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EVOLUTION OF MID-INFRARED EXCESS AROUND SUN-LIKE STARS: CONSTRAINTS ON MODELS OF TERRESTRIAL PLANET FORMATION

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ABSTRACT

We report observations from the *Spitzer Space Telescope* regarding the frequency of 24 μm excess emission toward Sun-like stars. Our unbiased sample is composed of 309 stars with masses 0.7–2.2 $M_{\odot}$ and ages from <3 Myr to >3 Gyr that lack excess emission at wavelengths $\leq$8 μm. We identify 30 stars that exhibit clear evidence of excess emission from the observed 24 μm/8 μm flux ratio. The implied 24 μm excesses of these candidate debris disk systems range from 13% (the minimum detectable) to more than 100% compared to the expected photospheric emission. The frequency of systems with evidence for dust debris emitting at 24 μm ranges from 8.5%–19% at ages <300 Myr to <4% for older stars. The results suggest that many, perhaps most, Sun-like stars might form terrestrial planets.

Subject headings: circumstellar matter — infrared: stars — planetary systems: formation

1. INTRODUCTION

Are planetary systems like our own common or rare in the Milky Way galaxy? The answer depends on what aspect of our planetary system one is investigating. Gas and dust rich circumstellar disks appear to be a common outcome of the star formation process (Strom et al. 1993). Gas giant planets within 5 AU (presumably formed from these disks) surround >6% of Sun-like stars (Marcy et al. 2005), while the detection of terrestrial planets is still in its infancy (Beaulieu et al. 2006). Although debates concerning theories of giant planet formation continue (Durisen et al. 2007; Lissauer & Stevenson 2007), there is some consensus regarding the formation of terrestrial planets (e.g., Nagasawa et al. 2007). Starting with a swarm of 1 km–sized planetesimals, orderly growth of larger bodies proceeds rapidly (< 1 Myr) out to at least 2 AU. When the gravitational cross section greatly exceeds the geometrical cross section of the largest objects, growth transitions from orderly to oligarchic with the biggest bodies growing fastest in a runaway process. The final stage, chaotic growth, is characterized by high-velocity collisions between the few remaining large bodies in the system. Remaining challenges include the formation of kilometer-sized planetesimals in the face of gas drag on meter-sized bodies (Weidenschilling 1977) and type I migration of lunar-mass objects in a remnant gas disk (Nelson 2005).

Yet there are few observational tests of this developed theory. The physical characteristics of the terrestrial planets, their satellites, and the asteroid belt provide constraints on the formation of our solar system (Bottke et al. 2005; O'Brien et al. 2006). Observations of circumstellar dust debris surrounding Sun-like stars can be used to trace the presence of planetesimal belts of larger parent bodies (Meyer et al. 2007) and thus constrain theories of planet formation. Far-IR observations at 70 μm with the *Spitzer Space Telescope* suggest that 10%–15% of Sun-like stars possess cool outer dust disks that are massive analogs of the Kuiper Belt (Bryden et al. 2006). Yet few mature stars exhibit mid-infrared excess indicative of terrestrial temperature material (Beichman et al. 2005). Recent work with *Spitzer* has begun to assess the frequency of this emission around younger stars (Chen et al. 2005; Hernández et al. 2006). In this contribution we use *Spitzer* data to investigate the frequency of mid-IR excess emission, which may originate from 1–10 AU, observed toward Sun-like stars over a wide range of ages spanning the epoch of terrestrial planet formation in our solar system.

2. OBSERVATIONS

Observations were obtained as part of the Formation and Evolution of Planetary Systems (FEPS) Legacy Science Program (Meyer et al. 2006). Our sample consists of 328 "Sun-like" stars with spectral types F5–K3 and masses ranging from 0.7 to 2.2 $M_{\odot}$ (although strongly peaked at 1.0 $M_{\odot}$). The sample was constructed so that roughly equal numbers of stars were selected in logarithmically spaced age bins from 3 Myr to 3 Gyr (each bin spanning a factor of 3 in age). Stars < 100 Myr were largely drawn from young stellar populations within the Local Association, often members of OB and T Associations. Ages for these stars were estimated from pre–main-sequence evolutionary tracks, as well as kinematic association with groups of known age (e.g., Mamajek et al. 2002). Older main sequence stars were selected from a volume-limited sample of stars taken from the *Hipparcos* catalog. Ages for these stars were estimated from calcium H and K emission-line indices which trace stellar activity levels using the calibration of Donahue (1998). Errors in age for both the young stellar populations as well as the main-sequence stars are estimated to be <50%, although uncertainties in the absolute calibration of these ages are not well understood. A fraction of our sample in the age range from 30 Myr to 1 Gyr were selected to be members of open clusters with well-determined ages (e.g., Stauffer et al. 2005). Our sample selection is

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described in Meyer et al. (2006) and details concerning the age estimates for each star are given in L. A. Hillenbrand et al. (in preparation). We fit Kurucz model atmospheres to *B*/*V* (Tycho) photometry from *Hipparcos* and JHK_s photometry from 2MASS. We assumed solar metallicity and surface gravities estimated from the position of each star in the H-R diagram, performing a nonlinear least-squares fit for $T_{\rm eff}$ and solid angle. For stars within 75 pc, we assumed $A_v = 0$, while for more distant targets A_v was a free parameter.

All sources were detected at 8 μm and 24 μm with $S/N > 30$ using *Spitzer*. Photometry at 8 μm was derived from subarray observations with the IRAC instrument (Fazio et al. 2004). We began our analysis with data processed through the S13 pipeline. Cosmic-ray rejection was implemented and corrections for spatially dependent pixel area and filter response variations were applied. Aperture photometry was derived from a 3.7″ radius aperture (with sky annuli ranging from 12.2″ to 24.4″) using a modified version of IDLPHOT and placed on the standard flux scale recommended by Reach et al. (2005). Systematic calibration errors are estimated to be <2% in each band. Random photometric uncertainties were estimated from the repeatability of 64 observations obtained at each dither position for each source resulting in minimum uncertainties of 1% at 8 μm. Photometry at 24 μm was derived from either 28 or 56 exposures with integration times of 3 or 10 s each with the MIPS instrument (Rieke et al. 2004). We began with S13 pipeline data and photometry was derived using the MOPEX software. Fluxes were estimated from a PSF-fitting algorithm and placed on the flux scale recommended by the SSC. Calibration errors are thought to be <4% (cf. Engelbracht et al. 2007). The minimum random uncertainties in the 24 μm photometry are 1%.

3. ANALYSIS

Of the parent sample of 328, 14 stars were selected for our initial IRS search for remnant circumstellar gas (Pascucci et al. 2006) on the basis of previously detected dust disk signatures. Our analysis starts with the unbiased FEPS sample of 314 ($= 328 - 14$) stars spanning a range of ages from <3 Myr to >3 Gyr. We use the 24 μm/8 μm flux ratio to search for stars that exhibit excess emission. These data are plotted in Figure 1 as a function of 8 μm flux. Note that the brighter sources tend to be nearby (older) field stars, while fainter targets tend to be more distant (and younger) sources. Several systems exhibit flux ratios indicative of a 24 μm excess. The expected photospheric ratio (24 μm/8 μm) in this diagram is approximately 0.116. In order to define an empirical "blue envelope" of stars without excess, we employed a sigma-clipping algorithm to the distribution of 24 μm/8 μm flux ratios. Initially, the mean flux ratio was computed to be 0.190 with $\sigma = 0.82$, and two outliers with ratios beyond 3 σ (indicating obvious excess). Removing these two outliers, we recompute the mean and sigma, resulting in identification of three additional sources with smaller excesses. Repeating this process a total of seven times, the values converge with a mean of 0.117 and $\sigma = 0.005$ as shown in Figure 1, consistent with model predictions. We identify 35 (positive) outliers. Of these, only five exhibit excess emission at ≤8 μm and were previously identified in Silverstone et al. (2006) as optically thick primordial gas rich disks. Because we are interested in understanding the transition to debris disks at 24 μm we remove these five from the sample of excess stars under consideration ($314 - 5 = 309$). Assuming that the color excesses observed are due to excess emission at 24 μm, our 3 σ detection limit of $0.117 + 3 \times 0.005 = 0.132$ corresponds to a 13% excess at 24 μm compared to the expected photospheric emission ($0.132/0.117 - 1$). The largest inferred 24 μm excess is just over 100% compared to the photosphere ($0.245/0.117 - 1$). The 30 sources with detectable excess from our sample of 309 are listed in Table 1 as a function of age. According to the Shapiro-Wilk test, the distribution of 24 μm/8 μm flux ratios for the 279 sources *without* excess is not Gaussian ($P < 0.01\%$). We tested to see whether the mean ratio of 24 μm/8 μm emission was a function of source brightness. For the 140 targets with 8 μm > 128 mJy the mean was 0.1137 with $\sigma = 0.0036$, while for the 139 fainter targets the mean was 0.1199 with $\sigma = 0.0047$. This small offset could be due to uncertainties in flux calibration as a function of integration time (J. M. Carpenter et al., in preparation; Engelbracht et al. 2007).[11] As a result, the errors quoted on the reported excesses include the random errors in the 24 μm/8 μm ratio (typically 1%–2%), as well as the dispersion in our estimate of the photospheric color (4.3%) rather than the error in the mean, added in quadrature.

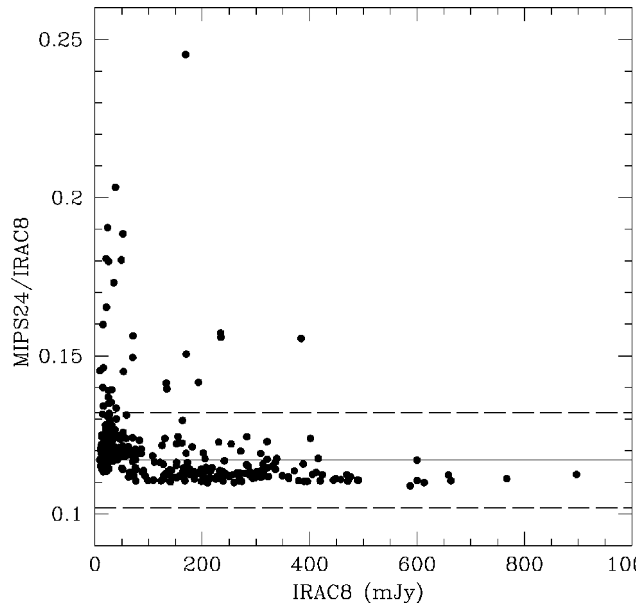

FIG. 1.—The 24 μm/8 μm flux ratio plotted as a function of 8 μm flux for 314 stars drawn from the unbiased FEPS sample. The sample mean (*solid line*) and 3 σ limits (*dashed lines*) as described in the text are shown.

In Figure 2, we present the fraction of stars exhibiting 24 μm excess emission in our sample as a function of age. Each bin spans a factor of 3 in age. The errors in the ordinate are Poisson, computed following Gehrels (1986) with excess fractions as follows: 5/30 for stars 3–10 Myr, 9/48 for 10–30 Myr, 5/59 for 30–100 Myr, 9/62 for 100–300 Myr, 2/53 for 300–1000 Myr, and 0/57 for stars 1–3 Gyr old. The KS test suggests that the distributions of 24 μm/8 μm flux ratios (Fig. 1) for the sample < 300 Myr ($N = 199$) and those > 300 Myr ($N = 110$) are inconsistent with having been drawn from the same parent population ($P < 10^{-10}$). We note that the errors in age quoted above act to diffuse sources to younger as well as older ages. Because there are more excess objects in younger bins, errors in age tend to increase the excess fractions at older ages. As a result, the abrupt drop in the excess fraction at 300 Myr may be even more dramatic than detected here.

[11] Adopting these offsets in the mean flux ratio (and associated 3 σ limits) would result in identification of one new excess object (HD 43989; 30–100 Myr old) and removal of [PZ99] 161618.0−233947 from Table 1.

TABLE 1
SYSTEMS WITH MIPS 24 μm EXCESS

Source	Distance (pc)	log(age) (yr)	$T_{\rm eff}$ (K)	$\log(L_\star/L_\odot)$ (dex)	$f_{24\,\mu{\rm m}}$(excess)/$f_{24\,\mu{\rm m}}$(phot)	σ
1RXS J051111.1+281353	199	6.5−7	5270	0.71	0.239	0.045
RX J1600.6−2159	161	6.5−7	5330	0.27	0.190	0.045
[PZ99] J161459.2−275023	114	6.5−7	5500	−0.14	0.628	0.047
[PZ99] J155847.8−175800	161	6.5−7	4660	0.20	0.479	0.046
[PZ99] J161618.0−233947	161	6.5−7	5250	0.22	0.141	0.045
HD 22179	68	7−7.5	5990	0.02	0.336	0.045
HD 116099	140	7−7.5	6010	0.19	0.188	0.045
HD 141943	67	7−7.5	5810	0.43	0.210	0.045
HD 281691	73	7−7.5	5140	−0.42	0.156	0.045
MML 8	108	7−7.5	5810	0.15	0.737	0.047
MML 17	124	7−7.5	6000	0.43	0.612	0.046
MML 28	108	7−7.5	5000	−0.35	0.413	0.046
MML 36	98	7−7.5	5270	0.03	0.541	0.046
MML 43	132	7−7.5	5410	0.06	0.154	0.045
HD 377	39	7.5−8	5850	0.09	0.332	0.045
HD 12039	42	7.5−8	5690	−0.05	0.287	0.045
HE 750	176	7.5−8	6360	0.28	0.197	0.046
HE 848	176	7.5−8	6310	0.47	0.537	0.047
W79	152	7.5−8	5380	−0.29	0.242	0.046
HD 19668	40	8−8.5	5420	−0.23	0.192	0.045
HD 61005	35	8−8.5	5460	−0.26	1.096	0.049
HD 72687	46	8−8.5	...	−0.05	0.208	0.046
HD 107146	28	8−8.5	5860	0.02	0.329	0.045
HII 152	133	8−8.5	5700	−0.10	0.366	0.046
HII 250	133	8−8.5	5770	−0.04	0.146	0.046
HII 514	133	8−8.5	5720	0.04	0.250	0.046
HII 1101	133	8−8.5	6070	0.08	0.545	0.046
HII 1200	133	8−8.5	6210	0.35	0.170	0.045
HD 85301	32	8.5−9	5600	−0.14	0.343	0.046
HD 219498	62	8.5−9	5670	−0.07	0.277	0.045

4. DISCUSSION

We associate the observed 24 μm excess with dust debris generated through collisions of planetesimals. One of our excess stars identified in Table 1 (HD 12039) was studied in detail by Hines et al. (2006). Models of this debris disk (with fractional 24 μm excess $0.151/0.117 - 1 = 0.29$) suggested a dust mass of $\sim 10^{-5}\ M_\oplus$ located between 4 and 6 AU. The magnitude of all our detected 24 μm excesses are within a factor of 3 (relative to the photosphere) compared to HD 12039. Results similar to ours have been reported for samples of FGK stars in open clusters (Gorlova et al. 2006; Siegler et al. 2007). Our sample is composed of 60 open cluster stars with discrete ages of 55 (5 members of IC 2602), 90 (13 members of α Per), 110 (20 Pleiades stars), and 600 Myr (22 Hyades stars), as well as 249 field stars. We have analyzed the statistics for subsamples where they overlap. While the excess fractions for open clusters with ages 30–100 Myr and 100–300 Myr are *greater* than the comparable field star samples (3/18 vs. 2/41 and 5/20 vs. 4/42, respectively), the results are formally consistent with each other. This suggests that there is no strong dependence of debris disk evolution on star-forming environment, although larger samples could reveal a difference.

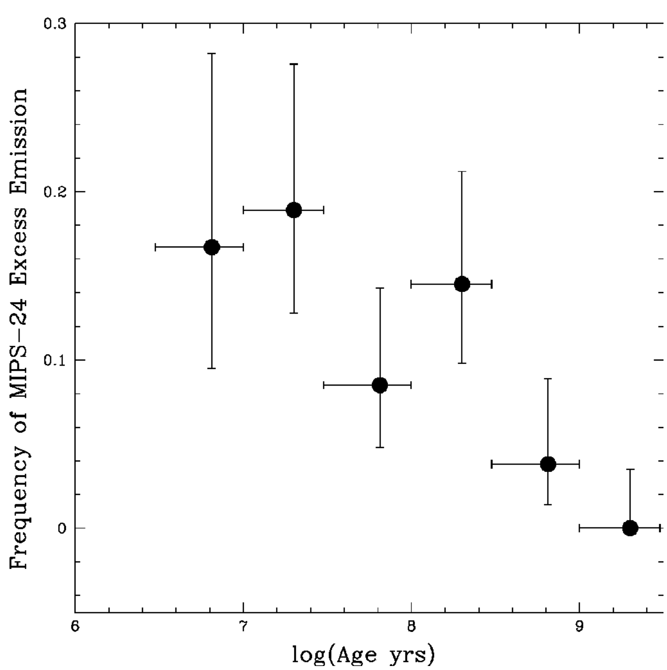

FIG. 2.—Fraction of stars in the sample with detectable 24 μm excess plotted as a function of age.

A key question is whether stars observed to have excess at 24 μm in one age bin are the same cohort of stars with 24 μm excess in another. In other words, do the same 10%–20% of Sun-like stars with excess evolve from one age bin to the next with a constant fraction, or are they distinct groups of stars that persist in the observed state for a short time? Our observations trace excess emission from 21.7 to 26.4 μm toward stars lacking excess emission ≤ 10 μm (corresponding to a lack of dust-generating planetesimals inside 1 AU; Silverstone et al. 2006). Assuming blackbody emission from large grains implies dust at radii from ~4 to 7 AU. Maximum dust production during the evolution of a planetesimal swarm is thought to occur between runaway and chaotic growth when the largest planetesimals reach ~2000 km at a given radius (Kenyon & Bromley 2004, 2006). The timescale for this goes as $\tau \sim a^{1.5}\sigma_{\rm disk}^{-1}$, where a is the orbital radius and $\sigma_{\rm disk}$ is the mass surface density of solids in the disk (Goldreich et al. 2004). Assuming $\sigma_{\rm disk} \sim \sigma_0 a^{-p}$, and that $0 < p < 1$ (Kitamura et al. 2002), a range of a factor of 2 in radius corresponds to a factor of 3–6 in time. Thus the emission we observe might not persist over timescales much larger than our age bins.[12] Perhaps many stars go through this phase of 24 μm excess, but at different times. A range of a factor of 100 in initial mass surface density (Andrews & Williams 2005) could translate into a range of a factor of 100 in evolutionary timescales. If so, one might expect smaller excesses at later times (produced by lower mass disks). In comparing the mean detected excess for stars 3–30 Myr old (0.359 with $\sigma = 0.199$) with that for stars 30–300 Myr old (0.345 with $\sigma = 0.116$), we find no evidence that this is the case (although the samples are dominated by stars lacking detectable excess). Nevertheless, one might consider *summing* the fractions of stars with 24 μm excess between 3 and 300 Myr, resulting in an overall fraction of stars with evidence for terrestrial planet formation greater than 60%! Averaging the results over factors of 10 in age results in excess fractions of 18%, 12%, and 2% at ages 3–30 Myr, 30–300 Myr, and 0.3–3 Gyr, implying at least 32% of Sun-like stars exhibit evidence for terrestrial planet formation (provided that the epoch of 24 μm excess emission lasts $\leq$ a factor of 10 in age). We note that in this scenario, the planets formed later from lower mass disks will be smaller (Kenyon & Bromley 2006).

Results to date suggest that (1) primordial disks between 0.3 and 3 AU dissipate or agglomerate into larger bodies on timescales comparable to the cessation of accretion (Haisch et al. 2001), and (2) few stars harbor optically thin inner disks between 3 and 30 Myr (Silverstone et al. 2006). Based on theoretical considerations, we expect that planetesimals belts evolved rapidly within 3 AU. Rieke et al. (2005) explore the evolution of 24 μm excess emission around a sample of A stars observed with *Spitzer* and *IRAS*. They deduce a characteristic timescale of 150 Myr for strong excesses to decay. However, care must be taken in comparing these results to ours as (1) the dust masses detected by Rieke et al. are likely *larger* than the dust masses detected here, and (2) similar temperature dust traces distinct radii for stars of different luminosity. In general, the fractional 24 μm excesses around A stars are larger than around G stars. The observed duration of the excess phase for both samples is longer than expected if the emission results solely from dust production well inside 10 AU. An important caveat to our results is that we have not assessed whether the 24 μm excesses we have detected are tracing warm dust in the terrestrial planet zone, or the Wien side of the Planck function from cooler dust. If, at 24 μm, we are seeing cooler dust generated at radii beyond 10 AU, we would expect to observe it at later times. We also note that the maximum excess ratios predicted by Kenyon & Bromley are larger than the excesses detected here.

Wyatt et al. (2007) provide steady-state models of warm dust production around Sun-like stars. On the basis of comparing the observed IR luminosity of several systems to these models as a function of age, they conclude that most (5/8) of the stars exhibiting evidence for warm dust must be in a transient state of evolution and not participating in a steady-state collisional cascade. However, the three systems with ages < 300 Myr (one of which is HD 12039) can be explained with equilibrium models. Global analysis of the SED for all sources identified here will be required to directly compare the evolutionary state of these systems with the models (J. M. Carpenter et al., in preparation).

More work is needed to define the transition from primordial to debris disk (e.g., Padgett et al. 2006). Given the short time expected for collisional evolution of inner planetesimals belts (< 3 Myr), and the 1–10 Myr lifetime of primordial disks, it may be difficult to detect the onset of collisional evolution. We suggest that *Spitzer* observations at 24 μm can be interpreted as evidence for terrestrial planet formation occurring around many (19%–32%), if not most (62%), Sun-like stars. This range is higher than the observed frequency of gas giant planets (6.6%–12% within 5–20 AU; Marcy et al. 2005) but comparable to the inference that cool dust debris beyond 10 AU might be very common (Bryden et al. 2006). Radial velocity monitoring of low-mass stars, microlensing surveys, and transit surveys such as *COROT* and *Kepler* will provide critical tests of our interpretation.

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[12] While the published Kenyon & Bromley models predict the duration of 24 μm excess emission greater than a factor of 3–6 in time, they also predict hot dust at smaller radii covering a wider range of radii than our observations imply.

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