Dust and Gas Debris Around Main Sequence Stars

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Abstract. Debris disks are dusty, gas-poor disks around main sequence stars (Backman & Paresce 1993; Lagrange, Backman & Artymowicz 2000; Zuckerman 2001). Micron-sized dust grains are inferred to exist in these systems from measurements of their thermal emission at infrared through millimeter wavelengths. The estimated lifetimes for circumstellar dust grains due to sublimation, radiation and corpuscular stellar wind effects are typically significantly smaller than the estimated ages for the stellar systems, suggesting that the grains are replenished from a reservoir, such as sublimation of comets or collisions between parent bodies. Since the color temperature for the excess emission is typically $T_{gr} \sim 110 - 120$ K, similar to that expected for small grains in the Kuiper Belt, these objects are believed to be generated by collisions between parent bodies analogous to Kuiper Belt objects in our solar system; however, a handful of systems possess warm dust, with $T_{gr} \geq 300$ K, at temperatures similar to the terrestrial planets. We describe the physical characteristics of debris disks, the processes that remove dust from disks, and the evidence for the presence of planets in debris disks. We also summarize observations of infalling comets toward $\beta$ Pictoris and measurements of bulk gas in debris disks.

1. Introduction

The observation of periodic variations in the radial velocities of nearby late-type stars has led to the discovery of $\sim 150$ giant planets (Marcy, Cochran, & Mayor 2000), including 14 multiple planet systems, suggesting that planetary systems may exist around $>5\%$ of solar-like main sequence stars. Giant planets, like Jupiter, are believed to form in proto-planetary disks made of gas and dust. As grains grow into larger bodies, the bulk of circumstellar gas dissipates from the system (e.g., via accretion onto the star or planetary objects) until the disk contains predominately large bodies, such as planets and/or planetesimals and dusty debris. Studying the dynamics of dust and gas in disks around main sequence stars reveals the presence of planets and small bodies, analogous to asteroids and comets in our solar system. Therefore, studying debris disks may allow us to determine the processes that shape the final architectures of planetary systems including our own solar system.

The lifetimes of dust grains in debris disks are believed to be significantly shorter than the ages of the systems, suggesting that the particles are replenished from a reservoir such as collisions between parent bodies. Our solar system shows evidence for collisions within the main asteroid belt that produce micron-sized dust grains. In 1918, Hirayama discovered concentrations of asteroids in three regions of $a - e - i$ ($a$ is the osculatory orbital semi-major axis; $e$ is the
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eccentricity, and \( i \) is the inclination) space which he named the Themis, Eos, and Koronis families. The clumping of these asteroids is widely attributed to the break up of larger parent bodies (Chapman et al. 1989). \textit{IRAS} observations of the zodiacal dust discovered the \( \alpha \), \( \beta \), and \( \gamma \) dust bands which have orbital properties identical to the Themis, Koronis, and Eos families, suggesting that the dust in each band was created by collisions between asteroids in each family. Non-equilibrium processes may be responsible for the generation of dust bands. Gravitational perturbations by Jupiter and other planets in our solar system are expected to cause the apsides and nodes of asteroid orbits to precess at different rates because of small differences in their orbital parameters. This precession leads to asteroid collisions that generate the small grains observed in the dust bands.

Observed debris disks typically possess luminosities 3 - 5 orders of magnitude higher than our zodiacal disk, suggesting that they are significantly more massive. The dust in these systems may be produced in steady state at earlier times when the planetesimal belt was more massive or during an epoch of intense collisions that produced especially large quantities of dust, triggered by the formation and/or migration of planets. Simulations of planetesimal disks, in which planets are forming from pairwise collisions, suggest that formation of massive planets may trigger collisional cascades between the remaining nearby planetesimals (Kenyon & Bromley 2004). Alternately, the migration of giant planets, soon after their formation, may also trigger collisions. In our solar system, the moon and terrestrial planets experienced an intense period of cratering 3.85 Gyr ago known as the Period of Late Heavy Bombardment. Two pieces of evidence suggest that the impactors during this period may have been asteroids. (1) Lunar impact melts, collected during Apollo missions, suggest that the composition of impactors is similar to asteroids. (2) The size distribution of impactors, inferred from the lunar highlands, is similar to that of the main asteroid belt. The migration of the Jovian planets during the Late Heavy Bombardment may have caused gravitational resonances to sweep through the main asteroid belt sending asteroids into the inner solar system (Strom et al. 2005).

2. Gross Properties

The debris disks around Vega, Fomalhaut, \( \epsilon \) Eridani, and \( \beta \) Pictoris were initially discovered from the presence of strong \textit{IRAS} 60 \( \mu \)m and 100 \( \mu \)m fluxes, 10 - 100 times larger than expected from the photosphere alone (Backman & Paresce 1993). Studies comparing the \textit{IRAS} fluxes with predictions for the photospheric emission of field stars subsequently discovered more than 100 debris disk candidates (e.g., Walker & Wolstencroft 1988; Oudmaijer et al. 1992; Backman & Paresce et al. 1993; Sylvester et al. 1996; Mannings & Barlow 1998; Silverstone 2000). The launch of the \textit{Spitzer Space Telescope} (Werner et al. 2004), with unprecedented sensitivity in the far-infrared, is making the discovery and statistical study of large numbers of debris disks possible. The first exciting results from this mission are determining the mean properties of debris disks and measuring the characteristic timescales for dust and gas decay. \textit{IRAS} and \textit{Spitzer} MIPS surveys of main sequence stars now suggest that \(~10 - 15\%\) of A- through K-type field stars possess 10 \( \mu \)m - 200 \( \mu \)m excesses indicative of the presence of
circumstellar dust (Bryden et al. 2005; Decin et al. 2003). However, surveys of M-type stars suggest that the fraction of dwarfs with infrared excesses is lower (Gautier et al. 2004; Song et al. 2002); only 2 out of 150 IRAS/Spitzer detected M-dwarfs possess far-infrared excess: Hen 3-600 in the TW Hydrae Association and AU Mic in the β Pic Moving Group, with estimated ages ∼10 Myr.

**Fractional Infrared Luminosity:** The average fraction of stellar luminosity reheated by the circumstellar dust grains in debris disks discovered by IRAS and ISO, $L_{IR}/L_\ast$, is typically between $\sim10^{-5}$ and $\sim5\times10^{-3}$ (Decin et al. 2003). As a result, the majority of debris disks discovered using these satellites are located around high luminosity A-type stars. The improved sensitivity of Spitzer may drive the discovery of debris disks at 70 μm and 160 μm with $L_{IR}/L_\ast$ as faint as $10^{-8}$. For comparison, the zodiacal dust in our solar system reprocesses, $L_{IR}/L_\ast = 10^{-7}$ (Backman & Paresce 1993), and the dust in the Kuiper Belt is estimated to reprocess, $L_{IR}/L_\ast = 10^{-7} - 10^{-6}$ (Backman, Dasgupta, & Stencel 1995).

**Grain Size:** The similarity between black body grain distances, inferred from SED modeling of IRAS fluxes, with the measured radii of debris disks in resolved systems implies that the circumstellar dust grains in debris disks are large. For example, a black body fit to the IRAS HR 4796A excess SED implies an estimated dust grain temperature, $T_{gr} = 110$ K, corresponding to a distance of 35 AU if the grains are large (the absorption coefficient, $Q_{abs} \propto (2\pi a/\lambda)^0$; Jura et al. 1998). However, if the grains are small ($2\pi a < \lambda$), then they radiate less efficiently ($Q_{abs} \propto (2\pi a/\lambda)$) and are expected to be located at a distance of 280 AU from the star. High resolution mid-infrared and coronagraphic imaging has resolved a narrow ring of dust around HR 4796A at a distance of 70 AU from the star, more consistent with large grains (Schneider et al. 1999; Telesco et al. 2000). In addition, Spitzer IRS spectroscopy (at 5 μm - 35 μm) of 60 main sequence stars with IRAS 60 μm excesses (including HR 4796A) do not detect silicate emission feature at 10 μm and 20 μm, suggesting that the grains have radii, $a > 10$ μm (Jura et al. 2004; Chen et al. 2006, in preparation).

**Disk Mass:** Scattered light and far-infrared imaging observations are sensitive to dust grains with radii <100 μm; however, the majority of the disk mass is probably contained in larger objects that do not possess as much surface area. Therefore, measurements of disk mass are made at submillimeter wavelengths where the grains are more likely to be optically thin. The typical dust mass in debris disks, is 0.01 $M_\oplus$ - 0.25 $M_\oplus$ (Zuckerman & Becklin 1993; Holland et al. 1998; Najita & Williams), a tiny fraction of the 10 - 300 $M_\oplus$ measured toward pre-main sequence T-Tauri and Herbig Ae/Be stars (Natta, Grinin, & Mannings 2000) and a tiny fraction of the dust mass expected in a minimum mass solar nebula with an interstellar gas:dust ratio (∼30 $M_\oplus$). The decline in submillimeter flux, as objects age from Herbig Ae stars to main sequence stars, may be the result of accretion of grains onto the central star or grain growth into larger bodies. After stars reach the main sequence, the decline in submillimeter flux may be the result of parent body grinding. The upper envelope of disk masses for A-type stars is higher than that of later-type stars, suggesting that high mass stars may initially possess more massive disks (Liu et al. 2004a). For comparison, the estimated total mass in the main asteroid belt is ∼0.0003 $M_\oplus$; the asteroid belt may have contained as much as 1000× more mass prior to the
period of Late Heavy Bombardment. The estimated total mass in the Kuiper Belt is 0.1 \( M_\oplus \).

**Gas: Dust Ratio** Current (uncertain) models suggest that Jovian planets form either via rapid gravitational collapse through disk instability within a few hundred years (Boss 2003) or via coagulation of dust into solid cores within the first \( \sim 1 \) Myr and accretion of gas into thick hydrogen atmospheres within the first \( \sim 30 \) Myr (Pollack et al. 1996). At present, the timescales on which giant planets form and accrete their atmospheres have not been well constrained observationally. CO surveys suggest that the bulk of molecular gas dissipates within the first \( \sim 10 \) Myr (Zuckerman, Forveille, & Kastner 1995). Since the bulk disk gas is expected to be composed largely of \( \mathrm{H}_2 \), recent surveys have focused on searching for this molecule. New high-resolution (R = 600) Spitzer IRS observations place upper limits on the \( \mathrm{H}_2 \) S(0) and S(1) emission toward \( \beta \) Pictoris, 49 Ceti, and HD 105 that suggest that \(< 1-15 \ M_\oplus \) \( \mathrm{H}_2 \) remains in these systems (Chen et al. 2006; Hollenbach et al. 2005). The gas:dust ratio in debris disks is probably \(<10:1\). UV absorption line studies have placed upper limits on the gas:dust ratios two nearly edge-on systems. FUSE and SITS observations constrain the gas:dust ratio in the AU Mic disk (\(<6:1\)) by placing upper limits on the \( \mathrm{H}_2 \) absorption in the \( \mathrm{O} \ \text{VI} \ \lambda \lambda 1032, 1038 \) emission lines and in the \( \mathrm{C} \ \text{II} \ \lambda \lambda 1036, 1037 \) and \( \lambda 1335 \) emission lines (Roberge et al. 2005). FUSE and SITS observations constrain the gas:dust ratio in the HR 4796A disk (\(<4:1\)) by placing upper limits on \( \mathrm{H}_2 \) and \( \lambda 2026 \) Zn II absorption (Chen & Kamp 2004).

3. Debris Disks as Solar System Analogs

Parallels are often drawn between parent body belts in debris disks and small body belts in our solar system. These analogies are based on the similarity of observed grain temperatures to those inferred for the main asteroid belt and the Kuiper Belt.

3.1. Dust in Extra-Solar Kuiper Belts

Numerous small bodies have been discovered in our solar system at distances of 30 - 50 AU from the Sun. These bodies are collectively referred to as the Kuiper Belt and are the likely source for short-period comets in our solar system. Kuiper Belt objects are expected to collide and grind down into dust grains that may be detected at far-infrared wavelengths (Backman, Dasgupta, & Stencel 1995). If these dust grains are large, then they are expected to have grain temperatures, \( T_{gr} = 40 - 50 \) K; if they are small, then \( T_{gr} = 110 - 130 \) K. The bulk of the energy radiated by grains with these temperatures should emerge at 30 \( \mu \)m to 90 \( \mu \)m, consistent with the properties of debris disks discovered using IRAS (Backman & Paresce 1993); therefore, the majority of discovered debris disks are envisioned to be massive analogs to the Kuiper Belt. Spitzer IRS spectroscopy of 60 IRAS-discovered debris disks suggests that the 5 \( \mu \)m - 35 \( \mu \)m spectra of IRAS 60 \( \mu \)m excess sources can be modeled using a single temperature black body (Chen et al. 2006; Jura et al. 2004). The peak of the IRS inferred grain temperature distribution lies at \( T_{gr} = 110 - 120 \) K; although, the lack of data beyond 35 \( \mu \)m makes this study insensitive to grains with \( T_{gr} < 65 \) K. Spitzer MIPS surveys of main sequence FGK stars have discovered a number of solar-like stars with
70 μm excess but no 24 μm excess, consistent with \( T_{gr} < 100 \) K (Bryden et al. 2005; Chen et al. 2005b; Kim et al. 2005).

The low luminosity of M-type stars makes detecting thermal emission from circumstellar dust around these stars challenging compared to detecting thermal emission from dust around high luminosity A-type stars. For example, dust located 50 AU from an M2V star is expected to possess \( T_{gr} = 17 \) K if \( L_\star = 0.034 L_\odot \) and the grains are black bodies. Since the dust around M-type stars is so cool, disks around M-dwarfs may be detected best at submillimeter wavelengths. At the distance of the closest stars (50 pc), a disk that reprocesses \( L_{IR}/L_\star = 2 \times 10^{-3} \) would produce an undetectable flux at 100 μm, \( F_\nu(100 \mu m) < 10 \) mJy. However, it would produce a robust excess at submillimeter wavelengths, \( F_\nu(850 \mu m) = 30 \) mJy. One star has been detected at submillimeter wavelengths despite the lack of IRAS excess. JCMT SCUBA photometry of TWA 7 at 850 μm detects thermal emission from dust, with \( F_\nu(850 \mu m) = 15.5 \) mJy (Webb 2000), even though the source does not appear in the IRAS catalog. A survey of three young M-dwarfs in the β Pic Moving Group (with an estimated age of 12 Myr) and the Local Association Group (with an estimated age of 50 Myr) discovered 450 μm and/or 850 μm excesses associated with two of the stars: AU Mic and Gl 182 (Liu et al. 2004a). The disk around AU Mic is warm enough and massive enough that its disk is bright at 70 μm (\( F_\nu(70 \mu m) = 200 \) mJy) while the disk around Gl 182 is not detected at either 24 μm or 70 μm (Chen et al. 2005b).

### 3.2. Dust in Extra-Solar Asteroid Belts

The zodiacal dust in our solar system possesses a grain temperature, \( T_{gr} = 150 - 170 \) K, suggesting that the bulk of the thermal energy is radiated at 20 μm - 25 μm. The Earth has a temperature, \( T_{gr} \sim 300 \) K, suggesting that the bulk of its thermal energy is radiated at \( \sim 10 \) μm. Searches for 10 μm excesses around main-sequence stars have revealed that 300 K dust around A - M dwarfs is rare. IRAS surveys of main sequence stars suggest that <5% of debris disks possess 12 μm excesses. In a survey of 548 A - K dwarfs, Aumann & Probst (1991) were able to identify IRAS 12 μm excesses only with β Pictoris and ζ Lep. Identifying objects with 12 μm excess is challenging because the photosphere usually dominates the total flux at this wavelength. High resolution mid-infrared imaging using LWS at Keck confirms that the debris disk around ζ Lep is compact. The disk is at most marginally resolved at 17.9 μm, suggesting that the dust probably lies within 6 AU although some dust may extend as far as 9 AU away from the star, consistent with the 230 K - 320 K color temperature inferred 10 μm - 60 μm photometry (Chen & Jura 2001). Similarly, 12 μm excess around M-dwarfs appears to be rare. Follow-up Keck LWS 11.7 μm photometry of nine late-type dwarfs with possible IRAS 12 μm excesses is unable to detect excess thermal emission from any of the candidates (Plavchan et al. 2005).

Warm silicates with grain temperatures, \( T_{gr} \sim 300 \) K, may produce emission in the 10μm Si-O stretch mode, if the dust grains are small, \( a < 10 \) μm. These features can provide insight into not only the composition but also the size of circumstellar dust grains. More than a decade ago, ground-based spectroscopy of β Pictoris revealed a broad 9.6 μm amorphous silicate and a weaker 11.2 μm crystalline olivine emission feature, similar to that observed toward comets Halley, Bradford, and Levy (Knacke et al. 1993), suggesting that the parent
bodies may be similar to small bodies in our solar system. Several systems with $T_{gr} > 300$ K have now been discovered that possess silicate emission features. Spitzer IRS spectra of HD 69830, a K0V star with an age of 2 Gyr, show mid-infrared emission features nearly identical to those observed toward Hale-Bopp but with a higher grain temperature, $T_{gr} = 400$ K instead of $T_{gr} = 207$ K (Beichman et al. 2005b). Gemini Michelle spectroscopy of BD+20 307 (HIP 8920), a G0V star with an estimated age of 300 Myr, suggests that amorphous and crystalline silicates are present; models of the 9 - 25 $\mu$m SED imply $T_{gr} = 650$ K and a remarkably high $L_{IR}/L_\star = 0.04$ for its age (Song et al. 2005). More warm dust systems with spectral features may soon be identified using Spitzer MIPS. For example, $\alpha^1$ Lib (a F3V star in the 200 Myr old Castor Moving Group) and HD 177724 (an A0V field star) possess such strong 24 $\mu$m excess that their 12 $\mu$m, 24 $\mu$m, and 70 $\mu$m fluxes can not be self-consistently modeled using a modified black body, suggesting that their strong 24 $\mu$m excesses may be the result of emission in spectral features (Chen et al. 2005b).

Since SED modeling is degenerate, high resolution imaging is needed to determine definitely the location of the dust and to search for structure in the disk. Nulling interferometers, now operational at Keck and the Multiple-Mirror Telescope (MMT), will allow dust in exo-zodial disks to be directly resolved. By placing the central star in a null, nulling interferometry destructively interferes stellar emission, obviating the need for accurate models of the stellar atmosphere. Without the bright central core, nulling observations can not only seek faint exo-zodial emission but can also apply the full diffraction limit of the telescope to resolve a source. For example, high-resolution Keck LWS imaging of the Herbig Ae star AB Aur at 18.7 $\mu$m (with a FWHM 0.5′′) struggles to resolve faint extended emission in the wings of the PSF at 0.4′′ from the star (Chen et al. 2003) while MMT nulling observations at 10.6 $\mu$m suppress all but 10% - 20% of the flux; fits of the percentage null versus rotation of the interferometer baseline suggest that the mid-infrared emitting component possess an angular diameter $\sim 0.2''$ with a position angle, $30^\circ \pm 15^\circ$, and an inclination, $45^\circ - 65^\circ$, from face-on (Liu et al. 2005). Nulling observations of Vega at 10.6 $\mu$m do not detect resolved emission at $> 2.1\%$ (3$\sigma$ limit) of the level of the stellar photospheric emission, suggesting that Vega possess $< 650 \times$ as much zodiacal emission as our solar system (Liu et al. 2004b).

4. Dust Removal Processes

Infrared spectroscopy and SED modeling suggest that the majority of debris disks possess central clearings. They may be generated by planets that gravitationally eject dust grains that are otherwise spiralling toward their orbit centers under Poynting-Robertson and stellar wind drag. However, a number of other processes may also contribute to presence of absence of central clearings:

Sublimation: If the grains are icy, then ice sublimation may play an important role in the destruction of grains near the star and may provide a natural explanation for the presence of central clearings in debris disks (Jura et al. 1998) implied from black body fits to Spitzer IRS spectra (Chen et al. 2006). The peak in the measured $T_{gr}$ distribution, estimated from black body fits to Spitzer IRS spectra, suggest that grains in debris disks typically have $T_{gr} = 110 - 120$ K
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(Chen et al. 2006), near the sublimation temperature of water ice in a vacuum, $T_{\text{sub}} = 150$ K. Since sublimation lifetimes are sensitively dependent on grain temperature, cool grains may possess ices. For example, $3.5 \mu m$ grains with $T_{\text{gr}} = 70$ K, have a sublimation lifetime, $T_{\text{subl}} = 1.3 \times 10^7$ Gyr while $16 \mu m$ grains with $T_{\text{gr}} = 160$ K, have a sublimation lifetime, $T_{\text{subl}} = 7.4$ minutes! Since the majority of debris disks have $T_{\text{gr}} < 120$ K, they could possess icy grains that may be detectable with Spitzer. Crystalline water ice possesses an emission feature at $61 \mu m$. Low resolution ($R = \lambda/\Delta\lambda = 15 - 25$) Spitzer MIPS SED mode observations may be able to detect emission from ices in debris disks.

**Radiation Effects:** The initial discovery of debris disks around high luminosity main sequence B- and A-type stars led to speculation that radiation pressure and the Poynting-Robertson effect may govern grain dynamics. The force due to radiation pressure acting on grains around A-type stars with radii $<\text{few} \mu m$ is larger than the force due to gravity; therefore, small grains are expected to be effectively removed from the circumstellar environment on timescales $\sim 10^4$ years (Artymowicz 1988). Larger particles are subject to the Poynting-Robertson effect in which dust grains lose angular momentum through interactions with outflowing stellar photons. As a result, larger grains spiral in toward their orbit center on timescales typically $<1$ Myr (Burns, Lamy, & Soter 1979). If a debris disk is composed of large black body grains which spiral inward under PR drag, then the dust should be contained in a continuous disk with constant surface density and an infrared spectrum, $F_\nu \propto \lambda$, at short wavelengths (Jura et al. 1998; Jura et al. 2004). **Spitzer** IRS spectroscopy of IRAS-discovered debris disks may have revealed one object that possess an excess spectrum better fit by $F_\nu \propto \lambda$ than a black body (HR 6670; Chen et al. 2006). Wyatt (2005) estimates that the grain density in IRAS-discovered debris disks is more than an order of magnitude too high for grains to migrate inward under Poynting-Robertson drag without suffering destructive collisions.

**Corpuscular Stellar Wind Effects:** The recent discovery of debris disks around solar-like and M-type stars has led to speculation that corpuscular stellar winds may contribute to grain removal in a manner analogous to radiation pressure and the Poynting-Robertson effect (Plavchan, Jura, & Lipsky 2005): (1) An outflowing corpuscular stellar wind produces a pressure on dust grains which overcomes the force due to gravity for small grains; however, the corpuscular stellar wind in only important for low luminosity stars (M-dwarfs) with strong stellar winds ($\sim 100 M_\odot$; Chen et al. 2005b). (2) Large particles orbiting the star are subject to a drag force produced when dust grains collide with protons in the stellar wind. These collisions decrease the velocities of orbiting dust grains and therefore their angular momentum, causing them to spiral in toward their orbit center. Stellar wind drag may explain the observed anti-correlation between Spitzer 24 $\mu m$ excess and ROSAT fluxes toward F-type stars in the 3 - 20 Myr Sco-Cen (Chen et al. 2005a) and the lack of 12 $\mu m$ excesses observed toward nearby, $>10$ Myr-old, late-type M-dwarfs (Plavchan et al. 2005). Recently, Strubbe & Chiang (2005) have reproduced the radial brightness profile of the AU Mic disk assuming that dust grains, produced in collisions between parent bodies on circular orbits at 43 AU, generate the resolved scattered light. In their model, large grains produce a surface density, $\sigma \propto r^0$, at $r < 43$ AU, under corpuscular and Poynting-Robertson drag modified by collisions; while,
Figure 1. (a) The grain lifetimes are plotted as a function of age around a B5V star. The Poynting-Robertson Drag/Stellar Wind drag lifetime is shown with a solid line; the sublimation lifetime is shown with a dotted line; and the collisional lifetime is shown with a dashed line, assuming $M_{\text{dust}} = 0.001, 0.01, 0.1, \text{ and } 1 \, M_{\odot}$ (from top to bottom). (b) same as (a) for an A5V star. No stellar wind drag is assumed. (c) same as (a) for a F5V star. The corpuscular stellar wind drag lifetime is shown with a solid line, assuming that $\dot{M}_{\text{wind}} = 100, 1000 \, \dot{M}_{\odot}$ (from top to bottom).

small grains, that are barely bound under corpuscular stellar wind and radiation pressure, produce a surface density, $\sigma \propto r^{-5/2}$, in the outer disk.

**Collisions:** If the particle density within the disk is high, then collisions may shatter larger grains into smaller grains that may be removed by radiation pressure and/or corpuscular stellar wind pressure. *Spitzer* MIPS imaging has recently resolved symmetric extended emission from the face-on disk around Vega with radii $>330$ AU, $>540$ AU, and $>810$ AU at 24 $\mu$m, 70 $\mu$m, and 160 $\mu$m, respectively, that may be explained by small grains that are radiatively driven from the system (Su et al. 2005). Comparison of the 24 $\mu$m emission with the 70 $\mu$m emission suggests that the system possesses 2 $\mu$m grains, well below the blow-out limit of 14 $\mu$m. Statistical studies of the decline in fractional infrared luminosity may as a function of time also shed light on the processes by which dust grains are removed. The fractional infrared luminosity of a debris disk is expected to decrease inversely with time, $L_{\text{IR}}/L_* \propto 1/t_{\text{age}}$, if collisions are the dominant grain removal process and is expected to decrease inversely with time squared, $L_{\text{IR}}/L_* \propto 1/t_{\text{age}}^2$, if corpuscular stellar wind and Poynting-Robertson drag are the dominant grain removal processes (Domink & Decin 2003). *Spitzer* MIPS, IRS and submillimeter studies of thermal emission from debris disks are consistent with a $1/t$ decay and a characteristic timescale, $t_o \sim 100 - 200$ Myr (Chen et al. 2006; Najita & Williams 2005; Liu et al. 2004a).

The dominant grain removal process within a disk is dependent not only on the luminosity of the central star and the strength of its stellar wind but also on grain distance from the central star. For example, Backman & Paresce (1993) estimate that collisions to small grain sizes and radiation pressure remove grains at 67 AU around Fomalhaut while the Poynting-Robertson effect removes grains at 1000 AU. In Figure 1, we plot the sublimation lifetime, the Poynting-
Robertson (and corpuscular stellar wind) drag lifetime, and the collision lifetime for average-sized grains around typical B5V, A5V, and F5V stars. Sublimation may quickly remove icy grains in the innermost portions of the disk. At larger radii, collisions dominate grain destruction, and at the largest radii, where the disk has the lowest density, Poynting-Robertson and corpuscular stellar wind drag may dominate grain destruction. For typical A5V and F5V stars, the collision lifetime is shorter than the drag lifetime if the disk has a dust mass between $0.001 M_⊕$ and $1 M_⊕$, even if the F5V star has a stellar wind with a mass loss rate as high as $\dot{M}_{\text{wind}} = 1000 M_⊙$. However, for a typical B5V star, the Poynting-Robertson and stellar wind drag lifetime may be shorter than the collision lifetime, especially at large radii, if the disk has a dust mass, $M_{\text{tot}} < 0.1 M_⊕$.

**Gas-Grain Interactions:** In disks with gas:dust ratios between 0.1 and 10, gas-grain interactions are expected to concentrate the smallest grains in the disk, with radii just above the blow-out size, at the outer edge of the disk, creating a ring of bright thermal emission. The presence of gas has been used to explain the central clearing in the HR 4796A disk (Takeuchi & Artymowicz 2001).

### 5. The Planet/Debris Disk Connection

The detection of asymmetries in the azimuthal brightness of debris disks can distinguish between whether the central clearings are dynamically sculpted by a companion or generated by other mechanisms. For example, a planet may create brightness peaks in a disk by trapping grains into mean motion resonances (Liou & Zook 1999; Quillen & Thorndike 2002). High resolution submillimeter imaging of $\epsilon$ Eri has revealed the presence of brightness peaks, that may be explained by dust trapped into the 5:3 and 3:2 exterior mean motion resonances of a $30 M_⊕$ planet, with eccentricity, $e = 0.3$, and semimajor axis, $a = 40$ AU (Ozernoy et al. 2000; Quillen & Thorndike 2002). Comparison of the 1997-1998 850 μm SCUBA map with the 2000-2002 850 μm SCUBA map, in Figure 2, indicates that three of the brightness peaks in the ring around $\epsilon$ Eri are orbiting counterclockwise at a rate of $1° \text{ yr}^{-1}$, consistent with that expected from planetary resonance models (Greaves et al. 2005; Ozernoy et al. 2000). The presence of two brightness peaks in submillimeter and millimeter maps of the face-on disk around Vega (Wilner et al. 2002) may also be explained by dust trapped, this time, into the 3:2 and 2:1 exterior mean motion resonances of a Neptune-mass planet that migrated from 40 AU to 65 AU over a period of 56 Myr (Wyatt 2003). However, the observation of orbital motion, the detection of the putative planet, and the observation of lower-level brightness asymmetries are needed to confirm this model.

If a planet in a debris disk has an eccentric orbit, then the planet may force circumstellar dust grains into elliptical orbits. Since dust grains at pericenter will be closer to the star and therefore warmer than grains at apocenter, disks with eccentric planets may possess brightness asymmetries (Wyatt et al. 1999). High resolution thermal infrared and submillimeter imaging of Fomalhaut has revealed a 30% - 15% brightness asymmetry in its disk ansae (Stapelfeldt et al. 2004; Holland et al. 2003). The dust grains in this disk may have experienced secular perturbations of their orbital elements by a planet, with $a = 40$ AU and
e = 0.15, which forces grains into an elliptical orbit with the star at one focus (Wyatt et al. 1999; Stapelfeldt et al. 2004). Recent HST ACS scattered light observations of Fomalhaut, shown in Figure 3, have confirmed that the star is not at the center of the dust grain orbits. Kalas, Graham, & Clampin (2005) measure an offset of \( \sim 15 \) AU between the geometric center of the disk and the position of the central star. A 15% - 5% brightness asymmetry is observed toward HR 4796A at near-infrared and mid-infrared wavelengths (Weinberger, Schneider, & Becklin 2000; Telesco et al. 2000), that may be explained if the orbit of HR 4796B has an eccentricity \( e = 0.13 \) or if there is a \( >0.1 M_{\text{Jup}} \) mass planet at the inner edge of the disk at 70 AU (Wyatt et al. 1998).

There is tantalizing evidence to suggest that giant planets and debris disks are correlated. A near-infrared coronagraphic survey of six FGK stars with radial velocity planets resolved disks around three objects (Trilling et al. 2000); however, NICMOS observations were unable to confirm the presence of a disk around one of the objects: 55 Cnc (Schneider et al. 2001). Spitzer MIPS observations of 26 planet-bearing FGK stars have discovered six objects that possess 70 \( \mu \)m excesses, corresponding to a disk fraction 23% (Beichman et al. 2005a), higher than the \( \sim 15\% \) observed toward field stars. The MIPS observations suggest that both the frequency and the magnitude of dust emission are correlated with the presence of known planets. Since the 70 \( \mu \)m excess is generated by cool dust (\( T_{gr} < 100 \) K) located beyond 10 AU, well outside the orbits of the discovered planets, the process which correlates the radial velocity planets at \(<5 \) AU with cool dust beyond 10 AU is not understood. By contrast, a submil-
Figure 3. (a) ACS scattered light observations of Fomalhaut with North up and East to the left. The star is offset from the geometric center of the disk by 15 AU, with the inner edge of the disk located at 133 AU - 158 AU from the star. (Courtesy P. Kalas, University of California, Berkeley); (b) The solid lines are line cuts, along the disk axis, through Spitzer MIPS 24 µm, 70 µm, and 160 µm images (from bottom to top) of Fomalhaut. The dashed lines are the profiles expected if a planet with $a = 40$ AU, $e = 0.15$ forces the eccentricity of dust grains in the disk. (Figure taken from Stapelfeldt et al. 2004)

6. Infalling Bodies and the Stable Gas Around $\beta$ Pictoris

Ultra violet and visual spectra of $\beta$ Pictoris possess time-variable, high velocity, red-shifted absorption features, initially discovered in Ca II H and K and Na I D and later in a suite of metal atoms (including C I, C IV, Mg I, Mg II, Al II, Al III, Si II, S I, Cr II, Fe I, Fe II, Ni II, Zn II); these features vary on timescales as short as hours and are non-periodic (Vidal-Madjar, Lecavelier des Etangs, & Ferlet 1998). The excitation of the atoms, the chemical abundance, the high measured velocities, and the rapid time-variability of the gas suggest that the material is circumstellar rather than interstellar. The velocity of the atoms, typically 100 km/sec - 400 km/sec, is close to the free fall velocity at a few stellar radii, suggesting that the absorption is produced as stellar photons
pass through the coma of infalling refractory bodies at distances <6 AU from the star (Karmann, Beust, & Klinger 2001; Beust et al. 1998). At these distances, refractory materials may sublimate from the surface of infalling bodies and collisions may produce highly ionized species such as C IV and Al III. If infalling bodies generate the observed features, then the fact that the features are preferentially red-shifted (rather than equally red- and blue-shifted) suggests that some process aligns their orbits. Scattering of bodies by a planet on an eccentric orbit (Levison, Duncan, & Wetherill 1994) and bodies in mean motion resonances with an eccentric planet, whose orbits decay via secular resonant perturbations by the planet (Beust & Morbidelli 1996), have been used to explain the preferentially red-shifted features; however, both models have difficulties.

The β Pictoris disk also possesses a stable component of gas at the velocity of the star. Many of the species that possess high velocity features also possess very low velocity features that vary slightly over timescales of hours to years. Spatially resolved visual spectra of β Pic have revealed the presence of a rotating disk of atomic gas, observed via emission from Fe I, Na I, Ca II, Ni I, Ni II, Ti I, Ti II, Cr I, and Cr II. Estimates of the radiation pressure acting on Fe and Na atoms suggest that these species should be accelerated to terminal velocities ∼1000s km/sec, significantly higher than is observed (Brandeker et al. 2004). One possible explanation for the low velocity of the atomic gas is that the gas is ionic and that Coulomb interactions between ions reduce the effective radiation pressure on the bulk gas. Fernández, Brandeker, & Wu (2005) suggest that ions in the disk couple together into a fluid, with an effective radiation pressure coefficient, that is bound to the system and that brakes the gas if $\beta_{eff} < 0.5$. In particular, they suggest that atomic carbon may be important for reducing the effective radiation pressure coefficient if the carbon abundance is greater than solar because the expected ionization fraction of atomic carbon is 0.5 and $F_{rad}/F_{grav} \approx 0$. Measurements of the line-of-sight abundance of ionized carbon, inferred from C II absorption in the O VI λ1038 emission using FUSE, confirm that the ionization fraction of carbon is ∼0.5 and suggest that carbon is overabundant by approximately a factor of 10 compared with measurements of the stable gas from the literature (Roberge et al. 2006, in preparation). Estimates of the total gas mass, inferred from measured elemental abundances and the gas density radial profile from scattered emission, suggest that the β Pic disk contains ∼0.004 M⊙ gas or a gas:dust ratio ∼0.1 (Roberge et al. 2006).

HST GHRS and STIS observations have also detected stable CO and C I (3P) absorption at the velocity of the star (Jolly et al. 1998; Roberge et al. 2000). Since CO and C I are expected to be photodissociated and photoionized by interstellar UV photons on timescales ∼200 years, these gases must be replenished from a reservoir. One possibility is that the CO is produced by slow sublimation of orbiting comets at several 10s of AU from the star; however, the observed CO possesses a low $^{12}$CO:$^{13}$CO ratio (R = 15±2) compared to solar system comets (R = 89). The overabundance of $^{13}$CO may be explained if it is produced from $^{12}$CO in the reaction

$$^{13}\text{C}^+ + ^{12}\text{CO} \leftrightarrow ^{13}\text{CO} + ^{12}\text{C}^+ + 35 \text{ K} \quad (1)$$

at temperatures below 35 K (Jolly et al. 1998). The order of magnitude difference in the measured column densities of C I (N(C I) = (2-4)×10^{16} cm^{-2};
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Roberge et al. (2000) and CO (N(CO) = 2.5 ± 0.5 × 10^{15} \text{ cm}^{-2}; K. H. Hinkel, private communication) suggest that C I is not produced by photodissociation of CO. Similarly, the disparity in the measured excitation temperatures for CO and C I, $T_{\text{ex}} = 20-25$ K and 80 K, suggests that the observed CO and C I are not cospatial (Roberge et al. 2000). One possibility is that the observed stable C I ($^3\text{P}$) is produced directly by sublimation of infalling bodies; if there are 100 bodies per year, then Roberge et al. (2000) estimate that each infalling object generates a C I ($^3\text{P}$) column density, $N_{\text{comet}} \sim 10^{11} \text{ cm}^{-2}$ if C I is only destroyed via ionization by interstellar photons with $\Gamma = 0.004 \text{ year}^{-1}$, consistent with evaporation of kilometer-sized objects.

7. Future Work

The age $\sim 10$ Myr appears to mark a transition in the gross properties of circumstellar disks. Pre-main sequence objects, such as T-Tauri and Herbig Ae/Be stars, possess optically thick, gaseous disks while young, main sequence stars possess optically thin, gas-poor disks. Recent studies of the 10 Myr old TW Hydrae association (Weinberger et al. 2004) and the 30 Myr Tucana-Horologium association (Mamajek et al. 2004) find that warm circumstellar dust ($T_{\text{gr}} = 200 - 300$ K), if present around young stars in these associations, reradiates less than 0.1% - 0.7% of the stellar luminosity, $L_{\text{IR}}/L_* < (1 - 7) \times 10^{-3}$. If the majority of stars possess planetary systems at an age of $\sim 10$ Myr, why do some stars, such as TW Hydrae, Hen 3-600, HD 98800, and HR 4796A in the TW Hydrae association, still possess large quantities of gas and/or dust? To investigate the origin of the dispersion in disk properties around $\sim 10$ Myr old stars, I have begun a multi-wavelength study of solar-like stars in the 5 - 20 Myr old (Preibisch et al. 2002; Mamajek et al. 2002) Scorpius-Centaurus OB Association, located at a distance of 118 - 145 pc away from the Sun.

One component of my study is a Spitzer MIPS 24 $\mu$m and 70 $\mu$m search for infrared excess around $\sim 100$ F- and G-type stars in Sco-Cen; the first results suggest that fractional 24 $\mu$m excess luminosity and fractional x-ray luminosity may be anti-correlated (Chen et al. 2005a). Observations of the first 40 targets detect strong 24 $\mu$m and 70 $\mu$m excess around six stars, corresponding to $L_{\text{IR}}/L_* = 7 \times 10^{-4} - 1.5 \times 10^{-2}$, and weak 24 $\mu$m excess around seven others, corresponding to $L_{\text{IR}}/L_* = 3.5 \times 10^{-5} - 4.4 \times 10^{-4}$. Only one of the 24 $\mu$m and 70 $\mu$m bright disks is detected by ROSAT while four of the weak 24 $\mu$m excess sources are. The presence of strong stellar winds, $\sim 1000 \times$ larger than our solar wind, may explain the depletion of dust in disks around x-ray emitting sources. Follow-up Spitzer IRS 5 - 35 $\mu$m spectroscopy may allow us to determine whether corpuscular stellar wind effectively removes dust grain in x-ray emitting systems. Since the inward drift velocity of dust grains under corpuscular stellar wind and Poynting-Robertson drag is $(1 + M_{\text{wind}}c^2/L_*)$ larger than under Poynting-Robertson drag alone, a disk influenced by strong stellar wind is expected to possess a constant surface density distribution. If the grains are large, then the infrared spectra will be well modeled by $F_\nu \propto \lambda$. However, if collisions and ejection by radiation pressure is the dominant grain removal mechanism, then the infrared spectra may be better modeled by a black body.
Other components of my study include Spitzer IRS 5 - 35 μm spectroscopy and MIPS SED mode observations of MIPS-discovered excess sources to search for emission from silicates and water ice and to constrain the composition and grain size. The minimum grain size, due to blow-out from radiation pressure, around stars in this sample is $a_{\min} \sim 0.5 - 2.0$ μm, small enough to produce spectral features. Ground-based 10 μm spectroscopy of HD 113766, an F3 binary member of the Sco-Cen subgroup Lower Centaurus Crux, suggests that the dust around this object is highly processed by an age of $\sim 16$ Myr. Fits to the 10 μm silicate feature suggest that $>90\%$ of the amorphous silicate mass is contained in large grains (with radii $a \sim 2$ μm) and that $\sim 30\%$ of the mass is contained in crystalline forsterite (Schutz, Meeus, & Sterzik 2005).

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