# Evolution of Circumstellar Disks Around Normal Stars: Placing Our Solar System in Context

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Over the past 10 years abundant evidence has emerged that many (if not all) stars are born with circumstellar disks. Understanding the evolution of post–accretion disks can provide strong constraints on theories of planet formation and evolution. In this review, we focus on developments in understanding: a) the evolution of the gas and dust content of circumstellar disks based on observational surveys, highlighting new results from the Spitzer Space Telescope; b) the physical properties of specific systems as a means to interpret the survey results; c) theoretical models used to explain the observations; d) an evolutionary model of our own solar system for comparison to the observations of debris disks around other stars; and e) how these new results impact our assessment of whether systems like our own are common or rare compared to the ensemble of normal stars in the disk of the Milky Way.

## 1. Introduction

At the original Protostars and Planets conference in 1978, the existence of circumstellar disks around sun–like stars was in doubt, with most researchers preferring the hypothesis that young stellar objects were surrounding by spherical shells of material unlike the solar nebula thought to give rise to the solar system (*Rydgren et al.*, 1978). By the time of Protostars and Planets II, experts in the field had accepted that young stars were surrounded by circumstellar disks though the evidence was largely circumstantial (*Harvey*, 1985). At that meeting, Fred Gillett and members of the IRAS team announced details of newly discovered debris disks, initially observed as part of the calibration program (*Aumann et al.*, 1984). At PPIII, it was well–established that many stars are born with circumstellar accretion disks (*Strom et al.*, 1993) and at PPIV, it was recognized that many of these disks must give rise to planetary systems (*Marcy et al.*, 2000). Over the last 15 years, debris disks have been recognized as playing an important role in helping us understand the formation and evolution of planetary systems (*Backman and Paresce*, 1993; *Lagrange et al.*, 2000; see also *Zuckerman*, 2001). After PPIV, several questions remained. How do debris disks evolve around sun–like stars? When do gas–rich disks transition to debris disks? Can we infer the presence of extra–solar planets from spectral energy distributions (SEDs) and/or resolved disk morphology? Is there any connection between debris disks and the radial velocity planets? Is there evidence for differences in disk evolution as a function of stellar mass?

In answering these questions, our objective is no less than to understand the formation and evolution of planetary systems through observations of the gas and dust content of circumstellar material surrounding stars as a function of stellar age. By observing how disks dissipate from the post–accretion phase through the planet building phase we can hope to constrain theories of planet formation (cf. *Boss et al.* and *Lissauer et al.* this volume). By observing how debris disks generate dust at late times and comparing those observations with physical models of planetary system dynamics, we can infer the diversity of solar system architectures as well as attempt to understand how they evolve with time.

Today, we marvel at the wealth of results from the Spitzer Space Telescope and high contrast images of spectacular individual systems. Detection statistics that were very uncertain with IRAS and ISO sensitivity now can be compared with models of planetary system evolution, placing our solar system in context. Advances in planetary system dynamical theory, the discovery and characterization of the Kuiper Belt (see *Chiang et al.*, this volume) have proceeded in parallel and further contribute to our understanding of extrasolar planetary systems. We attempt to compare current observations of disks surrounding other stars to our current understanding of solar system evolution. Our ultimate goal is to understand whether or not solar systems like our own are common or rare among stars in the disk of the Milky Way and what implications this might have on the frequency of terrestrial planets that might give rise to life.

Our plan for this contribution is as follows. In section 2, we describe recent results from observational surveys for gas and dust surrounding normal stars. Next we describe detailed studies of individual objects in section 3. In section 4, we review modeling approaches used in constraining physical properties of disks from the observations. Section 5 describes a toy model for the evolution of our solar system which we use to compare to the ensemble of observations. Finally, in section 6 we attempt to address whether or not planetary systems like our own are common or rare in the Milky Way galaxy and summarize our conclusions.

## 2. Evolution of Circumstellar Disks

In order to study the evolution of circumstellar disks astronomers are forced to observe sun–like stars at a variety of ages, in an attempt to create a history, hoping that on average, a younger population of similar mass stars can be assumed to be the evolutionary precursors of the older. Although deriving ages of stars across the H–R diagram is fraught with uncertainty (e.g. *Stauffer et al.*, 2004) it is a necessary step in studies of disk evolution. Such studies, combined with knowledge of our own solar system, are the only observational tools at our disposal for constraining theories of planet formation.

### 2.1. Statistics from Dust Surveys

#### *2.1.1. Circumstellar Dust within 10 AU*

Nearly all stars are thought to be born with circumstellar disks (*Beckwith and Sargent*, 1996; *Hillenbrand et al.*, 1998) and recent work has shown that these disks dissipate on timescales of order 3 Myr (*Haisch et al.*, 2001). However, these results are based largely on the presence of near–infrared excess emission which only traces optically–thick hot dust within 0.1 AU of the central star. Indeed the presence of an inner disk appears to correlate with the presence or absence of spectroscopic signatures of active accretion onto the star (*Hartigan et al.*, 1995; see also *Bouvier et al.*, this volume). As active disk accretion diminishes (*Hartmann et al.*, 1998), the fraction of young stars in clusters that show evidence for optically–thick inner disks diminishes. Yet what is often overlooked is that the very data that suggest a typical inner disk lifetime of $\sim$ 3 Myr, also *suggests a dispersion of inner disk lifetimes from 1–10 Myr* (*Hillenbrand*, 2006).

What has remained unclear until recently is how these primordial disks left over from the formation of the young star dissipate at larger radii and whether the termination of accretion represents an end of the gas–rich phase of the circumstellar disk. Even at the time of PPIII, it was recognized that young stars (with ages $<$ 3 Myr) lacking optically–thick near–infrared excess emission but possessing optically–thick mid–infrared emission were rare (*Skrutskie et al.*, 1990). This suggested that the transition time between optically–thick and thin from $<$ 0.1 AU to $>$ 3 AU was rapid, $<<$ 1 Myr (*Wolk and Walter*, 1996; *Kenyon and Hartmann*, 1995; *Simon and Prato*, 1995).

It is important to distinguish between surveys for primordial disks, gas and dust rich disks left over from the star formation process, and debris disks, where the opacity we see is dominated by grains released through collisions of larger parent bodies. Often this distinction is made based on whether remnant gas is left in the system. With a gas to dust ratio $>$ 0.1, dust dynamics are controlled by their interaction with the gas (*Takeuchi and Artymowicz*, 2001). In the absence of gas, one can argue based on the short dust lifetimes that observed dust is likely recently generated through collisions in a planetesimal belt (*Backman and Paresce*, 1993; *Jura et al.*, 1998). Observations that constrain evolution of the gas content in disks are described below.

Recent work has shown that even optically–thin mid–infrared emission (tracing material between 0.3–3 AU) is rare around sun–like stars with ages 10–30 Myr. *Mamajek et al.* (2004) performed a survey for excess emission around sun–like stars in the 30 Myr old Tucana–Horologium association and found no evidence for excess within a sample of 20 stars down to dust levels $< 3 \times 10^{-6}$ $M_{earth}$ for warm dust in micron–sized grains. Similar studies by *Weinberger et al.* (2004) of stars in the $\beta$ Pic moving group as well as TW Hya association (both $\sim$ 10 Myr old) uncovered only a handful of stars with mid–infrared excess emission. These results are being confirmed with cluster studies undertaken with the Spitzer Space telescope. As part of the *Formation and Evolution of Planetary Systems* (FEPS) Legacy Science Program (*Meyer et al.*, 2006) a survey has been conducted searching for warm dust at wavelengths from 3.6–8.0 $\mu$m around 74 sun–like stars with ages 3–30 Myr. Silverstone et al. (2006) reported only five detections from this survey and all of those were rare examples of long–lived optically–thick disks. *It appears that circumstellar disk material between 0.1–1 AU typically drops below detectable levels on timescales comparable to the cessation of accretion.* These levels are probably below what our solar system might have looked like at comparable ages (3–30 Myr).

However, Spitzer is uncovering a new population of transitional disks at mid–infrared wavelengths in the course of several young cluster surveys (*Forrest et al.*, 2004; *Calvet et al.*, 2005; *Allen et al.*, this volume). *Chen et al.* (2005) find that $\sim$ 30 % of sun–like stars in the subgroups of the 5–20 Myr Sco Cen OB association exhibit 24 $\mu$m excess emission, higher than that found by *Silverstone et al.* (2006) at shorter wavelengths. *Low et al.* (2005) find examples of mid–IR excess at 24 $\mu$m in the 10 Myr TW Hya association. The 24 $\mu$m emission is thought to trace material $>$ 1 AU, larger radii than the material traced by emission from 3–10

$\mu$m. Preliminary results from the FEPS program suggests that there is some evolution in the fraction of sun–like stars with 24 $\mu$m excess (but no excess in the IRAC bands) from 3–300 Myr. This brackets major events in our own solar system evolution with the terrestrial planets thought to have mostly formed $<$30 Myr and the late heavy bombardment at $>$300 Myr (see section 5).

It is interesting to note that there is now a small (5 member) class of debris disks with only strong mid–infrared excess and weak or absent far–IR/sub–mm excess emission: BD +20 307 at $>$300 Myr age (*Song et al.*, 2005), HD 69830 at $\sim$2 Gyr age (*Beichman et al.*, 2005), HD 12039 at 30 Myr (*Hines et al.*, 2006), HD 113766 at 15 Myr (*Chen et al.*, 2005), and HD 98800 at 10 Myr (*Low et al.*, 1999; *Koerner et al.*, 2000). In the two older systems, BD +20 307 and HD 69830, this excess is almost entirely silicate emission from small grains. These systems are rare, only 1–3 % of all systems surveyed. Whether they represent a short–lived transient phase that all stars go through, or a rare class of massive warm debris disks is not yet clear (section 4.4).

#### 2.1.2. *Circumstellar Disks at Radii $>$ 10 AU*

Surveys at far–infrared ($>$ 30 $\mu$m) and sub–millimeter wavelengths trace the coolest dust at large radii. Often, this emission is optically–thin and is therefore a good tracer of total dust mass at radii $>$ 10 AU. Early surveys utilizing the IRAS satellite focused on large optically–thick disks and envelopes surrounding young stellar objects within 200 pc, the distance of most star–forming regions (*Strom et al.*, 1993), and main sequence stars within 15 parsecs because of limitations in sensitivity (*Backman and Paresce*, 1993). Sub–millimeter work suggested that massive circumstellar disks appeared to dissipate within 10 Myr (*Beckwith et al.*, 1990; see also *Andrews and Williams*, 2005). Sub–millimeter surveys of field stars indicated that "typical" sub–millimeter emission from dust surrounding main sequence stars diminished as $t^{-2}$ (*Zuckerman and Becklin*, 1993).

Several new far–infrared studies were initiated with the launch of the Infrared Space Observatory (ISO) by ESA and the advent of the sub–millimeter detector SCUBA on the JCMT. *Meyer and Beckwith* (2000) describe surveys of young clusters with the ISOPHOT instrument on ISO which indicated that far–infrared emission became optically–thin on timescales comparable to the cessation of accretion (about 10 Myr). *Habing et al.* (1999, 2001) suggested that there was another discontinuity in the evolutionary properties of debris disks surrounding isolated A stars at an age of approximately 400 Myr. *Spangler et al.* (2001) conducted a large survey including both clusters and field stars finding that dust mass diminished at $t^{-1.8}$ as if the dust removal mechanism was P–R drag (see section 4 below). Based on the data available at the time, and limitations in sensitivity from ISO, it was unclear how to reconcile these disparate conclusions based on comparable datasets. For a small sample of sun–like stars, *Decin et al.* (2003) found that 10–20 % (5/33) of Milky Way G stars, regardless of their age, have debris disks, comparable to results obtained previously for A stars (*Lagrange et al.*, 2000).

Recent work with the Spitzer Space Telescope offers a new perspective. From the FEPS program, surveys for cold debris disks surrounding G stars have led to several new discoveries (*Meyer et al.*, 2004; *Kim et al.*, 2005; *Hillenbrand et al.*, in preparation). Over 40 debris disk candidates have been identified from a survey of 328 stars and no strong correlation of cold dust mass with stellar age has been found. *Bryden et al.* (2006; see also *Beichman et al.*, 2005) have completed a volume–limited survey of nearby sun–like stars with probable ages between 1–3 Gyr old. Overall the Spitzer statistics suggest a cold debris disk frequency of 10–20 % surrounding sun–like stars with a weak dependence on stellar age (Fig. 1). It should be noted that our own solar system cold dust mass would be undetectable in these surveys and it is still difficult to assess the mean and dispersion in cold disk properties based on the distribution of upper limits.

Sub–millimeter surveys of dust mass probe the coldest dust presumably at the larger radii. *Wyatt et al.* (2003) report observations of the Lindroos binary sample (see also *Jewitt et al.*, 1994) indicating a lifetime of 10–60 Myr for the massive primordial disk phase. *Carpenter et al.* (2005; see also *Liu et al.*, 2004), combined these data with a new survey from the FEPS sample and found that the distribution of dust masses (and upper limits) from 1–3 Myrs is distinguished (with higher masses) than that found in the 10–30 Myr old sample at the 5 $\sigma$ level (Fig 1). The data do not permit such a strong statement concerning the intermediate age 3–10 Myr sample. *Greaves et al.* (2003) found a dispersion in disk masses and lifetimes, arguing for a typical timescale of 0.5 Gyr for transient disk dissipation, which can occur throughout the lifetime of the star. *Najita and Williams* (2005) conducted a detailed study of $\sim$ 15 individual objects and find that debris disks do not become colder (indicating larger radii for the debris) as they get older surrounding sun–like stars in contrast to the predictions of *Kenyon and Bromley* (2004). Again we note that these surveys would not detect the sub-mm emission from our own Kuiper Debris Belt (see section 5 below). In contrast, *Greaves et al.* (2004) point out that the familiar tau Ceti is 30 times more massive than our solar system debris disk, even at comparable ages. *Greaves, Fischer & Wyatt* (2006) studied the metallicities of debris disk host stars showing that their distribution is indistinguishable from that of field stars in contrast to the exoplanet host stars which are metal-rich (*Fischer and Valenti*, 2005). Implications of the detected debris disk dust masses and their expected evolution is discussed in section 4 and compared to the evolution of our solar system in section 5.

The picture that emerges is complex as illustrated in Fig. 1. In general, we observe diminished cold dust mass with time as expected from models of the collisional evolution of debris belts (see section 4). However, at any one age there is a wide dispersion of disk masses. Whether this dispersion represents a range of initial conditions in disk mass, a range of possible evolutionary paths, or is evidence that many disks pass through short–lived phases of enhanced dust production is unclear. One model for the evolution of our solar system suggests a rapid decrease in observed dust mass associated with the dynamic rearrangement of the solar system at 700 Myr (and decrease in the mass of colliding parent bodies by $\times$ 10). If that model is correct, we would infer that our solar system was an uncommonly bright debris disk at early times, and uncommonly faint at late times (see section 6).

### 2.2. Statistics from Gas Surveys

While most energy is focused on interpreting dust observations in disks, it is the gas that dominates the mass of primordial disks and is the material responsible for the formation of giant planets. Observational evidence for the dissipation of gas in primordial disks surrounding young sun–like stars is scant. Millimeter wave surveys (*Dutrey et al.*, this volume) are on–going and confirm the basic results: 1) classical T Tauri stars with excess emission from the near–IR through the sub–millimeter are gas rich disks with some evidence for Keplerian support; and 2) complex chemistry and gas–grain interactions affect the observed molecular abundances. In a pioneering paper, *Zuckerman et al.* (1995) suggested that gas rich disks dissipate within 10 Myr. Recent work on disk accretion rates of material falling ballistically from the inner disk onto the star by *Muzerolle et al.* (2003) could be interpreted as indicating gas–rich primordial disks typically dissipate on timescales of 3–10 Myr. Other approaches include observations of warm molecular gas through near–infrared spectroscopy (see *Najita et al.*, this volume), UV absorption line spectroscopy of cold gas for favorably oriented objects (see next section), and mm–wave surveys for cold gas in remnant disks. One debris disk that showed evidence for gas in the early work of *Zuckerman et al.* (1995), the A star 49 Ceti, was recently confirmed to have CO emission by *Dent and Coulson* (2005). Transient absorption lines of atomic gas with abundances enhanced in refractory species would suggest the recent accretion of comet–like material (*Natta et al.*, 2000).

Since most of the mass in molecular clouds, and presumably in circumstellar disks from which giant planets form is molecular hydrogen, it would be particularly valuable to constrain the mass in $H_2$ directly from observations. ISO provided tantalizing detections of warm $H_2$ at 12.3, 17.0, and 28.2 $\mu$m tracing gas from 50–200 K in both primordial and debris disks (*Thi et al.*, 2001a, 2001b). However follow–up observations with high resolution spectroscopic observations (with a much smaller beam–size) have failed to confirm some of these observations (*Richter et al.*, 2002; Sheret et al., 2003). Several surveys for warm molecular gas are underway with the Spitzer Space Telescope. *Gorti and Hollenbach* (2004) present a series of models for gas rich disks with various gas to dust ratios. The initial stages of grain growth in planet forming disks, the subsequent dissipation of the primordial gas disk, and the onset of dust production in a debris disk suggest a wide range of observable gas to dust ratios (see *Dullemond et al.*, this volume). *Hollenbach et al.* (2005) placed upper limits of 0.1 $M_{JUP}$ to the gas content of the debris disk associated with HD 105, a 30 Myr old sun–like star observed as part of the FEPS project. *Pascucci et al.* (2006) have presented initial results for a survey finding no gas surrounding 20 stars with ages from 3–100 Myr at levels comparable to HD 105. Either these systems have already formed extra–solar giant planets, or they never will. Future work will concentrate on a larger sample of younger systems with ages 1–10 Myr in order to place stronger constraints on the timescale available to form gas giant planets.

## 3. Physical Properties of Individual Systems

An observational goal is to understand the composition and structure of debris disks. Presumably, the dust (see section 4.1) reflects the composition of the parent planetesimal populations, so measuring the elemental composition, organic fraction, ice fraction, and ratio of amorphous to crystalline silicates provides information on the thermal and coagulation history of the small bodies. These small bodies are not only the building blocks of any larger planets, they are also an important reservoir for delivering volatiles to terrestrial planets (e.g. *Raymond et al.*, 2004). Additionally, the grain size distribution reflects the collisional state of the disk (see section 4.1). The structure of the disk may reflect the current distribution of planetesimals and therefore the system's planetary architecture (see section 5).

The literature on resolved images of circumstellar disks begins with the pioneering observations of $\beta$ Pic by *Smith and Terrile* (1984). Since PPIV, there has been a significant increase in spatially resolved information on debris disks in two regimes – scattering and emission. Resolving scattered visual to near-infrared light requires high contrast imaging such as that delivered by HST, because the amount of scattered light is at most 0.5% of the light from the star. Resolving thermal emission requires a large aperture telescope because dust is warm closer to the star and so disks appear quite small in the infrared.

Compositional information is obtained from scattered light albedos and colors, from mid-infrared spectroscopy that reveals solid-state features, and from fitting the slopes observed in spectral energy distributions. Resolved imaging breaks degeneracies in the fits and can be used to investigate changes in composition with location. Structural information is best at the highest spatial resolution and includes observations of warps, rings, non-axisymmetric structures, and offset centers of symmetry.

Sensitivity to grain size depends on wavelength and each regime provides information on grains within approximately a range of 0.1-10 times the wavelength (Fig. 2). For example, scattered visible and near-infrared light mostly probes grains smaller than 2 $\mu$m and submillimeter emission mostly probes grains $>$ 100 $\mu$m in size.

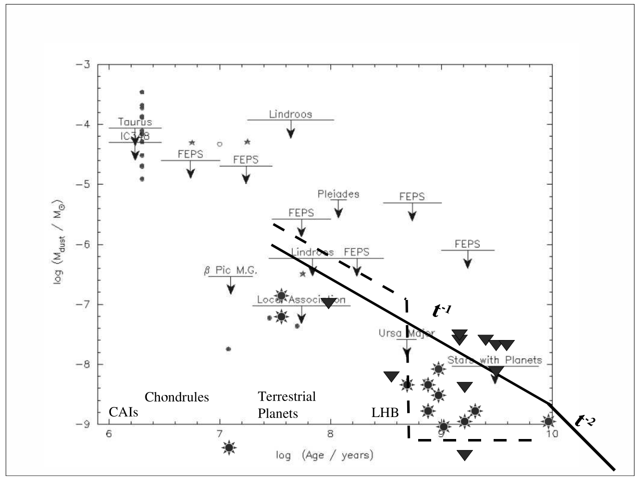


Fig. 1.— Evolution of circumstellar dust mass based on sub–mm observations from *Carpenter et al.* (2005). Over–plotted are Spitzer 70 $\mu$m detections from the FEPS program (stars) and upper limits (triangles). Slopes of $t^{-1}$ and $t^{-2}$ are shown as solid lines, along with a toy model for the evolution of our solar system (denoted with a dashed line) indicating an abrupt transition in dust mass associated with the late–heavy bombardment (LHB). Timescales associated with the formation of calcium–aluminum inclusions (CAIs), chondrules, and terrestrial planets are also shown.

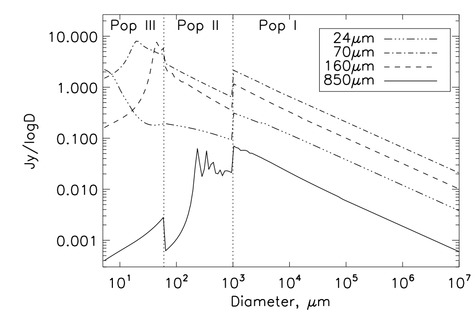


Fig. 2.— Contribution of different grain sizes to the fluxes observed in different wavebands in the Vega disk (*Wyatt*, 2006). The units of the y–axis are flux per log particle diameter so that the area under the curve indicates the contribution of different sized particles to the total flux for a given wavelength. The different wavebands probe different ranges in the size distribution and so are predicted to see very different structures.

### 3.1. Debris Disks Resolved in Scattered Light

The number of debris disks resolved in scattered light has increased from one at the time of PPIII ($\beta$ Pic) to two at the time of PPIV (HR 4796) to about 10 today (see Table 1). A detection of 55 Cnc reported in PPIV seems to be spurious (*Schneider et al.*, 2001; *Jayawardhana et al.*, 2002), and HD 141569 is not gas-free (*Jonkheid et al.*, 2005) and therefore is not counted here as a debris disk.

The scattered light colors are now known for six debris disks (see Table 1). In many of these an asymmetry factor (g) has also been measured; larger grains are generally more forward-scattering. For disks in which the mid-infrared emission has also been resolved, the amount of scattered light compared to the mid-infrared emission from the same physical areas enables a calculation of the albedo (albedo = Qsca/(Qsca+Qabs)). The albedo of canonical *Draine and Lee* (1984) astronomical silicates is such that (for 0.5-1.6 $\mu$m observations), grains smaller than 0.1 micron Rayleigh scatter and are blue, grains larger than 2 $\mu$m scatter neutrally, and grains in between appear slightly red. In the case of a power law distribution of grain sizes, such as that of a collisional cascade (equation 2), the scattering is dominated by the smallest grains. Thus the colors in the Table have been explained by tuning the smallest grain size to give the appropriate color. Rarely has the scattered color been modeled simultaneously with other constraints on similar sized grains such as 8–13 $\mu$m spectra. If observations of scattered light at longer wavelengths continue to show red colors, the fine tuning of the minimum grain size of astronomical silicates will fail to work. More realistic grains may be porous aggregates where the voids may contain ice. Few optical constants for these are currently available in the literature.

### 3.2. Debris Disks Resolved in Sub–mm Emission

Resolved observations from JCMT/SCUBA in the submillimeter at 850 $\mu$m by *Holland et al.* (1998) and *Greaves et al.* (1998) led the way in placing constraints on cold dust morphologies for four disks (Fomalhaut, Vega, $\beta$ Pic, and $\epsilon$ Eri), including rings of dust at Kuiper-belt like distances from stars and resolving clumps and inner holes. Since PPIV, higher spatial resolution images at 350 - 450 $\mu$m revealed additional asymmetries interpreted as indications for planets (*Holland et al.*, 2003; *Greaves et al.*, 2005; *Marsh et al.*, 2005). Perhaps most excitingly, the structure of the disk surrounding $\epsilon$ Eri appears to be rotating about the star. A longer time baseline for the motion of disk clumps will reveal the mass and eccentricity of the planet responsible for their generation (*Greaves et al.*, 2005). Finally, three additional disks – $\tau$ Ceti (*Greaves et al.*, 2004), HD 107146 (*Williams et al.*, 2004), and $\eta$ Corvi (*Wyatt et al.*, 2005), were resolved by JCMT/SCUBA. Interferometric imaging of one debris disk, Vega, allowed the first measurement of structure at a wavelength of 1 mm (*Koerner et al.*, 2001; *Wilner et al.*, 2002). Again, the presence of clumps could be explained by the influence of a planet (*Wyatt*, 2003). It is interesting to note that three A-type stars, with masses up to twice that of the Sun and luminosities up to tens of times higher show dynamical evidence for planets.

### 3.3. Debris Disks Resolved in IR Emission

Ground-based 8 m class telescopes provide the best spatial resolution for imaging disks, but are hampered by low sensitivity – only two debris disks ($\beta$ Pic and HR 4796) are definitively resolved at 12–25 $\mu$m from the ground.

Spitzer, with its ten times smaller aperture is able to resolve only nearby disks. With MIPS, Spitzer has surprised observers with images of $\beta$ Pic, $\epsilon$ Eri, Fomalhaut, and Vega that look quite different from their submillimeter morphologies. If Spitzer's sensitivity picked up the Wien tail of the submillimeter grain emission or if the smaller mid-infrared emitting grains were co-located with their larger progenitor bodies, then the morphologies would be the same. In the case of Fomalhaut, the MIPS 24 $\mu$m flux originates in a Zodiacal-like region closer to the star *and* the planetesimal ring while the 70 $\mu$m flux does indeed trace the ring (*Stapelfeldt et al.*, 2004, and Fig. 3). As for the solar system, there may be separate populations of planetesimals (analogous to the asteroid and Kuiper belts) generating dust.

Surprisingly, however, the 24 and 70 $\mu$m images of Vega actually have larger radii than the submillimeter ring or millimeter clumps (*Su et al.*, 2005). This emission seems to trace small grains ejected by radiation pressure. Vega is only slightly more luminous than Fomalhaut, so the minimum grain size generated in collisions within the disk would have to finely tuned to below the blowout size for Vega and above the blowout size for Fomalhaut for a unified disk model (see equation 3). $\epsilon$ Eri looks about as expected with the 70 $\mu$m emission from the region of the submm ring (*Marengo et al.*, 2006). An inner dust population might be expected if Poynting-Robertson drag is important for the dust dynamics of this system (see section 4). The absence of close-in dust may indicate that it is ejected by the postulated planet. It is also interesting that Spitzer did not resolve any of the other nearby disks imaged including ones resolved in the submm such as $\beta$ Leo (see however new results on $\eta$ Corvi by *Bryden et al.*, in preparation). It is possible in these cases that the grain sizes are so large that Spitzer cannot see the Wien-side of such cold emission and/or that their viewing geometries (nearly face-on) were unfavorable.

Spatially resolved spectroscopy has been obtained for only one debris disk, $\beta$ Pic. These spectra provided information on collision rates, with small silicate grains only observed within 20 AU of the star and thermal processing, with crystalline silicate fractions higher closer to the star (*Weinberger et al.*, 2003; *Okamoto et al.*, 2004). Of the stars in Table 1 with measured scattered light, only $\beta$ Pic, HR 4796, and Fomalhaut have been resolved in the infrared.

Only silicates with $D < 4\mu$m show silicate emission. In the Zodiacal dust, this is only $\sim 10\%$ and the "typical" grain size is 100 $\mu$m (*Love and Brownlee*, 1993). Without resolving disks, the line-to-continuum ratio of the mid-infrared silicate bands at 10–20 $\mu$m, which in principle reflects the

TABLE 1
RESOLVED DEBRIS DISK PROPERTIES

| Star | Sp. Typ. | Age (Myr) | Size (AU) | Scattered Light Color | g | albedo | Resolved in Emis? | References |
|---|---|---|---|---|---|---|---|---|
| HR 4796A | A0 | 8 | 70 | red (V-J) | 0.15 | 0.1-0.3 | yes | 1,2,3,4 |
| HD 32297 | A0 | 10? | 400 | blue (R-J) | Not Avail. | 0.5 | no | 5,6 |
| $\beta$ Pic | A5 | 12 | 10-1000 | neutral-red (V-I) | 0.3-0.5 | 0.7 | yes | 7,8,9,10 |
| AU Mic | M1 | 12 | 12-200 | neutral-blue (V-H) | 0.4 | 0.3 | no | 11,12,13,14 |
| HD 181327 | F5 | 12 | 60-86 | Red (V-J) | 0.3 | 0.5 | no | 15 |
| HD 92945 | K1 | 20-150 | 120-146 | Red (V-I) | Not Avail. | Not Avail. | no | 16 |
| HD 107146 | G2 | 30-250 | 130 | red (V-I) | 0.3 | 0.1 | yes | 17,18 |
| Fomalhaut | A3 | 200 | 140 | Not Avail. | 0.2 | 0.05 | yes | 19,20 |
| HD 139664 | F5 | 300 | 110 | Not Avail. | Not Avail. | 0.1 | no | 21 |
| HD 53143 | K1 | 1000 | 110 | Not Avail. | Not Avail. | 0.06 | no | 21 |
| Saturn's Rings | – | – | – | red (B-I) | -0.3 | 0.2-0.6 | – | 22 |
| Emission (Additional) | | | | | | | | |
| Vega | A0 | 200 | $>90$ | | | | | 23,24,25 |
| $\epsilon$ Eridani | K2 | $<1000$ | 60 | | | | | 26,27 |
| $\eta$ Corvi | F2 | $\sim1000$ | 100 | | | | | 28 |
| $\tau$ Ceti | G8 | $\sim5000$ | 55 | | | | | 29 |

NOTE.—Notes: The size given is the approximate radius or range of radii. It remains to be seen if the younger systems, particularly HD 32297, really are gas-free debris disks. The size for HD 32297 is the inner disk; it has a large circumstellar nebulosity as well (Kalas 2005).

References. — 1. *Schneider et al.* (1999), 2. *Schneider, G. and Debes, J.* (personal communication), 3. *Jayawardhana et al.* (1998), 4. *Koerner et al.* (1998), 5. *Schneider, Silverstone, and Hines* (2005), 6. *Kalas* (2005), 7. *Artymowicz, Burrows, and Paresce* (1989), 8. *Kalas and Jewitt* (1995), 9. *Telesco et al.* (2005), 10. *Golimowski et al.* (2005), 11. *Kalas, Liu, and Matthews* (2004), 12. *Liu* (2004), 13. *Metchev et al.* (2005), 14. *Krist et al.* (2005), 15. *Schneider et al.* (2005), 16. *Clampin et al.* (2006), 17. *Ardila et al.* (2004), 18. *Williams et al.* (2004), 19. *Wyatt and Dent* (2002), 20. *Kalas, Graham, and Clampin* (2005), 21. *Kalas et al.* (2006), 22. *Cuzzi et al.* (1984), 23. *Holland et al.* (1998), 24. *Wilner et al.* (2002), 25. *Su et al.* (2005), 26. *Greaves et al.* (2005), 27. *Marengo et al.* (2006), 28. *Wyatt et al.* (2005) 29. *Greaves et al.* (2004)

proportion of small grains, can be diluted by flux from cold grains. Many debris disks with $12\mu$m excess show no silicate emission (*Jura et al.*, 2004) with the implication that their grains are larger than 10 $\mu$m. The unfortunate consequence is that direct compositional information is hard to acquire.

### 3.4. Detections of Remnant Gas

A useful definition of a debris disk is that it is gas free, because then the dust dynamics are dominated by the processed described in Section 4 unmodified by gas drag (*Takeuchi and Artymowicz*, 2001). However, debris disks can have small amounts of gas released in the evaporation of comets or destructive grain-grain collisions. The most sensitive gas measurements are made with ultraviolet absorption spectroscopy of electronic transitions. These transitions are strong and trace atomic and molecular gas at a wide range of temperatures. Yet since absorption spectroscopy probes only a single line of sight, it is only very useful for edge-on disks and it remains uncertain how to go from measured column densities to total disk masses.

The edge-on disks around the coeval $\beta$ Pic and AU Mic provide strong constraints on the persistence of gas into the debris disk phase. The total measured gas mass in $\beta$ Pic is $7 \times 10^{-4}$M$_\oplus$ while the upper limit (set by limits on HI) is 0.03 M$_\oplus$ (*Roberge et al.*, 2006). Because the CO/$H_2$ ratio is more like that of comets than of the ISM (CO is actually more abundant than $H_2$), the gas is presumably second–generation just as the dust is (*Lecavelier des Etangs et al.*, 2001; *Natta et al.*, 2000). In AU Mic, the upper limit to the gas mass from the non-detection of molecular hydrogen is 0.07 M$_\oplus$ (*Roberge*, 2005). $\beta$ Pic and AU Mic differ in luminosity by a factor of 90 but both were able to clear their primordial gas in under 12 Myr. Similar upper limits on the gas mass are also observed for the slightly younger, slightly less edge-on disk around HR 4796A (*Chen*, 2002).

Beyond total mass, a detailed look at the $\beta$ Pic disk reveals a wide range of atomic species in absorption with an up-to-date inventory given in *Roberge et al.* (2006). In addition, the spatial distribution of gas in $\beta$ Pic is also imaged by long slit high spectral resolution spectroscopy (*Brandeker et al.*, 2004). Atomic gas species such as sodium, iron, and calcium are all distributed throughout the disk with Keplerian line-of-sight velocities. The observation that iron, which should experience strong radiation pressure and be ejected on orbital timescales, has such low velocities remains a puzzle (*Lagrange et al.*, 1998). At this time, the best explanation for why the gas is not ejected by radiation pressure is that the ions strongly couple via Coulomb forces enhanced by an overabundance of carbon gas (*Fernandez et al.*, submitted; *Roberge et al.*, 2006). Most of the gas in the disk is ionized by a combination of stellar and interstellar UV. Remaining puzzles are the vertical distribution of calcium gas, which is actually located predominantly away from the midplane (*Brandeker et al.*, 2004) and why there exists such a large overabundance of carbon in the stable gas (*Roberge et al.*, 2006).

## 4. Overview of Debris Disk Models

### 4.1. Basic Dust Disk Physics

As described above, knowledge concerning general trends in the evolution of dust as a function of radius (see section 2), as well as detailed information concerning particle composition and size distribution (see section 3), abounds. However, *understanding* these trends and placing specific systems in context requires that we interpret these data in the context of robust physical theory. Models of debris disks have to explain two main observations: the radial location of the dust and its size distribution. There are two competing physical processes that determine how these distributions differ from that of the parent planetesimals which are feeding the dust disk.

#### *4.1.1. Collisions*

All material in the disk is subject to collisions with other objects, both large and small. If the collision is energetic enough, the target particle is destroyed (a catastrophic collision) and its mass redistributed into smaller particles. Lower energy collisions result in cratering of the target particle or accretion of the target and impactor. It is catastrophic collisions that replenish the dust we see in debris disks, and collisional processes are responsible for shaping a disk's size distribution.

Both experimental (*Fujiwara et al.*, 1989) and numerical (*Benz and Asphaug*, 1999) work has been used to determine the specific incident energy required to catastrophically destroy a particle, $Q_D^\star$. This energy depends on particle composition, as well as the relative velocity of the collision ($v_{rel}$), but to a greater extent is dependent on the size of the target. It is found to lie in the range $Q_D^\star = 10^0 - 10^6$ J kg$^{-1}$, which means that for collision velocities of $\sim 1$ km s$^{-1}$ particles are destroyed in collisions with other particles that are at least $X = 0.01 - 1$ times their own size, $D$. The collision velocity depends on the eccentricities and inclinations of the particles' orbits, the mean values of which may vary with particle size after formation (e.g., *Weidenschilling et al.*, 1997). For planetesimal growth to occur both have to be relatively low $\sim 10^{-3}$ to prevent net destruction of particles. However to initiate a collisional cascade something must have excited the velocity dispersion in the disk to allow collisions to be catastrophic. Models which follow the collisional evolution of planetesimal belts from their growth phase through to their cascade phase show that this switch may occur after the formation of a planet sized object (*Kenyon and Bromley*, 2002a, 2004) or from excitation by a passing star (*Kenyon and Bromley*, 2002b).

A particle's collisional lifetime is the mean time between catastrophic collisions. This can be worked out from the catastrophic collision rate which is the product of the relative velocity of collisions and the volume density of cross-sectional area of the impactors larger than $XD$. For the smallest particles in the distribution, for which collisions

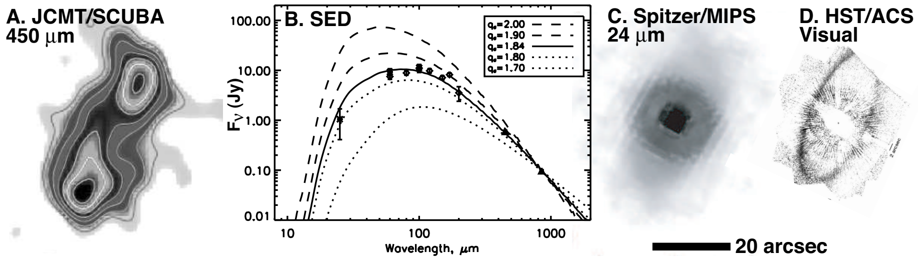


Fig. 3.— The Fomalhaut disk is one of the few to have been resolved in (A) the submillimeter (*Holland et al.*, 2003), (C) the thermal infrared (*Stapelfeldt et al.*, 2004), and (D) scattered visual light (*Kalas et al.*, 2005). When only mid-infrared total fluxes and the submillimeter images were available, *Wyatt and Dent* (2002) made models (B) using compact silicate grains. The addition of the mid-infrared images allows a separation between warm (T∼150 K) dust in an inner portion of the ring not seen in the submm and the outer colder ring. The addition of the scattered light image allows a more accurate determination of the ring geometry including a direct detection of the offset center of symmetry, similar to that observed in HR 4796 (*Wyatt et al.*, 1999). In future work, the silicate model must be tuned to fit the dust scattered light (albedo) as well as emissivity.

with any other member of the distribution is catastrophic, their collisional lifetime is given by:

$$t_{coll} = t_{per}/4\pi\tau_{eff}, \qquad (1)$$

where $t_{per}$ is the orbital period and $\tau_{eff}$ is the surface density of cross-sectional area in the disk which when multiplied by the absorption efficiency of the grains gives the disk's face–on optical depth (*Wyatt and Dent*, 2002). Larger particles have longer collisional lifetimes.

In an infinite collisional cascade in which the outcome of collisions is self-similar (in that the size distribution of collision fragments is independent of the target size), collisions are expected to result in a size distribution with

$$n(D) \propto D^{-3.5} \qquad (2)$$

(*Dohnanyi*, 1969; *Tanaka, Inaba and Nakazawa*, 1996). Such a distribution has most of its mass in the largest planetesimals, but most of its cross-sectional area in the smallest particles.

### *4.1.2. Radiation pressure and P-R drag*

Small grains are affected by their interaction with stellar radiation which causes a force on the grains which is parameterized by $\beta$, the ratio of the radiation force to stellar gravity. This parameter depends on the size of the grain, and to a lesser extent on its composition. For large particles $\beta$ can be approximated by

$$\beta = (0.4\mu m/D)(2.7gcm^{-3}/\rho)(L_\star/M_\star), \qquad (3)$$

where $\rho$ is the grain density and $L_\star$ and $M_\star$ are in units of $L_\odot$ and $M_\odot$ (*Burns et al.*, 1979). However, this relation breaks down for particles comparable in size to the wavelength of stellar radiation for which a value of $\beta$ is reached which is independent of particle size (*Gustafson*, 1994).

The radial component of the radiation force is known as radiation pressure. For grains with $\beta > 0.5$ (or $D < D_{bl}$), which corresponds to sub-micron sized grains near a Sun-like star, radiation pressure causes the grains to be blown out of the system on hyperbolic trajectories as soon as they are created. Since grains with $\beta = 1$ have no force acting on them, the blow-out timescale can be estimated from the orbital period of the parent planetesimal:

$$t_{bl} = \sqrt{a^3/M_\star}, \qquad (4)$$

where $a$ is the semimajor axis of the parent in AU, and $t_{bl}$ is the time to go from a radial distance of $a$ to $6.4a$. In the absence of any further interaction, such grains have a surface density distribution that falls off $\propto r^{-1}$.

The tangential component of the radiation force in known as Poynting-Robertson (P-R) drag. This acts on all grains and causes their orbits to decay in to the star (where the grains evaporate) at a rate $\dot{a} = -2\alpha/a$, where $\alpha = 6.24 \times 10^{-4} M_\star/\beta$. Thus the evolution from $a$ to the star takes

$$t_{pr} = 400(a^2/M_\star)/\beta \qquad (5)$$

in years. In the absence of any further interaction, such grains have a surface density distribution that is constant with the distance from the star.

### *4.1.3. Other processes*

Other physical processes acting on dust in debris disks range from gas drag to stellar wind drag, Lorentz forces on charged grains and sublimation. Many of these have been determined to be unimportant in the physical regimes of debris disks. However, it is becoming clear that for dust around M stars the force of the stellar wind is important both for its drag component (*Plavchan et al.*, 2005) and its pressure component (Augereau et al., in preparation). Gas drag may also be important in young debris disks. While the quantity of gas present is still poorly known, if the gas disk is sufficiently dense then gas drag can significantly alter the orbital evolution of dust grains. This can result in grains migrating to different radial locations from where they were created, with different sizes ending up at different locations (e.g., *Takeuchi and Artymowicz*, 2001; *Klahr and Lin*, 2001; *Ardila et al.*, 2005; *Takeuchi et al.*, 2005). For $\beta$ Pic it has been estimated that gas drag becomes important when the gas to dust ratio exceeds 1 (*Thébault and Augereau*, 2005).

### 4.2. Model Regimes

A debris disk that is not subjected to the stochastic mass–loss processes discussed in sections 4.4 and 5, will evolve in steady–state losing mass through radiation processes acting on small grains: through P-R drag and consequently evaporation close to the star, or through collisional grinding down and consequently blow-out by radiation pressure. The competition between collisions and P-R drag was explored in *Wyatt* (2005) which modeled the dust distribution expected if a planetesimal belt at $r_0$ is creating dust of just one size (see Fig. 4). The resulting distribution depends only on the parameter $\eta_0 = t_{pr}/t_{coll}$. If the disk is dense ($\eta_0 \gg 1$), then collisions occur much faster than P-R drag and the dust remains confined to the planetesimal belt, whereas if the disk is tenuous ($\eta_0 \ll 1$) then the dust suffers no collisions before reaching the star and the dust distribution is flat as expected by P-R drag. While this is a simplification of the processes going on in debris disks, which are creating dust of a range of sizes, it serves to illustrate the fact that disks operate in one of two regimes: collisional or P-R drag dominated. These regimes are discussed in more detail below.

#### *4.2.1. Collisionally dominated disks*

In a collisionally dominated disk ($\eta_0 \gg 1$) it is possible to ignore P-R drag, since the cumulative migration of particles over all generations from planetesimal to $\mu$m-sized grain is negligible (e.g., *Wyatt et al.*, 1999). This is because P-R drag lifetimes increase $\propto D$, whereas collisional lifetimes increase $\propto D^{0.5}$ (assuming the distribution of eq. 2) meaning that the migration undergone before a collision becomes vanishingly small for large particles.

There are two components to a collisionally dominated debris disk: dynamically bound grains at the same radial location as the planetesimals, and unbound grains with an $r^{-1}$ distribution beyond that. The short lifetime of the unbound grains (eq. 4) suggests that their number density should be extremely tenuous, and should fall below that expected from an extrapolation of the collisional cascade distribution. However, recent observations indicate that in some imaged debris disks they are being replenished at a rate sufficient for these grains to dominate certain observations (e.g., *Telesco et al.*, 2000; *Augereau et al.*, 2001; *Su et al.*, 2005), implying a comparable cross-sectional area in these particles to that in bound grains.

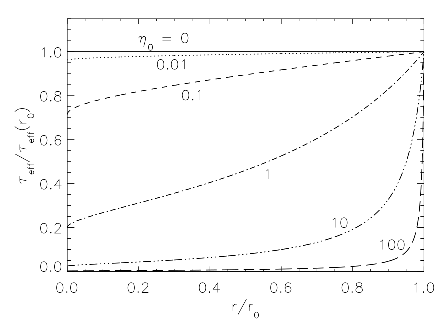


Fig. 4.— Surface density distribution of dust created in a planetesimal belt at $r_0$ which evolves due to collisions (which remove dust) and P-R drag (which brings it closer to the star) (*Wyatt*, 2005). Assuming the dust is all of the same size, the resulting distribution depends only on $\eta_0$, the ratio of the collisional lifetime to that of P-R drag.

The size distribution in a collisionally dominated disk varies somewhat from that given in eq. 2, since that assumes an infinite collisional cascade. If the number of blow-out grains falls below that of the collisional cascade distribution, then since these particles would be expected to destroy particles just larger than themselves, their low number causes an increase in the equilibrium number of particles just above the blow-out limit. This in turn reduces the equilibrium number of slightly larger particles, and so on; i.e., this causes a wave in the size distribution which continues up to larger sizes (*Thébault et al.*, 2003). If, on the other hand larger quantities of blow-out grains are present (e.g., because their number is enhanced by those driven out from closer to the star), then this can actually reduce the equilibrium number of particles just above the blow-out limit (*Krivov et al.*, 2000).

The long term evolution of a collisionally dominated disk was considered by *Dominik and Decin* (2003). They considered the case where the dust disk is fed by planetesimals of a given size, $D_c$, and showed how collisions cause the number of those planetesimals, $N_c$, to follow:

$$N_c(t) = N_c(0)/[1 + 2t/t_c(0)], \tag{6}$$

where $t_c$ is the collisional lifetime of the colliding planetesimals at $t = 0$. In other words, the evolution is flat until the disk is old enough for the majority of the planetesimals to have collided with each other (i.e., when $t > t_c$), thus eroding their population, at which point their number falls off $\propto t^{-1}$. Since the size distribution connecting the dust to the number of planetesimals is given by eq. 2, it follows that the cross-sectional area of emitting dust has the same flat or $t^{-1}$ evolution as does the total mass of material in the disk which is dominated by planetesimals of size $D_c$. *Dominik and Decin* (2003) also noted ways of changing the evolution, e.g., by introducing stirring.

The quantity of blow-out grains in the disk does not follow the same evolution, since their number is determined by the equilibrium between the rate at which the grains are created and that at which they are lost (eq. 4). The rate at which they are created depends on details of the physics of collisions, but since the rate at which dust is produced by planetesimals is $\propto N_c^2$, it follows that their population should fall off $\propto t^0$ or $t^{-2}$ depending on whether $t < t_c$ or $t > t_c$.

### 4.2.2. P-R drag dominated disks

A conclusion shared by *Dominik and Decin* (2003) and *Wyatt* (2005) is that none of the debris disks detected with current instrumentation is in the P-R drag dominated regime. *Wyatt* (2005) explained this as a consequence of the fact that such disks are of too low mass for their emission to be comparable to that of the stellar photosphere. Thus the detection of such disks requires calibration to a few % in the mid- to far-IR, or discovery in the sub-mm. However, the zodiacal cloud (and presumably dust from the Kuiper belt) in the solar system is a good example of a P-R drag dominated disk.

It is not possible to completely ignore collisions in a P-R drag dominated disk, since, while the smallest dust makes it to the star without suffering a collision, the largest grains are in a collisionally dominated regime, with intermediate sizes having distributions closer to that of $\eta_0 = 1$ in Fig. 4). Matters are complicated by the way P-R drag affects the size distribution. If collisional processes in a planetesimal belt are assumed to create dust at a rate that results in the size distribution of eq. 2 in the planetesimal belt, then since small dust migrates faster than small dust (eqs. 3 and 5) then the size distribution of the dust affected by P-R drag should follow

$$n(D) \propto D^{-2.5} \tag{7}$$

(*Wyatt et al.*, 1999), a distribution in which most of the cross-sectional area is in the largest particles in that distribution. In other words, the cross-sectional area should be dominated by grains for which P-R drag and collisional lifetimes are roughly equal, with that size varying with distance from the planetesimal belt. This reasoning is in agreement with observations of the size distribution of interplanetary dust in the vicinity of the Earth (*Love and Brownlee*, 1993; *Wyatt et al.*, 1999; *Grogan et al.*, 2001). *Dominik and Decin* (2003) also looked at the evolution of P-R drag dominated disks within the model described above. They concluded that the quantity of visible grains should fall off $\propto t^{-2}$.

## 4.3. Formation of inner hole

Perhaps the most important discovery about debris disks is the fact that there are inner holes in their dust distribution. It is often suggested that planet-sized bodies are required interior to the inner edge of the debris disk to maintain the inner holes, because otherwise the dust would migrate inward due to P-R drag thus filling in the central cavity (*Roques et al.*, 1994). It is certainly true that a planet could maintain an inner hole by a combination of trapping the dust in its resonances (*Liou and Zook*, 1999), scattering the dust outward (*Malhotra and Moro-Martin*, 2002), and accreting the dust (*Wyatt et al.*, 1999). However, a planet is not required to prevent P-R drag filling in the holes in the detected debris disks, since in dense enough disks collisional grinding down already renders P-R drag insignificant (*Wyatt*, 2005).

What the inner holes do require, however, is a lack of colliding planetesimals in this region. One possible reason for the lack of planetesimals close to the star is that they have already formed into planet-sized objects, since planet formation processes proceed much faster closer to the star (*Kenyon and Bromley*, 2002). Any remaining planetesimals would then be scattered out of the system by chaos induced by perturbations from these larger bodies (e.g., *Wisdom*, 1980). This would be an interpretation in line with our understanding of how the solar system formed and evolved. However, it is important to caution that debris disks could represent a different evolutionary outcome to that of the solar system.

## 4.4. Steady-state vs Stochastic Evolution

Much of our understanding of debris disks stems from our understanding of the evolution of the zodiacal cloud. This was originally assumed to be in a quasi steady-state. However, models of the collisional evolution of the asteroid belt, and the dust produced therein, showed significant peaks in dust density occur when large asteroids collide releasing quantities of dust sufficient to affect to total dust content in the inner solar system (*Dermott et al.*, 2002). Further evidence for the stochastic evolution of the asteroid belt came from the identification of asteroid families created in the recent (last few Myr) break-up of large asteroids (*Nesvorný et al.*, 2003). The link of those young families to the dust band features in the zodiacal cloud structure (*Dermott et al.*, 2002) and to peaks in the accretion rate of $^3$He by the Earth (*Farley et al.*, 2005) confirmed the stochastic nature of the inner solar system dust content, at least on timescales of several Myr. More recently the stochastic nature of the evolution of debris disks has been proposed by *Rieke et al.* (2005) based on the dispersion of observed disk luminosities. Several debris disks are observed to have small grains (with very short lifetimes) at radii inconsistent with steady-state configurations over lifetime of the star (e.g., *Telesco et al.*, 2005; *Song et al.*, 2005; *Su et al.*, 2005).

The arguments described previously considered the steady-state evolution of dust created in a planetesimal belt at single radius. The same ideas are still more generally applicable to stochastic models, since a situation of quasi-steady state is reached relatively quickly at least for small dust for which radiation and collision processes balance on timescales of order 1 Myr (depending on disk mass and radius).

Stochastic evolution of the type seen in the zodiacal cloud arises from the random input of dust from the destruction of large planetesimals. Whether it is possible to witness the outcome of such events in extrasolar debris disks is still debated for individual objects. This is unlikely to be the case for dust seen in the sub-mm, since the large dust mass observed requires a collision between two large planetesimals ($>$ 1400 km for dust seen in Fomalhaut), and while such events may occur, the expected number of such objects makes witnessing such an event improbable (*Wyatt and Dent*, 2002). Observations at shorter wavelengths (and closer to the star) probe lower dust masses, however, and these observations may be sensitive to detecting such events (*Telesco et al.*, 2005; *Kenyon and Bromley*, 2005).

Debris disk evolution may also be affected by external influences. One such influence could be stirring of the disk by stars which pass by close to the disk (*Larwood and Kalas*, 2001; *Kenyon and Bromley*, 2002b). However, the low frequency of close encounters with field stars means this cannot account for the enhanced dust flux of all debris disk candidates, although such events may be common in the early evolution of a disk when it is still in a dense cluster environment. Another external influence could be the passage of the disk through a dense patch of interstellar material which either replenishes the circumstellar environment with dust or erodes an extant, but low density debris disk (*Lissauer and Griffith*, 1989; *Whitmire et al.*, 1992).

Other explanations which have been proposed to explain sudden increases in dust flux include the sublimation of supercomets scattered in close to the star (*Beichman et al.*, 2005).

It is also becoming evident that the orbits of the giant planets have not remained stationary over the age of the solar system (*Malhotra*, 1993; *Gomes et al.*, 2005). The recently investigated stochastic component of giant planet orbital evolution can explain many of the features of the solar system including the period of Late Heavy Bombardment (LHB) which rapidly depleted the asteroid and Kuiper belts, leading to enhanced collision rates in the inner solar system. Such an event in an extrasolar system would dramatically increase its dust flux for a short period, but would likely do so only once in the system's lifetime. A similar scenario was also proposed by *Thommes et al.* (1999) to explain the LHB wherein the giant cores that formed between Jupiter and Saturn were thrown outwards into the Kuiper Belt by chaos at a late time. Again this would result in a spike in the dust content of an extrasolar system. These ideas are applied to own solar system in the next section.

## 5. Comparison to our Solar System

Our asteroid belt (AB) and Kuiper-Edgeworth belt (KB) contain planetesimals that accreted during the earliest epochs of the solar system's formation, plus fragments from subsequent collisions (e.g. *Bottke et al.*, 2005; *Stern and Colwell*, 1997). Collisions in both belts should generate populations of dust grains analogous to extrasolar debris disks. The dust population extending from the AB is directly observed as the zodiacal cloud, whereas dust associated with the KB is as yet only inferred (*Landgraf et al.*, 2002). An observer located 30 pc from the present solar system would receive approximately 70 microJy at 24 $\mu$m and 20 microJy at 70 $\mu$m from the AB plus zodi cloud, in contrast to 40 milliJy (24 $\mu$m) and 5 milliJy (70 $\mu$m) from the Sun. The luminosity of the KB dust component is less certain but flux densities from 30 pc of about 0.4 mJy at 24 $\mu$m and 4 mJy at 70 $\mu$m correspond to an estimated KB planetesimal mass of 0.1 $M_E$ (see below for details of these calculations).

The solar system's original disk contained much more solid mass in the AB and KB zones than at present. A minimum-mass solar nebula would have had 3.6 $M_E$ of refractory material in the primordial AB between r = 2.0 and 4.0 AU whereas now the AB contains only $5 \times 10^{-4}$ $M_E$, and only $2 \times 10^{-4}$ $M_E$ if the largest object Ceres is excluded. In contrast, the masses of Earth and Venus are close to the minimum-mass nebular values for their respective accretion zones. Likewise, the primordial KB must have had 10-30 $M_E$ so that the observed population of large objects could have formed in less than $10^8$ years before gravitational influence of the planets made further accretion impossible (*Stern*, 1996). The present KB contains no more than a few $\times 0.1$ $M_E$ based on discovery statistics of massive objects (discussed by *Levison and Morbidelli*, 2003) and upper limits to IR surface brightness of collisionally evolved dust (*Backman et al.*, 1995; *Teplitz et al.*, 1999).

How did the missing AB and KB masses disappear? It is unlikely that purely "internal" collisional processes followed by radiation pressure-driven removal of small fragments is responsible for depletion of either belt. Persistence of basaltic lava flows on Vesta's crust is evidence that the AB contained no more than 0.1 $M_E$ 6 Myr after the first chondrules formed (*Davis et al.*, 1985; *Bottke et al.*, 2005). This implies a factor of at least 40x depletion of the AB zone's mass by that time, impossible for purely collisional evolution of the original amount of material (reviewed by *Bottke et al.*, 2005; cf. section 4 of this paper). Also, the present AB collisional "pseudo-age", i.e. the model time scale for a purely self-colliding AB to reach its present density, is of order 10 Gyr. This is further indication that the AB's history includes significant depletion processes other than comminution. Proposed depletion mechanisms include sweeping of secular resonances through the AB as the protoplanetary disk's gas dispersed (*Nagasawa et al.*, 2005) and as Jupiter formed and perhaps migrated during the solar system's first 10 Myr or so (*Bottke et al.*, 2005).

Similarly, several investigators have concluded that the primordial KB was depleted by outward migration of Neptune that swept secular resonances through the planetesimal population, tossing most of the small objects either inward to encounter the other planets or outward into the KB's "scattered disk". That scenario neatly explains several features of the present KB in addition to the mass depletion (*Levison and Morbidelli*, 2003; *Gomes et al.*, 2005; *Levison et al.*, this volume). This substantial re-organization of the solar system could have waited a surprisingly long time, as much as 1.0 Gyr, driven by slow evolution of the giant planets' orbits before becoming chaotic (*Gomes et al.*, 2005). The timing is consistent with the epoch of the Late Heavy Bombardment (LHB) discerned in lunar cratering record. Furthermore, *Strom et al.* (2005) point out that, because Jupiter should have migrated inward as part of the same process driving Neptune outward, the AB could have been decimated (perhaps for its second time) at the same late era as the KB.

The simple model employed herein to track the history of the solar system's IR SED involves calculating the collisional evolution of the AB and KB. Each belt is divided into 10 radial annuli that evolve independently. At each time step (generally set to $10^6$ years) for each annulus is calculated: (1) the number of parent body collisions, (2) the fragment mass produced and subtracted from the parent body reservoir, and (3) mass lost via "blowout" of the smallest particles plus P-R drift from the belt inward toward the Sun. Parent body collisions are considered only statistically so the model has no capacity to represent "spikes" from occasional large collisions as discussed in section 4.4. Mass in grains that would be rapidly ejected via radiation pressure "blowout" is removed from the model instantaneously when created. If the collision timescale for bound grains of a given size and location is shorter than the P–R removal time, those grains are not allowed to drift interior to the belt and contribute to the inner zodiacal cloud. Thus, based on the theory explained in the previous section, if the belt fragment density is above a certain threshold, the net mass loss is only outward via direct ejection, not inward. The terrestrial planets are not considered as barriers to P-R drift but Neptune is assumed able to consume or deflect all grains, so the model dust surface density is set to zero between 4 and 30 AU. The system SED is calculated using generic grain emissivity that depends only on particle size. An indication that the model works well is that it naturally predicts the observed zodiacal dust density as the output from the observed AB large-body mass and spatial distributions without fine-tuning.

Our simple results agree with *Bottke et al.* (2005) and others' conclusion that the AB and KB must both have been subject to depletions by factors of 10-100x sometime during their histories because simple collisional evolution would not produce the low-mass belts we see today. The present AB and KB masses cannot be produced from the likely starting masses without either (A) an arbitrary continuous removal of parent bodies with an exponential time scale for both belts of order 2 Gyr, shown in Fig 5 (top), or (B) one sudden depletion event shown in Fig 5 (bottom), which involves collisionally evolving the starting mass for 0.5 Gyr, then reducing each belt mass by amounts necessary to allow collisional evolution to resume and continue over the next 4.0 Gyr to reach the observed low masses of the two belts.

The toy model scenario A simply predicts that a planetary system would have significant 10-30 micron flux up to an age of 1 Gyr. The general lack of observed mid-IR excesses in Spitzer targets older than 30 Myr could mean: a) most systems do not have belts at temperatures like our asteroid belt, or b) most have LHB-like events earlier in their histories. A corollary of the present depleted AB having a large-body collision time scale of 10 Gyr is that the AB/zodi system is nearly constant in time (e.g., equation 6). Thus, extrapolating backward by *Dominik and Decin* (2003) $t^{-1}$ or $t^{-2}$ scaling laws is inappropriate (cf. Fig 1). Our model predicts that the AB/zodi and KB IR luminosities both would only decrease by about 30 per cent in 4.0 Gyr after the LHB or equivalent major clearing. This agrees with the lunar cratering record indicating that the AB, the earth-crossing asteroid population, and the zodiacal cloud have had nearly constant density for at least the past 3.0 Gyr.

*Levison et al.* (this volume) discuss the idea that our planetary system had a traumatic re-organization about 700 Myr after its formation. An intriguing extension of this idea is that extrasolar debris disk systems that seem brighter than their age cohorts may represent LHB-like events, i.e. collisions of small bodies excited by planet migration that can occur late in a system's development at a time determined by details of the original planetary system architecture. Our "toy" model results compared with Spitzer observations (*Kim et al.*, 2005; *Hillenbrand et al.*, in preparation) support a picture in which many systems evolve according to the principles articulated by *Dominik and Decin* (2003) unless interrupted by an LHB event that might occur almost any time in the system's history. After the LHB event the system is nearly clear of planetesimals and dust and evolves very slowly. It remains to be seen whether single super-collisions or late episodes of debris belt clearing are likelier to be observed in the Spitzer nearby star samples, and whether an observational test might be devised to distinguish between the two hypotheses.

## 6. Summary and Implications for Future Work

Based on the discussions presented above, it is clear that the question of how common solar systems like our own might be, depends in part on what radius in the disk one looks and at what age the comparison is made. We summarize our main results as follows: 1) Warm circumstellar material inside of 1 AU dissipates rapidly on timescales comparable to the cessation of accretion; 2) The gas content of disks much older than 10 Myr is incapable of forming giant planets; 3) While massive analogues to our asteroid belt lacking outer disks appear to be rare overall (1–3 %), warm disks (lacking inner hot dust) seem to enjoy a preferred epoch around stars with ages between 10–300 Myr old; 4) Cold outer disks (analogous to our own Kuiper Belt, but much more massive) are found around 10–20 % of sun–like stars; 5) Resolved images of disks are crucial in order to remove degeneracies in debris disk modeling from SEDs alone; 6) Most debris disks observed to date are collisionally dominated dust systems and do not require the dynamical action of planets to maintain the observed inner holes; 7) At least some disks are observed in a short–lived phase of evolution and are not examples of the most massive debris disks; and 8) Comparing the ensemble of observations of disks surrounding other stars as a function of age to the evolution of our solar system requires detailed understanding of its dynamical evolution including the late–heavy bombardment era. Yet in affecting these comparisons, we must remember that we do not yet have the sensitivity to observe tenuous debris disks comparable to our own asteroid belt or our Kuiper Belt.

It is unclear whether debris systems significantly more massive (and therefore more easily detectable) than our

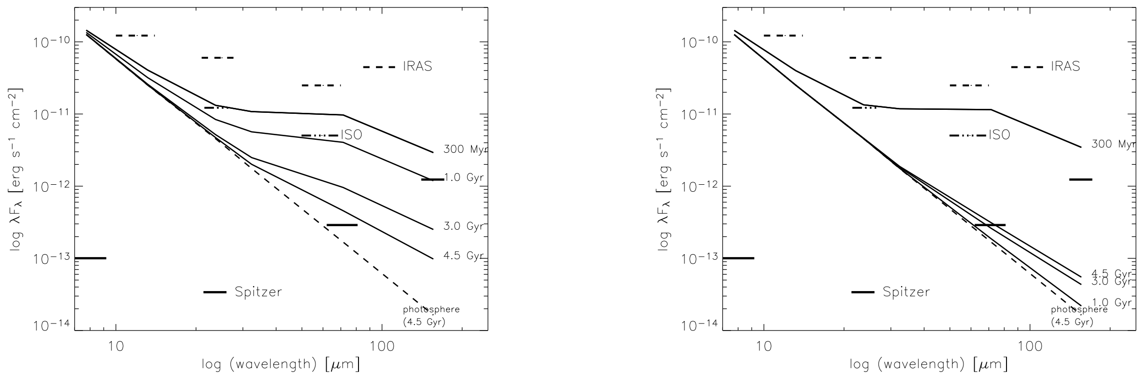


Fig. 5.— Toy models for the evolution of the solar system spectral energy distribution from an age of 300 Myr to 4.5 Gyr: (A) with no late heavy bombardment shown (left) and (B) including the LHB (right) as discussed in the text. The long wavelength excess in (B) grows with time after the LHB because the Kuiper Belt has not yet reached equilibrium between dust production and dust removal. Also shown are the 3 $\sigma$ sensitivity limits of IRAS, ISO, and Spitzer for a sun–like star at a distance of 30 parsecs for comparison.

own represent a more or less favorable condition for planet formation. It may be that systems with planets might arise from disks with higher mass surface density and thus stronger debris signatures at early times than disks lacking planets. However, if events comparable to the dynamical re–arrangement of our solar system (perhaps related to the lunar late–heavy bombardment) are common in planetary systems within the first few hundred million years we might expect that debris disks lacking planets might be brighter than those with planets at late times. *Beichman et al.* (2005) present preliminary evidence that there may be some connection between the presence of a massive debris disk and a radial velocity planet within 5 AU. It is interesting to note that extrapolations of the detection frequency of extra–solar planets as a function of radius beyond current survey limits (*Udry et al.* this volume) suggest a frequency of extra–solar giant planets $> 1$ M$_{JUP}$ $\sim$ 10–20 % out to 20 AU, consistent with our debris disk statistics for G stars.

How do results on debris disks compare as a function of stellar mass? On theoretical grounds, one can argue that the mass of a circumstellar disk should not exceed $\sim$ 10–25 % the mass of the central star (*Hartmann*, 1998). Indeed *Natta et al.* (2000) presents evidence that the disk masses around early type pre–main sequence stars are more massive than their lower mass T Tauri counter–parts. *Muzerolle et al.* (2003) also show that disk accretion rates appear to correlate with stellar mass. Historically, debris disks have been more commonly associated with A stars rather than G or M stars, but that has been largely attributable to a selection effect: it is easier to see smaller amounts of dust surrounding higher luminosity objects in flux–limited surveys. *Rieke et al.* (2005) present evidence for a diminution in the frequency of mid–IR excess emission surrounding A stars over 100–300 Myr. Their data indicate that over and above an evelope of decay consistent with a t$^{-1}$ fall off, several objects show evidence for greater dust generation rates consistent with their interpretation of stochastic processes in planetesimal disks (see sections 3 and 4 above). In general, the overall picture of A star debris disk evolution is remarkably consistent with that presented for sun–like stars suggesting that stellar mass does not play a defining role in debris disk evolution. In contrast, primordial disks around higher mass stars are more massive, and have shorter lifetimes (*Hillenbrand et al.*, 1998; *Lada et al.*, in press), than disks around lower mass stars.

*Greaves et al.* (2003) also present evidence from sub–mm observations concerning the frequency of debris disks as a function of mass. They find that debris surrounding A stars is more common than around G stars, even for stars of the same age (though the observations were sensitive to different amounts of debris as a function of stellar luminosity). They suggest that the difference is due to characteristic lifetimes of debris becoming an increasing fraction of of the main sequence lifetime for higher mass (shorter lived) stars. *Plavchan et al.* (2005) present a survey for warm inner debris surrounding young M dwarfs. They explain their lack of detections, which is contrary to expectations from the timescale for P–R drag as a function of stellar luminosity, due to the effects of an enhanced particulate wind from late–type stars compared to early–type stars. Yet, it is clear from recent work on low mass stars and brown dwarfs that they too possess primordial circumstellar disks when they are young (see *Luhman et al.*, this volume; *Apai et al.*, 2005) however their evolutionary properties are as yet unclear. Spitzer studies of debris disks surrounding low mass stars and brown dwarfs at longer wavelengths are now underway. Combining data on A stars, G dwarfs, and M dwarfs, there is, to date, no evidence for wildly divergent evolutionary histories for debris disks as a function of stellar mass averaged over main sequence lifetimes. Observed differences to date can be explained in part by differences in dust mass upper limits as a function of stellar luminosity and assuming that the typical star to disk mass is roughly constant.

It is important to remember that most *sun–like* stars in the disk of Milky Way are binary (*Duquennoy and Mayor*, 1991), while the binary fraction of low mass stars and brown dwarfs may be lower (*Burgasser et al.*, this volume). It is clear that the evolution of disks in the pre–main sequence phase can be influenced by the presence or absence of a companion (*Monin et al.*, this volume; *Jensen et al.*, 1996). Preliminary results from Spitzer suggest that debris disk evolution is not a strong function of multiplicity, and may even be enhanced in close binaries (*Trilling et al.*, in preparation).

What are the implications for the formation of terrestrial planets in disks surrounding stars of all masses in the disk of the Milky Way? We know that primordial accretion disks commonly surround very young stars (approaching 100 %), and that gas–rich disks around more (less) massive stars are bigger (smaller), but last shorter (longer) amounts of time. Because of the surface density of solids in the disk, more massive disks surrounding higher mass stars will probably form planetesimals faster. What is unclear is whether remnant gas is needed to damp the eccentricities of forming planetesimals enabling larger terrestrial mass planets to accumulate (*Kominami & Ida*, 2002). If so, then more massive stars (with shorter gas disk lifetimes) might not be suitable candidates for large terrestrial planets like Venus and Earth. Yet the planetesimal growth time in disks surrounding low mass stars and brown dwarfs might be prohibitive given the low surface densities of solids (see however *Beaulieu et al.*, 2006). Perhaps, just like Goldilocks, we will find that terrestrial planets are found in abundance around sun–like stars from 0.3–3 AU. Whether these planets have liquid water and the potential for life as we know it to develop will depend on many factors (see *Gaidos et al.*, this volume). As results from Spitzer and other facilities continue to guide our understanding in the coming years, we can look forward to steady progress. Hopefully, new observational capabilities and theoretical insights will provide answers to some of these questions at PPVI.

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