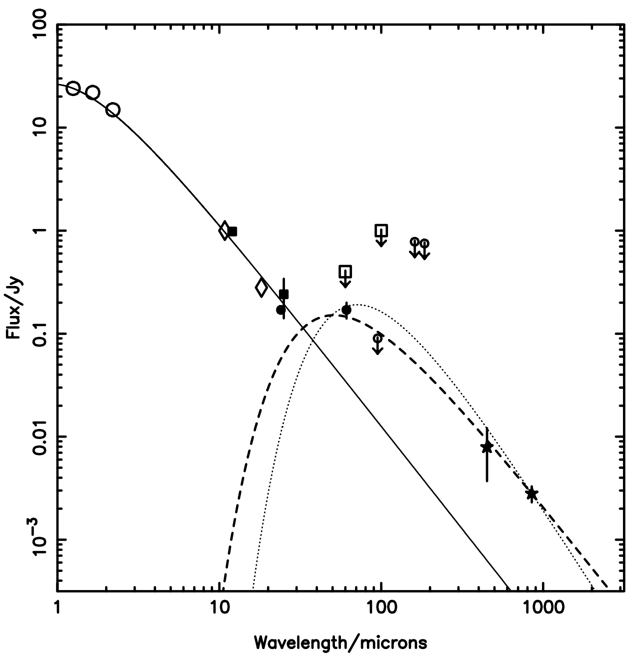

FIG. 1.—Composite spectral energy distribution (SED) of 55 Cancri from infrared to submillimeter wavelengths. The near-infrared fluxes (*open circles*) are from Persson, Aaronson, & Frogel (1977). *ISO* measurements are shown as filled circles and *ISO* upper limits as open circles, while filled squares and open squares designate *IRAS* measurements and upper limits, respectively. Our mid-infrared fluxes are shown as diamonds, and our JCMT measurements are indicated by filled stars. All error bars are smaller than the symbols except where shown. Also shown are the photospheric emission with $T_* = 5250$ K (*solid line*), modified blackbodies with $\beta = 0.0$, $T = 100$ K (*dashed line*), and $\beta = 0.5$, $T = 60$ K (*dotted line*), constrained to fit the 850 μm flux.

To better constrain the disk parameters using data at all wavelengths, we used the model discussed by Dent et al. (2000). Calculations are made with a two-dimensional continuum radiative transfer code that includes the star and a thin disk with inner and outer boundaries r_{in}, r_{out} and a power-law midplane density r^{-p}. The dust emission is characterized by a single characteristic grain size a, a critical wavelength λ_0, and an opacity index β; shortward of λ_0, the grains act as blackbodies, while longward, the emissivity is given by $Q \propto (\lambda/\lambda_0)^{-\beta}$.

We have assumed that the r^{-3} power-law density distribution derived from the near-infrared observations also continues down to the inner radius r_{in}. For 55 Cnc, the best-fit model (Fig. 2) has r_{in} of 10 AU, a grain size $a = 100$ μm, and opacity index $\beta = 0.5$. Both the simple fit and the model are roughly consistent with the *ISO* 90 μm upper limit, although the lower β may provide a better fit to these data. The model indicates an upper limit to the dust density in the region 3 AU $\leq r_{\mathrm{in}} \leq$ 10 AU of less than 10% of the density at 10 AU; thus, the region where planets are detected is significantly depleted of dust.

Since the submillimeter flux is less sensitive to the temperature of the grains than the infrared flux, we can use it to

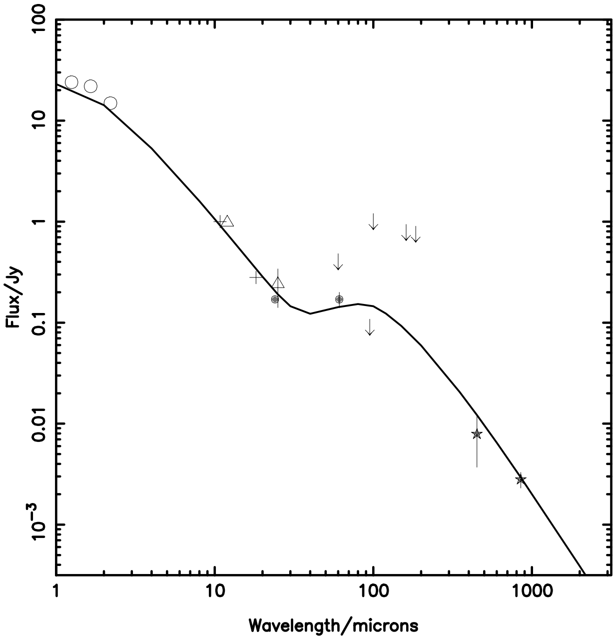

FIG. 2.—Best-fit model for the 55 Cnc SED. The model assumes a thin disk with an inner radius $r_{\rm in} = 10$ AU, a grain size $a = 100$ μm, and an opacity index $\beta = 0.5$. Symbols are the same as in Fig. 1.

estimate the dust mass. Following Jura et al. (1995), the dust mass M_d is given by

$$M_d = F_\nu R^2 \lambda^2 / [2kT_{\rm gr} K_{\rm abs}(\lambda)] , \qquad (1)$$

if R denotes the distance from the Sun to 55 Cnc. Assuming a dust absorption coefficient $K_{\rm abs}(\lambda)$ between 1.7 and 0.4 $\rm cm^2\ g^{-1}$ at 850 μm (Greaves et al. 1998), we obtain a dust mass of 0.0008–0.005 Earth masses, for $T = 100$–130 K. The lower value of $K_{\rm abs}(\lambda)$ is suggested by models of large, icy grains (Pollack et al. 1994), while the higher estimate has been used for previous observations of debris disks (Holland et al. 1998). However, as for all the extrasolar debris disks, very large grains could dominate the total mass while adding little submillimeter emission, so our mass estimates provide only lower limits.

Our dust mass estimates are consistent with Dominik et al. (1998), who derive $M_d > 4 \times 10^{-5} M_{\rm Earth}$ by fitting a disk model to the *ISO* and *IRAS* data. On the other hand, using a low albedo (near-infrared reflectance of 6%) and an average particle density of 1 $\rm g\ cm^{-3}$, Trilling & Brown (1998) estimate a dust mass of 0.4 $M_{\rm Earth}$ in the 55 Cnc disk from their scattered-light observations. Their estimate is inconsistent with ours. The reason for the discrepancy is not clear. One possibility is that Trilling & Brown (1998) may have overestimated the disk brightness in the near-infrared because of difficulties in background subtraction.

The amount of dust in our solar system's Kuiper Belt is not well determined. Based on far-infrared observations of *COBE* and *IRAS*, Backman, Dasgupta, & Stencel (1995) and Stern (1996) have placed an upper limit of 10^{-5} $M_{\rm Earth}$ on the Kuiper Belt mass in the form of dust (particles with $a \leq 1$ cm). However, Teplitz et al. (1999) show that the dust mass could be as high as 7×10^{-4} $M_{\rm Earth}$ depending on assumptions about albedo, distribution in particle size, contribution of foreground and background sources to the far-infrared emission, etc. Thus, the 55 Cnc disk may be somewhat "dustier" than our Kuiper Belt. It also appears somewhat "over-dusty" for 55 Cnc's stellar age of ∼5 Gyr (Gonzalez & Vanture 1998; Baliunas et al. 1997), when compared with dust masses in the handful of nearby, well-studied debris disks.

Trilling & Brown (1998) suggest that the apparent dust mass excess in 55 Cnc is consistent with the idea that the inner planet migrated toward the star from its birthplace (Trilling et al. 1998; Murray et al. 1998). In this scenario, a planet migrates inward by exchanging angular momentum with a circumstellar disk that initially extends to a few stellar radii. This migration could transfer material from the inner part of the disk to the outer part, enhancing the mass at Kuiper Belt distances. If that is true, other extrasolar planetary systems with "hot Jupiter" planets should also harbor appreciable amounts of dust in their outer regions. We expect to test this prediction during our ongoing submillimeter survey of parent stars of radial velocity planets.

The radiation field of a G8 star is generally too weak to expel dust grains by radiation pressure. In the case of 55 Cnc, the Poynting-Robertson timescale is much shorter than the estimated ∼5 Gyr age of the star (Dominik et al. 1998). Therefore, the dust grains in the system must be replenished by collisions or sublimation of larger bodies such as asteroids, comets, and Kuiper Belt objects.

In summary, we have detected submillimeter thermal emission from dust in the 55 Cnc planetary system. Our results confirm that state-of-the-art submillimeter instruments are able to detect continuum emission from even a relatively small amount of dust surrounding nearby Sun-like stars. The observed dust mass in the 55 Cnc system appears to be somewhat higher than that associated with the Kuiper Belt in our solar system. Far-infrared observations from the *Space Infrared Telescope Facility* and the *Stratospheric Observatory for Infrared Astronomy* as well as detailed modeling will be crucial for reliably constraining the spatial extent, size distribution, and composition of the dust.

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