Formation and Evolution of Planetary Systems:
Evolution of Mid–IR Excess Around Sun–like Stars

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ABSTRACT

We report observations from the Spitzer Space Telescope concerning the frequency of 24 μm excess emission found toward sun-like stars as part of the FEPS Legacy Science Program. Our sample is comprised of 314 stars with masses 0.7-2.2 Msun with ages from 3 Myr to 3 Gyr. We identify 36 stars that exhibit strong excess emission, five of which are associated with previously known primordial gas-rich disks. The ratios of observed to expected photospheric emission ranges from 1.2–2.0, smaller than predictions from models of collisional evolution of terrestrial planetesimals within 3 AU. We find that the frequency of dust debris emitting at 24 μm (tracing distributions of larger parent body planetesimal belts) ranges from 10–20 % from 3–300 Myr and drops to 2 % for older stars. The results are broadly consistent with previous results based on open cluster studies, models of terrestrial planet formation, and the inferred evolution of our own solar system. These observations suggest that many, perhaps most, sun-like stars exhibit evidence for processes that are believed to lead to terrestrial planet formation.

Subject headings: circumstellar disks; planet formation; planetesimals; dust

1. Introduction

Are planetary systems like our own common or rare in the Milky Way galaxy? The answer to this question depends on what aspect of our planetary system one is comparing against. Gas and dust rich circumstellar disks appear to be a common outcome of the star formation process (Strom et al. 1993). Gas giant planets (presumably formed from these disks) surround between 6-12 % of sun-like stars (Marcy et al. 2005) while direct detection of terrestrial planets remains a distant goal. Much progress has been made in recent years constraining the times available for building gas giant planets from evolutionary studies of gas-rich disk surrounding young stars (Haisch et al. 2001; Pascucci et al. 2006). However, debate concerning the physical mechanism of their formation continues to rage (Durisen et al. 2006; Lissauer & Stevenson, 2006). In contrast, the theory of terrestrial planet formation is relatively mature (Wetherill et al. 1993; Chambers, 2001; Kenyon & Bromley, 2006). Starting with a swarm of 1 km-sized planetesimals, orderly growth of larger bodies proceeds rapidly (0.3-1 Myr) out to at least 2 AU. When the gravitational cross section exceeds the geometrical cross section of the largest bodies, 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.

Ironically, there are few observational tests of this mature 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). Observations of circumstellar dust debris surrounding sun-like stars can be used to trace the presence of planetesimal belts of larger parent bodies (see Meyer et al. 2007 for a recent review). Far-infrared observations with the Spitzer Space Telescope suggest that 10-20 % of sun-like stars possess massive cool outer dust analogous to our Kuiper Belt (Meyer et al. 2004;

Beichman et al. 2005a; Kim et al. 2005; Bryden et al. 2006). Shorter wavelength emission traces hotter material at smaller radii in the terrestrial planet zone. Results to date suggest that: a) primordial disks between 0.3-3 AU dissipate or agglomerate into larger bodies on timescales comparable to the cessation of accretion (Mamajek et al. 2004); and b) few stars harbor optically-thin disks between 3-30 Myr (Silverstone et al. 2006). A few exceptional stars exhibit warm infrared excess indicative of terrestrial temperature material (Beichman et al. 2005b; Hines et al. 2006; Low et al. 1999; Meyer et al. 2001). Recent work with the Spitzer Space Telescope has begun to assess the frequency of this emission as a function of age (Chen et al. 2005; Gorlova et al. 2006; Siegler et al. 2006). In this contribution we use the FEPS database (Meyer et al. 2006) to investigate the frequency of mid-IR excess emission as a function of age. In section 2, we describe the data used, while in section 3, we describe our analysis. Finally in section 4, we discuss our results in light of current understanding concerning the formation of the solar system, theoretical models of terrestrial planet formation, and speculate on the implications concerning planetary system architectures.

2. Observations

Observations were obtained as part of the Formation and Evolution of Planetary Systems (FEPS) Legacy Science Program (Meyer et al. 2006). Our parent sample consistents of 328 "sun-like" stars with spectral types F5-K3 with masses ranging from 0.7-2.2 Msun (though strongly peaked at 1.0 Msun). The initial 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 x3 in age). Stars from 3-100 Myr were largely drawn from young stellar populations within the Local Association, often from kinematically-selected groups of stars as part 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 selected from the HIPARCOS catalogue. Ages for these stars were estimated from calcium H & K emission-line indices which trace stellar activity levels association with rotation (e.g. Soderblom et al. 1993). A fraction of our sample in the age range from 30 Myr to 1 Gyr were selected to be members of open clusters of known ages (e.g. Stauffer et al. 2005). The ages of these stars are more secure than the other age estimates. Details concerning our sample selection are described in Meyer et al. (2006) and details concerning the age estimates for each star are given in Hillenbrand et al. (in prep). We fit Kurucz model atmospheres to B/V (Tycho) photometry from HIPPARCOS and JHK photometry from 2MASS. We assumed solar metalicity and surface gravities appropriate for each star, performing a non-linear least squares fit for temperature, solid angle (radius/distance), and extinction. For stars within 50 pc, we assumed Av=0.

Photometry at 8 microns was derived from sub–array observations with the IRAC instrument (Fazio et al. 2004). We began with SSC pipeline data S13. Cosmic ray rejection was implemented and corrections for spatially-dependent pixel area and filter response variations were applied. Aperture photometry was derived from a modified version of IDLPHOT and placed on the standard flux scale recommended by Reach et al. (2005). Residual calibration errors are estimated to be less than 2 % in each band. Photometric uncertainties were estimated from the photometric repeatability from 64 observations obtained at each dither position for each source resulting in minimum uncertainties of less than 1 % for IRAC8. See Carpenter et al. 2007 for further details.

Photometry at 24 microns was derived from either 28 or 56 exposures with integration times of 3 or 10 seconds each with the MIPS instrument (Rieke et al. 2004). We began with

SSC S13 pipeline data and photometry was derived using the MOPEX software (provided through the SSC). Fluxes were estimated from a PSF–fitting algorithm and placed on a flux scale recommended by the SSC. Calibration errors are thought to be less than 4 % (cf. Engelbracht et al. 2006). Mean fluxes are reported and the error in the mean was judged to be a good estimate of the uncertainty. The minimum errors in the 24 micron photometry are less than 1 %. Carpenter et al. (2007) report systematic offsets < 3 % in MIPS24 fluxes derived from 3 second versus 10 second exposures, as well as offsets < 4 % in MIPS24/IRAC8 flux ratios as a function of IRAC frametime (after MIPS24 exposure–time dependent offsets are corrected). We do not apply those corrections here. A more detailed analysis of these data appears in Carpenter et al. (2007). All photometry and model atmospheric fits used in this study are available through the Spitzer Legacy Science archive reported through the FEPS public data release 4 (Hines et al. 2005; see also Carpenter et al. 2007).

3. Analysis

We begin with the unbiased FEPS sample of 314 stars spanning a range of ages from 3 Myr year to beyond 1 Gyr selected without regard to whether they may or may not possess a circumstellar disk. We use the MIPS24/IRAC8 flux ratio diagram to search for stars that exhibit infrared excess emission. These data are plotted in Figure 1 as a function of IRAC8 source brightness. Note that the brighter sources tend to be nearby (older) field stars, while the fainter targets tend to be distant (younger) sources. Several sources exhibit an excess in this flux ratio diagram indicative of a MIPS24 excess. The vast majority of the stars in our sample lack excess emission in the IRAC bands out to 8 μm and the expected photospheric ratio in this diagram based on Kurucz model atmospheres is approximately 0.1. In order to define an emperical “blue envelope” of stars that lack excess that will enable us to identify sources with true excess emission, we employ a sigma–clipping algorithm to the distribution of MIPS24/IRAC8 flux ratios. Initially, the mean flux ratio was computed to be 0.121 with $\sigma = 0.85$, and two outliers exhibiting ratios beyond 3σ (thus real excesses). For a sample of 314 sources, we expect approximately 1 source to lie beyond 3σ from the mean if the distribution is gaussian (which the marginal y–distribution in Figure 1 is decidedly not). 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 six times, the mean and sigma converge with a mean of 0.117 with $\sigma = 0.004$ as shown in Figure 1. We identify 36 (positive) outliers which we attribute to excess emission in the MIPS24 band. These sources are listed in Table 1.

Of these 36 stars, five possess optically–thick disks identified in Silverstone et al. (2006) which are likely gas–rich primordial disks (see also Bouwman et al. 2007). Because we are most interested in understanding the transition to debris disks at 24 μm we remove these five from the sample of excess stars under consideration here. In Figure 2, we plot the ratio of the observed 24 μm emission to that expected from the photospheric model fits described above as a function of stellar age. For those sources that lack excess emission as identified above, we computed the mean (1.11) and RMS (0.07) for the sample of 278 sources. This mean and "3–σ" limit is also shown in Figure 2. This offset between the models and the observations could be explained through a systematic error in calibration, in our model fitting procedure, or the models themselves. Emperically, it appears that there is a trend in the offset with age. Because the older stars in our sample tend to be the nearest and brightest stars, this could be a flux–dependent offset. On the other hand, the younger targets tend to be slightly cooler, and lower surface gravity stars as many stars younger than 100 Myr are still pre–main sequence, which could contribute to the model offsets. The dispersion also appears to be larger for the younger sources. Because we fit the entire dataset with a constant ratio, we are likely missing older sources with smaller excesses relative to the photosphere, and (possibly) identifying a few young stars spuriously with excess. More refined analysis, including comparison of the IRS data available for these sources, suggest that the vast majority of these excesses identified are real (Carpenter et al. 2007). The magnitude of the observed excesses range from 20 % of the expected photospheric value for the smallest excesses identified to roughly twice the expected flux. HD 61005, recently resolved by HST in scattered light (Hines et al. 2007), has one of the largest excess values (ratio = 2.3) at an age of 30–100 Myr. HD 38207 has a slightly larger excess (ratio = 2.4) at an age of 100–300 Myr. The oldest source (1–3 Gyr) exhibiting 24 μm excess is HD 85301 (ratio = 1.4).

In Figure 3, 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 are computed using Poisson statistics with samples ranging from 46–66 stars per bin except for the 3–10 Myr bin which only has 30 stars. The fraction of stars exhibiting 24 μm excess emission ranging from 10–20 % at ages of 3 Myr to 300 Myr. This fraction drops to 2 % for ages 300 Myr through 3 Gyr.

4. The Discussion

Our main result is that 3-300 Myr appears to be the preferred epoch for the generation of 24 micron debris excess around sun-like stars. Further the magnitude of excesses observed ranges from facotrs of 1.2 – 2 compared to the expected stellar emission. Similar results, drawn from similar ranges of detectable excesses, have been reported by the MIPS Instrument Team using Spitzer to study samples of young FGK stars based on surveys of stars in open clusters (Stauffer et al. 2005; Gorlova et al. 2006; Siegler et al. 2006), as well as old nearby field stars (Bryden et al. 2006). Our sample contains a mix of open cluster and field stars at all ages suggesting that these results do not depend strongly on star–forming environment.

Studies of extinct radio-active nuclides suggest that the Earth-Moon system was formed about 30 Myr after the formation of the Sun (e.g. Kleine et al. 2002). This is also consistent with numerical models of terrestrial planet formation (Wetherill et al. 1993; Chambers et al. 2001). One interesting question is whether the stars observed to have strong excess at 24 microns from 10-30 Myr are the same types of stars that exhibit 24 micron excess between 30-100 Myr. 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 (with 24 μm excess) for a short time, but exhibiting this behavior at different times? Perhaps many stars go through this phase of 24 micron excess indicative of a collisional planetesimal swarm evolution from inside out, but at different times. If so, then one might consider *summing* the fractions of stars with 24 micron excess between 3-300 Myr, resulting in an overall fraction of stars with evidence for terrestrial planet formation greater than 50 %!

Based on theoretical considerations, we expect that planetesimals belts evolved rapidly in the inner solar system. During or very shortly after gas disk dissipation (1-10 Myr; e.g. Pascucci et al. 2006) orderly growth transitions to runaway growth in an era of maximum dust production (Kenyon and Bromley 2004; 2006). Evolution inside of 3 AU should be done within 1-3 Myr. Yet we have not yet assessed whether the 24 μm excess we are tracing is confined to warm dust in the terrestrial planet zone, or is also tracing the Wein–side of the Planck function from cooler dust. We note that many of the objects identified in Table 1, also possess 70 μm excess emission (Hillenbrand et al. 2007). Yet even some of these exhibit evidence for an extended debris disk with dust at a range of temperatures. Future work will focus on constraining the temperature of the dust detected here, as well as comparison to models that explore dust production over a wide range of orbital radii. We also note that the magnitude of the excesses predicted by Kenyon and Bromley are much larger (factors of several, including emission that can be optically–thick) than the excesses observed here (factors of 1.2–2.0).

Rieke et al. (2005; see also Su et al. 2006) explore the evolution of 24 μm excess emission around a sample of A stars observed with Spitzer and IRAS. We note that because both our survey and that of Rieke et al. rely on color selection compared to expected stellar photospheric emission, the same excess threshold (e.g. 20 %) around more (less) luminous stars are sensitive to greater (smaller) amounts of dust. Thus the dust masses detected by Rieke et al. around the A star sample are *larger* than the dust masses detected here around sun–like stars. In addition, when comparing surveys around stars of different luminosity, the same wavelength (tracing the same temperature dust) is tracing different radii. Rieke et al. (2005) observe a characteristic timescale of 180 Myr for most of the strongest excesses around A stars to decay. The observed timescales for both A stars and G stars are much longer (x10) than the those expected for the rapid formation of the first swarm of planetesimals and dust production (1-3 Myr) according to Kenyon and Bromley (2006). However, as noted above, we may also be seeing the Wein–tail of emission from cooler dust generated at radii between 3–20 AU which will peak at later times.

More work is needed to define the the transition from primordial to debris disk. 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. Further, collisional models of planetesimals belts are only now beginning to consider the effects of gas giant planets on the evolution of the planetesimals swarm. Bottke et al. (2005) point to the formation of Jupiter at 3 Myr as a driving force in early sculpting of the asteroid belt. Radial velocity monitoring of low mass stars, microlensing surveys, as well as space–based transit surveys such as COROT and Kepler, will provide a critical test of whether our ascertion that Spitzer observations provide evidence that processes leading to terresetrial planet formation are common around sun–like stars is correct.

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Fig. 1.— MIPS24/IRAC8 flux ratio plotted as a function of IRAC8 flux for 314 stars drawn from the unbiased FEPS sample. After running six iterative sigma-clipping (3σ) algorithms, the mean of the sample converged to a value of MIPS24/IRAC = 0.117 with final variance characterized by $\sigma = 0.004$. This mean (solid line) and 3σ limits (dashed lines) are show. We identify 36 sources with strong MIPS24 excess that lie above our conservative limit for detection from this analysis.

Fig. 2.— The observed MIPS24 micron flux divided by the expected photospheric flux at 24 μm plotted as a function of stellar age for the 309 stars remaining in our sample after the optically–thick disks from Silverstone et al. (2006) are removed, 31 of which exhibit strong excess emission in Figure 1. From the 278 sources that lack excess, we show the mean ratio (1.11) of observed to photospheric flux (solid line) as well as the 3σ limit (dashed line) from the dispersion ($\sigma = 0.07$) of this ratio.

Fig. 3.— The fraction of stars in the sample exhibiting strong MIPS24 excess plotted as a function of age. Data are binned logarithmically in age from 3–10, 10–30, 30–100, 100–300, 300–1000 Myr, and ages $>$ 1000 Myr. At least 10–20 % of sun–like stars exhibit evidence for processes that are consistent with the formation of terrestrial planets between 3–300 Myr.