Extra-Solar Kuiper Belt Dust Disks

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The dust disks observed around mature stars are evidence that plantesimals are present in these systems on spatial scales that are similar to that of the asteroids and the KBOs in the Solar System. These dust disks (a.k.a. "debris disks") present a wide range of sizes, morphologies and properties. It is inferred that their dust mass declines with time as the dust-producing planetesimals get depleted, and that this decline can be punctuated by large spikes that are produced as a result of individual collisional events. The lack of solid state features indicate that, generally, the dust in these disks have sizes $\gtrsim$10 μm, but exceptionally, strong silicate features in some disks suggest the presence of large quantities of small grains, thought to be the result of recent collisions. Spatially resolved observations of debris disks show a diversity of structural features, such as inner cavities, warps, offsets, brightness asymmetries, spirals, rings and clumps. There is growing evidence that, in some cases, these structures are the result of the dynamical perturbations of a massive planet. Our Solar System also harbors a debris disk and some of its properties resemble those of extra-solar debris disks. From the cratering record, we can infer that its dust mass has decayed with time, and that there was at least one major "spike" in the past during the Late Heavy Bombardment. This offers a unique opportunity to use extra-solar debris disks to shed some light in how the Solar System might have looked in the past. Similarly, our knowledge of the Solar System is influencing our understanding of the types of processes which might be at play in the extra-solar debris disks.

1. INTRODUCTION

During the last two decades, space-based infrared observations, first with $IRAS$ and then with ISO and $Spitzer$, have shown that main sequence stars are commonly surrounded by dust disks (a.k.a. debris disks), some of which extend to 100s of AU from the central star. With the recent $Spitzer$ observations, the number of debris disks known to date is approaching 100, of which 11 are spatially resolved.

Dust particles are affected by radiation pressure, Poynting-Robertson and stellar wind drag, mutual collisions and collisions with interstellar grains. All these processes contribute to make the lifetime of the dust particles significantly shorter than the age of the star. Therefore, it was realized early on that this dust could not be primordial, i.e. part of the original molecular cloud where the star once formed, but it had to be a second generation of dust, likely replenished by a reservoir of (undetected) dust-producing planetesimals like the asteroids, comets and Kuiper Belt Objects (KBOs) in our solar system (*Backman and Paresce*, 1993). This represented a major leap in the search for other planetary systems: by 1983, a decade before extra-solar planets were discovered, $IRAS$ observations proved that there is planetary material surrounding nearby stars (*Aumann et al.*, 1984).

How do the extra-solar debris disks compare with our own Solar System? The existence of an inner planetary dust complex has long been known from observations of zodiacal light (*Cassini*, 1683). In the inner Solar System, dust is produced by debris from Jupiter family short period comets and asteroids (*Liou, Dermott and Xu*, 1995; *Dermott et al.*, 1994). The scattering of sunlight by these grains gives rise to the zodiacal light and its thermal emission dominates the night sky between 5 μm and 500 μm. This thermal emission dust was observed by the $IRAS$ and $COBE$ space telescopes, and the interplanetary dust particles (IDPs) were detected *in situ* by dust detectors on Pioneer 10 and 11, Voyager, Galileo and Ulyses spacecrafts. Its fractional luminosity is estimated to be $L_{dust}/L_* \sim 10^{-8}$–$10^{-7}$ (*Dermott et al.*, 2002). In the outer Solar System, significant dust production is expected from the mutual collisions of KBOs and collisions with interstellar grains (*Backman and Paresce*, 1993; *Stern*, 1996; *Yamamoto and Mukai*, 1998). The thermal emission of the outer Solar System dust is overwhelmed by the much stronger signal from the inner zodiacal cloud (so KB dust is not seen in the $IRAS$ and $COBE$ infrared maps). However, evidence of its existence comes from the Pioneer 10 and 11 dust collision events measured beyond the orbit of Saturn (*Landgraf et al.*, 2002). Extrapolating from the size distribution of KBOs, its fractional luminosity is estimated to be $L_{dust}/L_* \sim 10^{-7}$–$10^{-6}$ (*Stern*, 1996).

In this chapter we describe the debris disk phenomenon: how debris disks originate (§2); how they evolve in time (§3); what are they made of (§4); whether or not they are related to the presence of close-in planets (§5); and how planets can affect their structure (§6). We then discuss how debris disks compare to the Solar System's dust disk in the present and in the past (§7), and finish with a discussion of the prospects for the future of debris disk studies (§8). In summary, the goal of the chapter is to review how debris disks can help us place our Solar System into context within extra-solar planetary systems.

2. FROM PRIMORDIAL TO DEBRIS DISKS

Stars form from the collapse of dense regions of molecular clouds, and a natural by-product of this process is the formation of a circumstellar disk (*Shu, Adams and Lizano*, 1987; *Hartmann*, 2000). Observations show that young stars with masses below $\sim$4 $M_\odot$ down to brown dwarfs and planetary-mass objects have disks, while disks around more massive stars are more elusive, due to fast disk dissipation and observational difficulties as they tend to be highly embedded and typically very distant objects. Disk masses are estimated to be in the range 0.003 $M_\odot$–0.3 $M_\odot$, showing a large spread even for stars with similar properties (*Natta*, 2004 and references therein). For one solar mass stars, disk masses are 0.01 $M_\odot$–0.10 $M_\odot$ (*Hartmann*, 2000 and references therein). With regard to the disks sizes, there is evidence for gas on scales from 10 AU to 800 AU (*Simon, Dutrey and Gilloteau*, 2000). Both the disk masses and scales are comparable to the minimum mass solar nebula, $\sim$0.015 $M_\odot$. This is the total mass of solar composition material needed to produced the observed condensed material in the Solar System planets ($\sim$50 $M_\oplus$; *Hayashi*, 1981; *Weidenschilling*, 1977).

Eventually, infall to the disk stops and the disk becomes depleted in mass: most of the disk mass is accreted onto the central star; some material may be blown away by stellar wind ablation or by photo-evaporation by high-energy stellar photons, or stripped away by interactions with passing stars; the material that is left behind might coagulate or accrete to form planets (only $\sim$10% of the solar nebula gas is accreted into the giant planet's atmospheres). After $\sim 10^7$ years, most of the primordial gas and dust have disappeared (see e.g. *Hollenbach et al.*, 2005; *Pascucci et al.*, 2006), setting an important time constraint for giant planet formation models.

However, many main sequence stars older than $\sim 10^7$ years still show evidence of dust. The timescale of dust grain removal due to radiation pressure is of the order of an orbital period, while the Poynting-Robertson (P-R) drag lifetime of a dust grain located at a distance R is given by

$$t_{PR} = 710(\frac{b}{\mu m})(\frac{\rho}{g/cm^3})(\frac{R}{AU})^2(\frac{L_\odot}{L_*})\frac{1}{1+albedo}\ yr,$$

where b and ρ are the grain radius and density, respectively (*Burns, Lamy and Soter*, 1979 and *Backman and Paresce*, 1993). Grains can also be destroyed by mutual grain collisions, with a collisional lifetime of

$$t_{col} = 1.26 \times 10^4(\frac{R}{AU})^{3/2}(\frac{M_\odot}{M_*})^{1/2}(\frac{10^{-5}}{L_{dust}/L_*})yr$$

(*Backman and Paresce*, 1993). Because all the above timescales are generally much shorter than the age of the disk, it is inferred that the observed dust is not primordial but is likely produced by a reservoir of undetected kilometer-sized planetesimals producing dust by mutual collisions or by evaporation of comets scattered close to the star (*Backman and Paresce*, 1993).

2.1 Debris Disk Diversity as a Result of the Starting Conditions

At any particular age, observations show a great diversity of debris disks surrounding similar type stars (see §3.1 and *Andrews and Williams*, 2005). This may be due to the following factors that can influence the disks at different stages during their evolution: a) different initial masses and sizes, caused by variations in the angular momentum of the collapsing protostellar cloud; b) different external environments, causing variations in the dispersal time scales of the outer primordial disks, and therefore strongly affecting the formation of planets and planetesimals in the outer regions; and c) different planetary configurations, affecting the populations and velocity dispersions of the dust-producing planetesimals.

For example, the formation environment can have an important effect on the disk size and its survival. If the star is born in a sparsely populated Taurus-like association, the possibility of having a close encounter with another star that could truncate the outer protoplanetary disk is very small. In this environment, the probability of having a nearby massive star is also small, so photoevaporation does not play an important role in shaping the disk, and neither does the effect of explosions of nearby supernovae (*Hollenbach and Adams*, 2004). However, if the star is born in a densely populated OB association, the high density of stars results in a high probability of close encounters that could truncate the outer protoplanetary disk. In addition, nearby massive stars and supernovae explosions are likely to be present, affecting the size of the disk by photoevaporation, a process in which the heated gas from the outer disk evaporates into interstellar space, dragging along dust particles smaller than a critical size of 0.1 cm –1 cm before they have time to coagulate into larger bodies. Dust coagulation to this critical size takes $\sim 10^5$ yr–10^6 yr at 30 AU–100 AU (*Hollenbach and Adams*, 2004) , and therefore occurs rapidly enough for

KB formation to take place inside 100 AU, even around low mass stars in OB associations like the Trapezium in Orion. However, in Trapezium-like conditions (*Hillenbrand and Hartman*, 1998), where stars form within groups/clusters containing $>$100 members , at larger distances from the star photoevaporation takes place on a faster time scale than coagulation, and the dust is carried away by the evaporating gas causing a sharp cutoff in the formation of planetesimals beyond $\sim 100(\mathrm{M}_{star}/1\mathrm{M}_{\odot})$ AU, and therefore suppressing the production of debris dust (*Hollenbach and Adams*, 2004 and references therein). Debris disks can present a wide range of sizes because the distance at which photoevaporation takes place on a faster time scale than coagulation depends not only on the mass of the central star, but also on the initial disk mass and the mass and proximity of the most massive star in the group/cluster.

It is thought that the sun formed in an OB association: meteorites show clear evidence that isotopes with short lifetimes ($<10^5$ yr) were present in the solar nebula, which indicates that a nearby supernova introduced them immediately before the dust coagulated into larger solids (*Cameron and Truran*, 1977; *Tachibana et al.*, 2006); and in addition, it has been suggested that the edge of the KB may be due to the dynamical interaction with a passing star (*Kobayashi, Ida and Tanaka*, 2005), indicating that the sun may have been born in a high density stellar environment. In contrast, kinematic studies show that the majority of the nearby spatially resolved debris disks formed in loosely populated Taurus-like associations (see e.g. *Song, Zuckerman and Bessell*, 2003).

Debris disks found around field stars may be intrinsically different than those found around stars that once belonged to densely populated clusters, and one needs be cautious of the conclusions drawn from comparing these systems directly, as well as the conclusions drawn from stellar samples that include indiscriminately debris disks forming in these two very different environments.

3. DEBRIS DISKS EVOLUTION AND FREQUENCY

The study of debris disk evolution, i.e. the dependency on stellar age of the amount of dust around a main sequence star, is of critical importance in the understanding of the timescales for the formation and evolution of planetary systems, as the dust production rate is thought to be higher during the late stages of planet formation, when planetesimals are colliding frequently, than later on, when mature planetary systems are in place, planet formation is complete and the planets are not undergoing migration. Because it is obviously not possible to observe in real time the evolution of a particular system during Myr–Gyr, the study of debris disk evolution is based on the observations of a large number of stars with different ages, with the goal of determining how the amount of excess emission (related to the dust mass) and the probability of finding an excess depend on stellar age. The assumption is that all the disks will evolve in a similar way (but see caveats in §2.1).

The age-dependency of the dust emission (a.k.a "excess" with respect to the photospheric values) has been elusive until recently. The limited sensitivity of $IRAS$ allowed only the detection of the brightest and nearest disks, mostly around A stars. In addition, with its limited spatial resolution it was not possible to determine whether the infrared excess emission was coming from the star (i.e., from a debris disks) or from extended galactic cirrus or background galaxies. ISO, with its improvement of a factor of two in spatial resolution and a factor of 10 in sensitivity over $IRAS$, made a big step forward in the study of debris disks evolution. However, the ISO samples were too small to establish any age-dependency on a sound statistical basis. More recently, the $Spitzer$/MIPS instrument, with its unprecedented sensitivity at far-IR wavelengths (a factor of $\sim$100-1000 better than $IRAS$, and at least a factor of 10 in spatial resolution), has extended the search of disks around main sequence stars to more tenuous disks and to greater distances, providing more homogeneous samples. This is still on-going research but is leading to new perspective on debris disk evolution. The following subsections summarize the main results so far.

3.1 Observations

3.1.1 A stars

Using $Spitzer$/MIPS at 24 μm, *Rieke et al.* (2005) carried out a survey of 76 A-stars (2.5 $\mathrm{M}_{\odot}$) of ages 5 Myr–580 Myr, with all the stars detected to 7–σ relative to their photospheric emission. These observations were complemented with archival data from ISO and $IRAS$, resulting in a total of 266 A-stars in the final sample studied. The results show an overall decline in the average amount of 24 μm excess emission. Large excesses (more than a factor of 2 relative to the photosphere) decline from $\sim$25% in the youngest age bins to only one star ($\sim$1%) for ages $>$190 Myr; a functional fit to this data suggest a t_0/t decline, with t_0=100 Myr–200 Myr. Intermediate excesses (factors of 1.25–2) decrease much more slowly and are present in $\sim$7% of stars older than several hundred Myr. The persistence of excesses beyond 200 Myr rules out a fast $1/t^2$ decay. Using a sub-sample of 160 A-stars (including the ones in *Rieke et al.*, 2005), *Su et al.* (2006) confirmed that the 24 μm excess emission is consistent with a t_0/t decay, where $t_0\sim$150 Myr, while the 70 μm excess (tracing dust in the KB region) is consistent with t_0/t, where $t_0\gtrsim$400 Myr.

Even though there is a clear decay of the excess emission with time, *Rieke et al.* (2005) and *Su et al.* (2006) showed that at a given stellar age there are at least two orders of magnitude variations in the amount of dust: as many as 50%–60% of the younger stars ($<$30 Myr) do not show dust emission at 24 μm, while $\sim$ 25% of disks are still detected at 150 Myr.

3.1.2. FGK stars

For FGK stars, the excess rates at 24 μm decrease from $\sim$30%–40% for ages $<$50 Myr, to $\sim$9% for 100 Myr–200 Myr, and $\sim$1.2% for ages $>$1 Gyr (see Figure 1; *Siegler et al.*, 2006; *Gorlova et al.*, 2006; *Stauffer et al.*, 2005; *Beichman et al.*, 2005a; *Kim et al.*, 2005; *Bryden et al.*, 2006). At 70 μm, the excess rate is 10%–20% and is fairly constant for a wide range of ages (*Bryden et al.*, 2006; *Hillenbrand et al.*, in preparation). At first sight, it appears that for the older stars warm asteroid belt-like disks are rare (few percent), while cold KB-like disks are common (10%–20%). However, one needs to keep in mind that the sensitivity thresholds at 24 μm and 70 μm are different: $Spitzer$/MIPS is currently able to constrain dust masses at KB-like distances (10 AU–100 AU) that are 5–100 times the level of dust in our Solar System, and at AB-like distances (1–10 AU) that are 1000 times our zodiacal emission (*Bryden et al.*, 2006). However, spectroscopy observations with $Spitzer$/IRS are better suited to search for hot dust. Preliminary results by *Beichman et al.* (2006a) indicated that indeed warm excesses ($<$25 μm) with luminosities 50–1000 times the zodiacal emission are rare for stars $>$1 Gyr, found around only 1 out of 40 stars and in agreement with theoretical calculations of disk dispersal by *Dominik and Decin* (2003) that indicate that the fractional luminosity of the warm dust will generally drop below the IRS detectability level after 1 Gyr of evolution. In contrast, colder disks with excesses at 30–34μm, are found around 5 out of 41 stars, 12$\pm$5%, in agreement with *Bryden et al.*, (2006).

Even though the $Spitzer$/MIPS detection rate of excess emission for FGK stars is lower than for A-stars (see Figure 1), this is also a result of a sensitivity threshold: similar levels of excess emission are more easily detected around hotter stars than around colder stars. Accounting for this, the actual frequency of debris disks does not seem to be a strong function of stellar type (*Siegler et al.*, 2006), but it drops to zero for stars later than K1 (*Beichman et al.*, 2006b).

As for A-stars, FGK stars also show large variations in the amount of excess emission at a given stellar age at 24 μm (see Figure 2) and 70 μm. In addition, *Siegler et al.* (2006) found that the upper envelope of the ratio of the excess emission over the stellar photosphere at 24 μm also decays as t_0/t, with t_0=100 Myr and ages $>$20 Myr. At younger ages, $<$25 Myr, the decay is significantly faster and could trace the fast transition of the disk between primordial and debris stages (*Siegler et al.*, 2006). For colder dust (at 70 μm), even though there is a general trend to find less dust at older ages, the decay time is longer than for warmer dust (at 24 μm).

3.2 Theoretical Predictions

3.2.1 Inverse-Time Decay

If all the dust is derived from the grinding down of planetesimals, and assuming the planetesimals are destroyed after one collision, and that the number of collisions is proportional to the square of the number of planetesimals (N), then dN/dt $\propto$ -N^{-2} and $N \propto 1/t$. Therefore, the dust production rate, $R_{prod} \propto$ dN/dt $\propto N^2 \propto 1/t^2$. To solve for the amount of dust in the disk in steady state, one needs equate the dust production rate to the dust loss rate, R_{loss}, and this gives two different solutions depending on the number density of the dust in the disk (*Dominik and Decin*, 2003): (1) In the collisionally-dominated disks ($M_{dust} \gtrsim 10^{-3}$ M$_\oplus$), the dust number density is high and the main dust removal process are grain-grain collisions, so that $R_{loss} \propto n^2$, where n is the number of dust grains. From R_{prod} = R_{loss}, we get that $n \propto 1/t$. (2) In the radiatively-dominated disks ($M_{dust} \lesssim 10^{-3}$ M$_\oplus$), the dust loss rate is dominated by Poynting-Robertson drag, and therefore is proportional to the number of particles, $R_{loss} \propto n$, and from R_{prod} = R_{loss}, we get that $n \propto 1/t^2$.

The Kuiper Belt disk has little mass and is radiatively dominated. However, all the debris disks observed so far are significantly more massive than the KB because the surveys are sensitivity limited. *Wyatt* (2005a) estimates that the observed disks are generally collisionally dominated, so one would expect that the dust emission will evolve as $1/t$, in agreement with the Spitzer/MIPS observations of debris disks around A and FGK stars.

3.2.2. Episodic Stochastic Collisions

Numerical simulations of the evolution of dust generated from the collision of planetesimals around solar-type stars by *Kenyon and Bromley* (2005) predict that after 1 Myr there is a steady decline of the 24 μm excess emission, as the dust-producing planetesimals get depleted, a decay that is punctuated by large spikes produced by individual collisional events (see Figure 3). Therefore, the high degree of debris disk variability observed by Spitzer/MIPS - seen as spikes in Figure 2 - may be the result of recent collisional events. It is thought that these events initiate a collisional cascade leading to short-term increases in the density of small grains, which increases the brightness density of the disk by an order of magnitude. Because the clearing time of dust in the 24 μm-emitting zone (10 AU–60 AU) is $\sim$1 Myr–10 Myr (*Dominik and Decin*, 2003; *Kenyon and Bromley*, 2004), these individual events could dominate the properties of debris disks over Myr timescales (*Rieke et al.*, 2005). However, there is a discrepancy between these numerical simulations and the observations because the models do not predict excess ratios larger than two for stars older than 50 Myr, in disagreement with the existence of two of the outliers in Figure 2 (HIP 8920 and 2M0735-1450).

In addition to the large differences in excess emission found among stars within the same age range (for both A stars and FGK stars), the presence of large amounts of small grains in systems like HIP 8920 and HD 69830 (two of the outliers in Figure 2), Vega, and in a clump in β-Pic (*Telesco et al.*, 2005), indicate that recent collisional events have taken place in these systems (see discussion in §4).

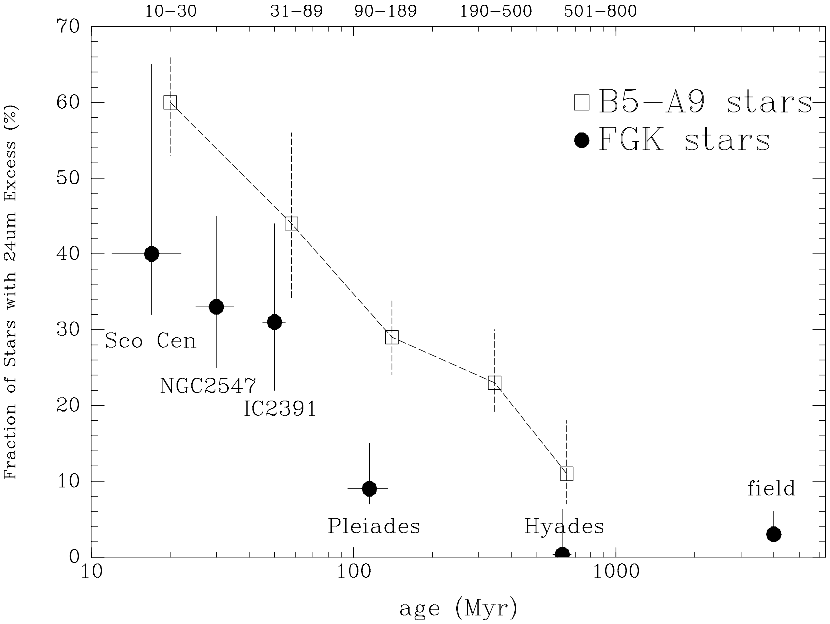

Fig. 1.— Fraction of early-type stars (open squares) and FGK stars (circles) with excess emission at 24 μm as a function of stellar age. Figure from *Siegler et al.* (2006) using data from *Chen et al.* (2005), *Gorlova et al.* (in prep), *Stauffer et al.* (2005), *Gorlova et al.* (2006), *Cieza, Cochran and Paulson* (2005), *Bryden et al.* (2006), *Rieke et al.* (2005) and *Su et al.* (2006). The age bins used in the early-type star survey are shown across the the top horizontal axis. Vertical error bars are 1-sigma binomial distribution uncertainties.

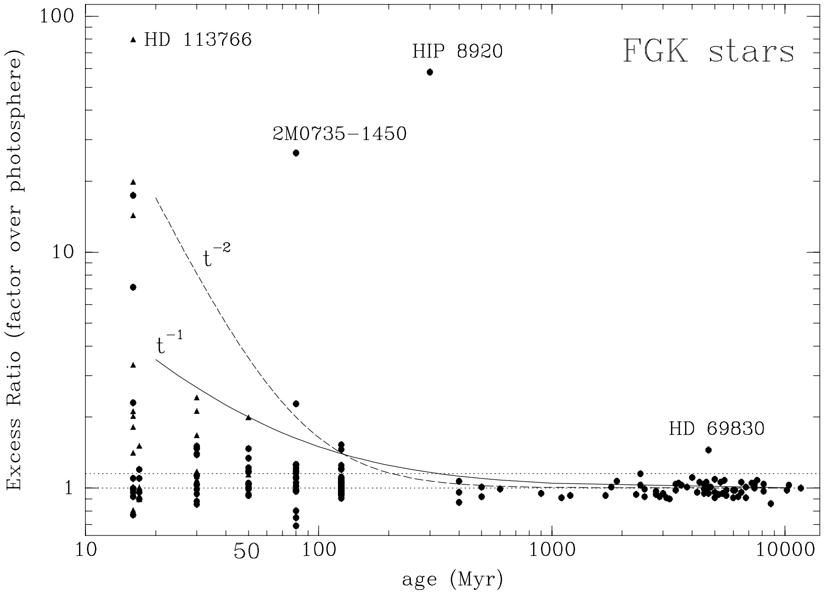

Fig. 2.— Ratio of the 24 μm excess emission to the predicted photospheric value for FGK stars as a function of stellar age. Triangles represent F0–F4 stars and circles represent F5–K7 stars (similar to the Sun). Stars aligned vertically belong to clusters or associations. Figure from *Siegler et al.* (2006) using the same data as in Figure 1 and from *Gorlova et al.* (2004), *Hines et al.* (2006) and *Song et al.* (2005).

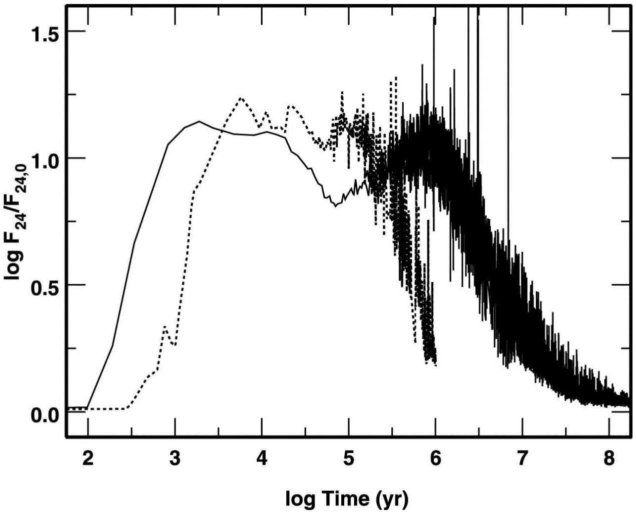

Fig. 3.— Evolution of the 24 μm excess as a function of time for two planetesimal disks extending from 0.68–1.32 AU (dashed line) and 0.4–2 AU (solid line). The central star is solar type. Excess emission decreases as planetesimals grow into Mars-sized or larger objects and collisions become increasingly rare. Figure from *Kenyon and Bromley* (2005).

The argument goes as follows: because small grains are removed quickly by radiation pressure, the dust production rate needed to account for the observations is very high, implying a mass loss that could not be sustained during the full age of the system. For example, in the Spitzer/MIPS observations of Vega (350 Myr old A star) show that the disk at 24 μm and 70 μm extends to distances of 330 AU and 540 AU from the star, respectively (*Su et al.*, 2006), far outside the $\sim$80 AU ring of dust seen in the submillimeter (*Wilner et al.*, 2002) that probably traces the location of the dust-producing planetesimals. *Su et al.* (2006) suggested that the dust observed in the mid-IR comes from small grains that were generated in a recent collisional event that took place in the planetesimals belt, and that are being expelled from the system under radiation pressure. This scenario would explain the large extent of the disk and the unusually high dust production rate (10^{15} g/s), unsustainable for the entire lifetime of Vega.

4. DEBRIS DISK GRAIN SIZE AND COMPOSITION

Most debris disk spectroscopy observations show little or no solid state features, indicating that at those stages the dust grains have sizes $\gtrsim$10 μm (*Jura et al.*, 2004; *Spapelfeldt et al.*, 2004), much larger than the sub-micron amorphous silicate grains that dominate the dust emission in young protoplanetary disks. While for A-stars, the lack of features is explained by the ejection of dust grains $<$10 μm by radiation pressure, the reason why this is also the case in debris disks around solar-type stars is still under debate. However, there are a few debris disks where spectral features have been observed, allowing us to set constrains on the particle size and composition. We briefly describe three of these systems: β-Pictoris, for which small quantities of silicates have been observed, and HIP 8920 and HD 69830, showing very strong silicate features.

β-Pictoris is one of the youngest and closest (19 pc) stars to Earth harboring a disk. It is an A5V star (2 $M_\odot$) with an estimated age of 12 Myr probably in the process of clearing out its protoplanetary disk, as the Solar System did 4 billion years ago. The disk is likely in the transition between the primordial and debris stages. Its dust disk, seen edge-on, extends to 1000 AU (i.e. $\sim$10 times that of the solar system) and contains a few lunar masses in grains that are relatively large ($>1\mu$m), with a large fractional luminosity, $L_{dust}/L_{star} \sim 3\times10^{-3}$. The break in the surface brightness profile of the disk indicates that the outer edge of the dust-producing planetesimal belt is at $\sim$ 120 AU (*Heap et al.*, 2000). Small particles produced by collisions in the belt are diffused out by radiation pressure, explaining the power law index of the brightness profile. On a smaller scale, spatially resolved spectroscopy observations indicate that the disk emission is dominated by grains emitting in the continuum, with moderate silicate emission features (amorphous and crystalline) seen only within 25 AU of the star. This indicates that the ratio of small to large silicate grains decreases with distance (*Weinberger, Becklin and Zuckerman*, 2003). Additional spatially resolved spectroscopy observations by *Okamoto et al.* (2004) showed that the sub-micron amorphous silicate grains have three peaks in their distribution around 6 AU, 16 AU and 30 AU, and their locations possibly trace three belts of dust-producing planetesimals. Finally, in the innermost system, the gas absorption lines detected toward the star indicate that there is a stable gas component that is located at about 1 AU and can be explained by the replenishment of gas by evaporating comets near the star, which would also give rise to the transient redshifted absorption events observed in the spectra. The frequency of star-grazing comets needed to explain the observations is several orders of magnitude higher than that found in the Solar System (see review in *Lagrange, Back-*

man and Artymowicz, 2000).

HIP 8920 (one of the outliers in Figure 2) is a 300 Myr old star with a disk that has a high surface density of small ($\lesssim$2.5 μm) dust grains at 1 AU from the star. Mid-infrared spectroscopy observations of the dust emission at 8 μm–13 μm show a very strong silicate feature with broad peaks at 10 and 11 μm that can be modeled with a mixture of amorphous and crystalline silicate grains (pyroxenes and olivines), with sizes of 0.1 μm–2.5 μm. Because HIP 8920 is too old for the dust to be primordial, it has been suggested that the anomalous large quantities of small grains could be the result of a recent collision (*Weinberger et al.*, priv. comm.).

HD 69830 is a 2 Gyr old K0V star (0.8 $M_\odot$, 0.45 $L_\odot$) with an excess emission at 8 μm–35 μm (60% over the photosphere at 35 μm, and with fractional luminosity $L_{dust}/L_{star} \sim 2\times10^{-4}$) that shows strong silicate features remarkably similar to the ones in the comet C/1995 O1 (a.k.a Hale-Bopp – see Figure 4 from *Beichman et al.*, 2005b). The spectral features are identified as arising from mostly crystalline olivine (including fosterite), and a small component of crystalline pyroxene (including enstatite), both of which are also found in interplanetary dust particles and meteorite inclusions (*Yoneda et al.*, 1993; *Bradley*, 2003). Observations show that there is no 70 μm emission, and this indicates that the dust is warm, originating from dust grains with a low long-wavelength emissivity, i.e. with sizes $\lesssim$70 μm/2π $\sim$ 10 μm, located within a few AU of the star, with the strong solid state features arising from a component of small, possibly submicron grains (*Beichman et al.*, 2005b). Upper (3-σ) limits to the 70 μm emission ($L_{dust}/L_{star} < 5\times10^{-6}$) suggest a potential Kuiper Belt less than 5 times as massive as the Solar System's. The emission between the crystalline silicate features at 9–11 μm, 19 μm and 23.8 μm indicates that there is a source of continuum opacity, possibly a small component of larger grains (*Beichman et al.*, 2005b). The emitting surface area of the dust is large (2.7×10^{23} cm^2, $>$1000 times the zodiacal emission), and the collisional and P-R drag time for submicron (0.25 μm) grains is $<$1000 yr. This indicates that the dust is either produced by the grinding down of a dense asteroid belt (22–64 times more massive than the Solar System's) located closer to the star, or originates in a transient event. *Wyatt et al.* (2006) ruled out the massive asteroid belt scenario and suggested that it is a transient event, likely the result of recent collisions produced when planetesimals located in the outer regions were scattered toward the star in a Late Heavy Bombardment-type event.

The disk around β-Pic seems to be "normal" in terms of its mass content with respect to the stellar age, and does not contain large amounts of small silicate grains; on the other hand, the disks around HIP 8920 and HD 69830 are unusually dusty and show strong silicate emission features, indicating that silicate features may be related to recent collisional events (*Weinberger et al.*, priv. comm.).

The composition of the disk can also be studied from the colors of the scattered light images. In general, debris disks are found to be red or neutral. Their redness has commonly been explained by the presence of 0.4 μm silicate grains, but except for the two exception mentioned above (HIP 8920 and HD 69830), spatially resolved spectra have shown that debris disks do not generally contain large amounts of small silicate grains; a possible explanation for the colors could be that grains are intrinsically red, perhaps due to an important contribution from organic materials (*Weinberger et al.*, priv. comm; see also *Meyer et al.*, 2006). For comparison, KBOs present a wide range of surface colors, varying from neutral to very red (see chapter by *Doressoundiram et al.* in this book).

5. DEBRIS DISKS AND CLOSE-IN PLANETS: RELATED PHENOMENA?

The observation of debris disks indicates that planetesimal formation has taken place around other stars. In these systems, did planetesimal formation proceed to the formation of one or move massive planets, as was the case of the Sun? In the following cases the answer is yes: HD 33636, HD 50554, HD 52265, HD 82943, HD 117176 and HD 128311 are stars known from radial velocity observations to have at least one planet, and they all show 70 μm excess (with an excess SNR of 15.4, 14.9, 4.3, 17.0, 10.2 and 7.1, respectively) arising from cool material ($T<100$ K) located mainly beyond 10 AU, implying the presence of outer belt of dust-producing plantesimals. Their fractional luminosities, L_{dust}/L_{star}, in the range $(0.1–1.2)\times10^{-4}$ are $\sim$100 times that inferred for the KB (*Beichman et al.*, 2005a). Similarly, HD 38529 is a two-planet system that also shows 70 μm excess emission (with an excess SNR of 4.7; *Moro-Martín et al.*, 2007b). HD 69830 is a three-planet system with a strong 24 μm excess (see §4; *Beichman et al.*, 2005b). And finally, ϵ-Eridani has at least one close-in planet (*Hatzes et al.*, 2000) and a spatially resolved debris disk (*Greaves et al.*, 2005).

The nine systems above confirm that debris disks and planets co-exist. But are debris disks and the presence of massive planets related phenomena? *Moro-Martín et al.* (2007a) found that from the observations of the Spitzer Legacy Program FEPS and the GTO results in *Bryden et al.* (2006), there is no sign of correlation between the presence of IR excess and the presence of radial velocity planets (see also *Greaves et al.*, 2004a). This, together with the observation that high stellar metallicities are correlated with the presence of giants planets (*Fischer and Valenti*, 2005) but not correlated with the presence of debris disks (*Greaves, Fischer and Wyatt*, 2006), may indicate that planetary systems with KBOs producing debris dust by mutual collisions may be more common than planetary systems harboring gas giant planets (*Greaves, Fischer and Wyatt*, 2006; *Moro-Martín et al.*, 2007a).

Most of the debris disks detected with $Spitzer$ emit only at 70 μm, i.e. the dust is mainly located at distances $>$10 AU, while the giant planets detected by radial velocity studies are located within a few AU of the star, so the dust and

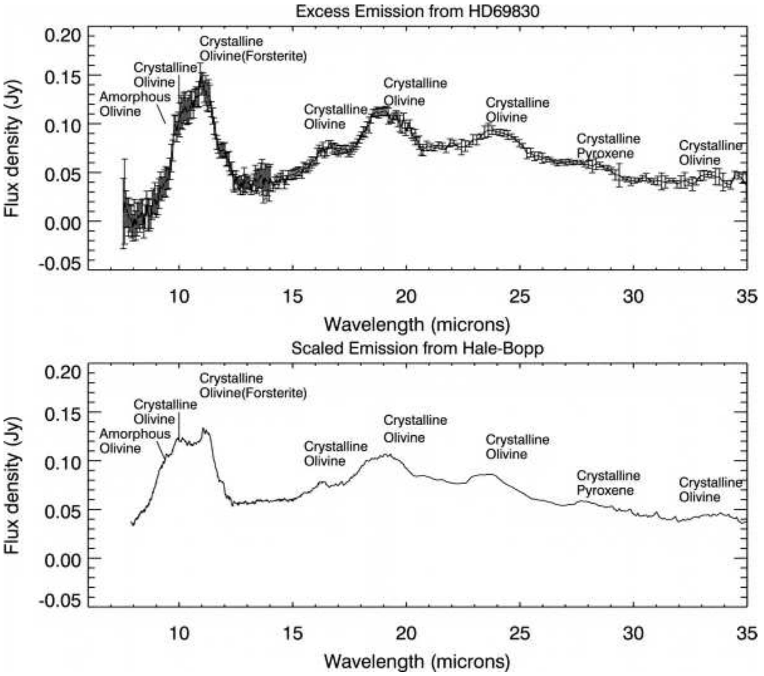

Fig. 4.— Top: Spectrum of the excess of HD 69830. Bottom: spectrum of the comet Hale-Bopp from *Crovisier et al.* (1996) normalized to a blackbody temperature of 400 K to ease the comparison of the two spectra (the observed blackbody temperature is 207 K). Figure from *Beichman et al.* (2005b).

the giant planet(s) could be dynamically unconnected (but see *Moro-Martín et al.*, 2007b). What about more distant giant planets? Do debris disk observations contain evidence for long-period planets? We discuss this issue in the next section.

6. DEBRIS DISK STRUCTURE

The gravitational perturbations produced by a massive planet on both, the dust-producing planetesimals and on the dust particles themselves, can create structure in the debris disk giving rise to observable features (see e.g. *Roques et al.*, 1994; *Mouillet et al.*, 1997; *Wyatt et al.*, 1999; *Wyatt*, 2005, 2006; *Liou and Zook*, 1999; *Moro-Martín and Malhotra*, 2002, 2003, 2005; *Moro-Martín, Wolf and Malhotra*, 2005; *Kuchner and Holman*, 2003).

If the disk is radiatively-dominated, $M_{dust} \lesssim 10^{-3}$ M$_\oplus$, as is the case of the KB dust disk, and if the system contains an outer belt of planetsimals and one or more inner planets, the disk structure is created because the dust grains migrate inward due to the effect of P-R drag, eventually coming in resonance with the planet and/or crossing its orbit. This has important consequences on their dynamical evolution and therefore on the debris disk structure.

If the disk is collisionally-dominated, $M_{dust} \gtrsim 10^{-3}$ M$_\oplus$, before the dust grains migrate far from their parent bodies, they will suffer frequent collisions that could grind them down into smaller grains that are blown away by radiation pressure. In this case, the dust grains may not survive long enough to come into resonance with an inner planet. However, the structure of the KBOs gives strong evidence that Neptune migrated outward. This process may have also taken place in other planetary systems, where the outward migration of a planet could have scattered planetesimals out of the system or trapped them into Plutino-like orbits. Because the larger dust particles trace the location of the parent bodies, this outward migration can strongly affect the debris disk structure.

In this section we summarize the processes by which planets can affect the debris disk structure and the observational evidence that indicates that planets may be responsible for some of the features seen.

6.1 Theoretical Predictions

6.1.1. Gravitational Scattering

Massive planets can eject planetesimals and dust particles out of the planetary system via gravitational scattering. In the radiatively-dominated disks, if the sources of dust are outside the orbit of the planet, this results in an $inner\ cavity$, a lower density of dust within the planet's orbit, as the particles drifting inward due to P-R drag are likely to be scattered out of the system when crossing the orbit of the planet (*Roques et al.*, 1994). Similarly, planetesimals can get scattered out by a planet migrating outward, resulting in a depletion of planetesimals and dust inside the orbit of the planet. Planets with masses of 3 M$_{Jup}$–10 M$_{Jup}$ located between 1 AU–30 AU in a circular orbit around a solar type star eject $>$90% of the dust grains that go past their orbits by P-R drag; a 1 M$_{Jup}$ planet at 30 AU ejects $>$80% of the grains, and about 50%–90% if located at 1 AU, while a 0.3 M_{Jup} planet is not able to open a gap, ejecting $<$ 10% of the grains (*Moro-Martín and Malhotra*, 2005). These results are valid for dust grains sizes in the range 0.7 μm–135 μm, but are probably also applicable to planetesimals (in the case of an outward migrating planet), because gravitational scattering is a process independent of mass as long as the particle under consideration can be considered a "test particle", i.e. its mass is negligible with respect to that of the planet.

6.1.2. Resonant Perturbations

Resonant orbits are locations where the orbital period of the planet is $(p+q)/p$ times that of the particle (which can be either a dust grain or a planetesimals), where p and q are integers, $p>0$ and $p+q \geqslant 1$. Each resonance has a libration width that depends on the particle eccentricity and the planet mass, in which resonant orbits are stable. The region close to the planet is chaotic because neighboring resonances overlap (*Wisdom*, 1980). Because of the finite width of the resonant region, resonant perturbations only affect a small region of the parameter space, but this region can be over-populated compared with the size of that parameter space by the inward migration of dust particles under the effect of P-R drag or by the outward migration of the resonance as the planet migrates (*Malhotra*, 1993; *Malhotra*, 1995; *Liou and Zook*, 1995; *Wyatt*, 2003). When the particle crosses a mean motion resonance ($q>0$), it receives energy from the perturbing planet that can balance the energy loss due to P-R drag, halting the inward motion of the particle and giving rise to planetary resonant rings. Due to the geometry of the resonance, the spatial distribution of material in resonance is asymmetric with respect to the planet, being concentrated in clumps. There are four basic high-contrast resonant structures that a planet with eccentricity $\lesssim 0.6$ can create in a disk of dust released on low eccentricity orbits: a $ring\ with\ a\ gap$ at the location of the planet; a $smooth\ ring$; a $clumpy\ eccentric\ ring$; and an $offset\ ring$ plus a pair of $clumps$, with the appearance/dominance of one of these structures depending on the mass and eccentricity of the planet (*Kuchner and Holman*, 2003).

6.1.3. Secular Perturbations

When a planet is embedded in a debris disk, its gravitational field perturbs the orbits of the particles (dust grains or planetesimals). Secular perturbations are the long-term average of the perturbing forces, and act on timescales $>$0.1 Myr (see overview in *Wyatt et al.*, 1999). As a result of secular perturbations, the planet tries to align the particles with its orbit. The first particles to be affected are the ones closer to the planet, while the particles further away are perturbed at a later time, therefore, if the planet's orbital plane is different from that of the planetesimal disk, secular perturbations will result in the formation of a $warp$. A warp will also be created if there are two planets on non-coplanar orbits.

If the planet is in an eccentric orbit, the secular perturbations will force an eccentricity on the dust particles, and this will create an $offset$ in the disk center with respect to the star and a $brightness\ asymmetry$ in the re-emitted light, as the dust particles near periastron are closer to the star and therefore hotter than the dust particles at the other side of the disk.

Because secular perturbations act faster on the particles closer to the planet, and the forced eccentricities and pericenters are the same for particles located at equal distances from the planet, at any one time the secular perturbations of a planet embedded in a planetesimal disk can result in the formation of two $spiral\ structures$, one inside and one outside the planet's orbit (*Wyatt*, 2005b).

6.2 Observations

Some of the structural features described above have indeed been observed in the spatially resolved images of debris disks (see Figure 5).

6.2.1. Inner Cavities

Inner cavities have long been known to exist. They were first inferred from the $IRAS$ spectral energy distributions (SEDs) of debris disks around A stars, and more recently from the $Spitzer$ SEDs of debris disks around AFGK stars. From the modeling of the disk SED, we can constrain the location of the emitting dust by fixing the grain properties. Ideally, the latter can be constrained through the modeling of solid state features, however, most debris disk spectroscopy observations show little or no features, in which cases it is generally assumed that the grains have sizes $\gtrsim$10 μm and are composed of "astronomical silicates" (i.e. silicates with optical constants from *Weingartner and Draine*, 2001). In most cases, the SEDs show a depletion (or complete lack) of mid-infrared thermal emission that is normally associated with warm dust located close to the star, and this lack of emission implies the presence of an inner cavity (or more accurately, a depletion of grains that could be traced observationally – see e.g. *Meyer et al.*, 2004; *Beichman et al.*, 2005a; *Bryden et al.*, 2006; *Kim et al.*, 2005; *Moro-Martín, Wolf and Malhotra*, 2005; *Moro-Martín et al.*, 2007b; *Hillenbrand et al.*, in preparation).

Spatially resolved observations of nearby debris disks have confirmed the presence of central cavities. From observations in scattered light, *Kalas et al.* (2006) concluded that debris disks show two basic architectures, either narrow belts about 20–30 AU wide and with well-defined outer boundaries (HR 4796A, Fomalhaut and HD 139664); or wide belts with sensitivity-limited edges implying widths $>$50 AU (HD 32297, β-Pic, AU-Mic, HD 107146 and HD 53143). Millimeter and sub-millimeter observations show that inner cavities are also present in ϵ Eri (50 AU; *Greaves et al.*, 1998), Vega (80 AU; *Wilner et al.*, 2002) and η Corvi (100 AU; *Wyatt et al.*, 2005).

Are all these cavities created by the gravitational ejection of dust by massive planets? *Wyatt* (2005a) pointed out that

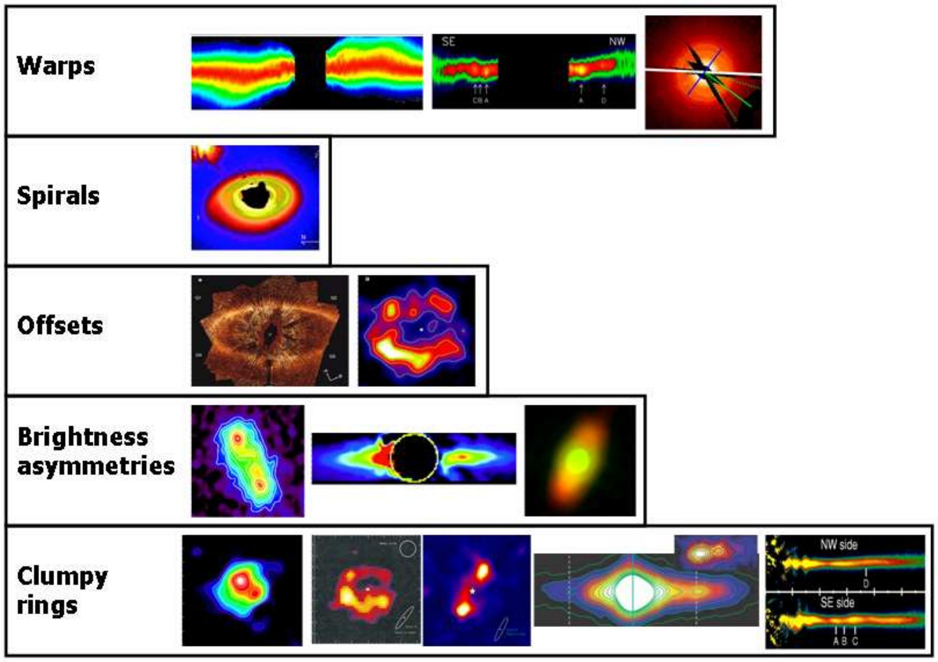

Fig. 5.— Spatially resolved images of debris disks showing a wide diversity of debris disk structure. From left to right the images correspond to: (*1st row*) β-Pic (STIS CCD coronography at 0.2–1 μm; *Heap et al.*, 2000), AU-Mic (Keck AO at 1.63 μm; *Liu*, 2004) and TW Hydra (STIS CCD coronography at 0.2–1 μm; *Roberge, Weinberger and Malumuth*, 2005); (*2nd row*) HD 141569 (HST/ACS at 0.46–0.72 μm; *Clampin et al.*, 2003); (*3rd row*) Fomalhaut (HST/ACS at 0.69–0.97 μm; *Kalas et al.*, 2005) and ϵ-Eri (JCMT/SCUBA at 850 μm; *Greaves et al.*, 2005); (*4th row*) HR4796 (Keck/OSCIR at 18.2 μm; *Wyatt et al.*, 1999), HD 32297 (HST/NICMOS coronography at 1.1 μm; *Schneider, Silverstone and Hines*, 2005) and Fomalhaut (Spitzer/MIPS at 24 and 70 μm; *Stapelfeldt et al.*, 2004); (*5th row*) Vega (JCMT/SCUBA at 850 μm; *Holland et al.*, 1998), ϵ-Eri (JCMT/SCUBA at 850 μm; *Greaves et al.*, 1998), Fomalhaut (JCMT/SCUBA at 450 μm; *Holland et al.*, 2003), β-Pic (Gemini/T-ReCS at 12.3 μm; *Telesco et al.*, 2005) and Au-Mic (HST/ACS at 0.46–0.72 μm; *Krist et al.*, 2005). All images show emission from 10s to 100s of AU.

because of the limited sensitivity of the instruments, most of the debris disks observed so far have large number densities of dust particles and therefore are collisionally-dominated. In this regime, mutual collision naturally create inner cavities without the need of invoking the presence of a planet to scatter out the dust particles. But this scenario assumes that the parent bodies are depleted from the inner cavity, and the presence of an inner edge to the planetesimal distribution may still require the presence of a planet.

Planet formation theories predict the formation of cavities because the planets form faster closer to the star, depleting planetesimals from the inner disk regions. But planet formation and circumstellar disk evolution are still under debate, so even though cavities may be credible evidence for the presence of planets, the connection is not well understood.

6.2.2. Rings and Clumps

Face-on debris disks showing structure that could be associated with resonant trapping are Vega (*Wilner et al.*, 2002), ϵ-Eridani (*Ozernoy et al.*, 2000; *Quillen and Thorndike*, 2002) and Fomalhaut (*Wyatt and Dent*, 2002), while in edge-on debris disks resonant trapping may lead to the creation of brightness asymmetries like those observed in β-Pic (*Thommes and Lissauer*, 2003) and AU-Mic.

6.2.3. Warps, Offsets, Spirals and Brightness Asymetries

The debris disk around β-Pic has two warps, one in the outer disk (*Heap et al.*, 2000) and another one in the inner disk (with a wavy structure consisting of 4 clumps with counter parts at the other side of the disk and none of them aligned with each other; *Wahhaj*, 2005). New $Hubble$/ACS observations in scattered light show that the inner "warp" in beta-Pic is really a secondary disk inclined by 5 degrees with respect to the primary disk. This secondary disk extends to ∼80 AU and is probably sustained by a planet that has perturbed planetesimals from the outer primary disk into coplanar orbits. Another debris disk showing a warp is AU Mic, where the outer part of the disk ($>$80 AU) is tilted by 3 degrees, while the rest of the disk is seen mostly edge-on.

The debris disks around HR 4796 shows a 5% brightness asymmetry that could be the result of a small forced eccentricity imposed by the binary companion HR 4796B, or by an unseen planet located near the inner edge of the disk (*Wyatt et al.*, 1999). Other debris disks showing brightness asymmetries are HD 32297 (*Schneider, Silverstone and Hines*, 2005) and Fomalhaut (*Stapelfeldt et al.*, 2004), and showing offsets are Fomalhaut (15 AU; *Kalas*, 2005) and ϵ-Eridani (6.6 AU–16.6 AU; *Greaves et al.*, 2005).

A spiral structure has been seen at 325 AU in the debris disk around HD 141569, thought to be created by a 0.2 M$_{Jup}$–2 M$_{Jup}$ planet located at 235 AU–250 AU with an eccentricity of 0.05–0.2 (*Wyatt*, 2005b).

In summary, dynamical simulations show that gravitational perturbations by a massive planet can result in the formation of the inner cavities, warps, offsets, brightness asymmetries, spirals, rings and and clumps, and these features have indeed been observed in several debris disks.

6.3 Other Possible Causes of Debris Disk Structure

Clumps could trace the location of a planetesimal suffering a recent massive collision, instead of the location of dust-producing planetesimals or dust particles trapped in mean motion resonances with a planet. This alternative interpretation has been proposed to explain the brightness asymmetries seen in the mid-IR observations of the inner β-Pic disk (*Telesco et al.*, 2005). The brightness asymmetry could arise from the presence of a bright clump composed of dust particles with sizes smaller than those in the main disk, that could be the result of the collisional grinding of resonantly trapped planetesimals (making the clump long-lived, and likely to be observed), or the recent cataclysmic break-up of a planetesimal with a size $>$100 km (in which case there is no need to have a massive planet in the system, with the disadvantage that the clump is short-lived and we are observing it at a very particular time, maybe within ∼50 yr of its break-up; *Telesco et al.*, 2005). However, the clumps seen in the submillimeter in systems like Fomalhaut are not easily explained by catastrophic planetesimal collisions because the dust masses involved are too large, implying the unlikely collision of two ∼ 1400 km sized planetesimals (*Wyatt and Dent*, 2002). Brightness asymmetries could also be due to "sandblasting" of a debris disk by interstellar dust particles, as the star moves with respect to the ISM, but this effect would only affect (if anything) the outskirts of the disk, $\gtrsim$400 AU from the central star (*Artymowicz and Clampin*, 1997). Asymmetries and spiral structure can also be produced by binary companions, but e.g. cannot explain all structure seen in the HD141569 disk. And spiral structure and subsequent collapse into nested eccentric rings can also be produced by a close stellar flyby (*Kalas, Deltorn and Larwood*, 2001). This could in principle explain the clumps seen in the NE of the β-Pic disk, however, it would require a flyby on the scale of $<$1000 AU and these encounters are expected to be very rare. In addition, now the same type of structure is seen in AU-Mic, another star of the same stellar group, making it unlikely that both stars suffered such a fine tuned close encounter. Other effects that could be responsible for some of the disk features include instrumental artifacts, background/foreground objects, dust migration in a gas disk, photoevaporation, interaction with the stellar wind and magnetic field, and dust avalanches (*Grigorieva, Artymowicz and Thebault*, 2006).

6.4 Debris Disks as a Planet Detection Technique

The two well established planet detection techniques are the radial velocity and the transit studies, and both are sensitive to close-in planets only. Direct detection of massive planets has proven to be very difficult even in their younger (i.e. brighter) stages. This means that old long-period planets are likely to remain elusive in the foreseeable future. However, we have seen that debris disk structure is sensitive to the presence of massive planets with a wide range of semimajor axis (out to 100s of AU), complementing the parameter space covered by the other techniques. In this regard, the study of debris disk structure has the potential to characterize the diversity of planetary systems and to set constrains on the outward migration of extra-solar ”Neptunes”.

However, before claiming that a planet is present in a debris disk system, the models should be able to explain observations at different wavelengths and to account for dust particles of different sizes. Different wavelengths trace different particles sizes, and different particle sizes have different dynamical evolutions that result in different features. Large particles dominate the emission at longer wavelengths, and their location might resemble that of the dust-producing planetesimals. The small grains dominate at short wavelengths; they interact with the stellar radiation field more strongly so that their lifetime in the disk is shorter, and therefore their presence may signal a recent dust-producing event (like a planetesimal collision). And even shorter wavelengths are needed to study the warm dust produced by asteroid-like bodies in the terrestrial planet region. In addition, some of the dynamical models are able to make testable predictions, as for example the position of resonant structures in multi-epoch imaging, as it is expected that they will orbit the planet with periods short enough to result in detectable changes within a decade. This rotation may have already been detected in ϵ-Eri to a 2-σ level (*Greaves et al.*, 2006). Dynamical models can also predict the location of the planets, but detecting the planet directly is not feasible with current technology.

7. THE SOLAR SYSTEM DEBRIS DISK

Our Solar System harbors a debris disk, and the inner region is known as the zodiacal cloud. The sources of dust are very heterogeneous: asteroids and comets in the inner region, and KBOs and interstellar dust in the outer region. The relative contributions of each of these sources to the dust cloud is likely to have changed with time, and even the present relative contributions are controversial: from the He content of the interplanetary dust particles collected at Earth, it is possible to distinguish between low and high velocity grains, associated with an asteroidal and a cometary origin, respectively. The ratio between the two populations is not well known, but is thought to differ by less than a factor of 10. The contribution of the asteroids to the zodiacal cloud is confirmed by the observation of dust bands (associated with the formation of individual asteroidal families), and must amount to at least a few 10%. The contribution from the comets is also confirmed by the presence of dust trails and tails. In the outer Solar System, on spatial scales that are more relevant for comparison with other debris disks, significant dust production is expected from the mutual collisions of KBOs and collisions with interstellar grains (*Backman and Paresce*, 1993; *Stern*, 1996; *Yamamoto and Mukai*, 1998). There is evidence for the presence of KB dust from the Pioneer 10 and 11 dust collision events that took place beyond the orbit of Saturn (*Landgraf et al.*, 2002), but the dust production rates are still uncertain.

In parallel to the debris disks properties described in the previous sections, we will now review some of the properties of the Solar System debris disk. Comparison of these with the extra-solar systems, can shed some light into the question of whether or not our Solar System is unique.

7.1 Evolution

Debris disks evolve with time. Therefore, the imaging of debris disks at different evolutionary stages could be equivalent to a Solar System “time machine”. However, one needs to be cautious when comparing different systems because: (1) the initial conditions and forming environment of the disks may be significantly different (see §2.1); (2) the Solar System debris disk is radiatively-dominated, while the extra-solar debris disks observed so far, being significantly more massive, are collisionally-dominated, so they are in different physical regimes; and (3) the physical processes affecting the later evolution of the disks depend strongly on the planetary configuration, e.g. by exciting and/or ejecting planetesimals, and radial velocity observations indicate that planetary configurations are very diverse. With those caveats in mind, we can draw some broad similarities between the time evolution of debris disks and the dust in our Solar System.

As we saw in §3, debris disk evolution consists of a slow decay of dust mass, punctuated by spikes of high activity, possibly associated with stochastic collisional events. Similarly, numerical simulations by *Grogan et al.* (2001) indicated that over the lifetime of the Solar System, the asteroidal dust surface area slowly declined by a factor of 10, and that superimposed on this slow decay, asteroidal collisions produced sudden increases of up to an order of magnitude, with a decay time of several Myr. Overall, for the 4 Gyr old Sun, the dust surface area of the zodiacal cloud is about twice its quiescent level for 10% of the time. Examples of stochastic events in the recent Solar System history are the fragmentation of the asteroid giving rise to the Hirayama asteroid families, the creation 8.3 Myr ago of the Veritas asteroid families, that gave rise to a collisional cascade still accounting for ∼25% of the zodiacal thermal emission (*Dermott et al.*, 2002), as well as collisional events resulting in the formation of the dust bands observed by $IRAS$ (*Sykes and Greenberg*, 1986). In addition to these small “spikes” in the dust production rate at late times, there has been one major event in the early Solar System evolution that produced much larger quantities of dust. Between 4.5 Gyr to 3.85 Gyr there was a heavy cratering phase that resurfaced the Moon and the terrestrial planets, creating the lunar basins and leaving numerous impact craters in the Moon, Mercury and Mars (all with little surface erosion). This "Heavy Bombardment" ended $\sim$3.85 Gyr ago, 600 Myr after the formation of the Sun. Thereafter, the impact rate decreased exponentially with a time constant ranging from 10 Myr–100 Myr (*Chyba*, 1990). *Strom et al.* (2005) argue that the impact crater record of the terrestrial planets show that the Late Heavy Bombardment was an event lasting 20–200 Myr, that the source of the impactors was the main asteroid belt, and that the mechanism for this event was the orbital migration of the giant planets which caused a resonance sweeping of the asteroid belt and a large scale ejection of asteroids into planet-crossing orbits. This event would have been accompanied by a high rate of asteroid collisions; the corresponding high rate of dust production would have caused a large spike in the warm dust luminosity of the Solar System. Although this phenomenon has not been modeled in any detail, it is likely to be similar to the spikes inferred for extra-solar debris disks.

A massive clearing of planetesimals is thought to have occurred also in the Kuiper Belt. This is inferred from the observation that the total mass in the KB region (30 AU–55 AU) is $\sim$0.1 $M_\oplus$, insufficient to have been able to form the KBOs within the age of the Solar System (*Stern*, 1996). It is estimated that the primordial KB had a mass of 30 $M_\oplus$–50 $M_\oplus$ between 30 AU-55 AU, and was heavily depleted after Neptune formed and started to migrate outward (*Malhotra, Duncan and Levison*, 2000; *Levison et al.*, 2006). This resulted in the clearing of KBOs with perihelion distances near or inside the orbit of Neptune, and in the excitation of the KBOs' orbits, which increased their relative velocities from 10s m/s to $>$1 km/s, making their collisions violent enough to result in a significant mass of the KBOs ground down to dust and blown away by radiation pressure.

As we have seen in §3.2.2 and §4, detailed studies of nearby debris disks show that unusually high dust production rates are needed to explain the properties of several stars, including Vega, ζ-Lep, HIP 8920, HD 69830 and η Corvi. Even though one needs to be cautious about claiming that we are observing all these stars at a very special time during their evolution (possibly equivalent to the Late Heavy Bombardment), this remains to date the most straightforward explanation of their "unusual" properties.

Observations therefore indicate that the solar and extrasolar debris disks may have evolved in broadly similar ways, in the sense that their dust production decays with time but is punctuated by short periods of increased dust production. However, the details of this evolution and the comparison of the absolute quantities of dust produced are difficult to assess. Preliminary results from the *Spitzer* FGK survey (*Bryden et al.*, 2006) indicated that even though the disks observed have a luminosity of $\sim$100 times that of the KB dust disk, using the observed cumulative distribution and assuming the distribution of disk luminosities follows a Gaussian distribution, the observations are consistent with the Solar System having an order of magnitude greater or less dust than the typical level of dust found around similar nearby stars, with the results being inconsistent with most stars having disks much brighter than the Solar System's. However, from the *Spitzer FEPS* Legacy, *Meyer et al.* (2006) arrives to a different preliminary conclusion, suggesting that at times before the Late Heavy Bombardment (10 Myr–300 Myr), the dust production rate in the Solar System was much higher than that found around stars of similar ages, while at times after the Late Heavy Bombardment (1 Gyr–3 Gyr), the dust production rate was much lower than average. For example, τ-Ceti is a G8V (solar-type) star with an estimated age of 10 Gyr, surrounded by a debris disk that is 20 times dustier than the Solar System's Kuiper Belt (*Greaves et al.*, 2004b). Which star is "normal", τ-Ceti or the Sun? If the present dust production rate in τ-Ceti has been going on for the last 10 Gyr, shouldn't all these dust-producing planetesimals have been ground down to dust? Have potential planets around τ-Ceti undergone a heavy bombardment for the last 10 Gyr, or is the dust the result of a recent massive collision?

7.2 Grain Size and Composition

As discussed in §4, most debris disk spectra show little or no solid state features, indicating that dust particles have grown to sizes $\gtrsim$10 μm. The lack of silicate features, resulting from a lack of small dust grains, is also confirmed by the spatially resolved spectroscopy observations of a few nearby debris disks. In this regard, our zodiacal cloud is similar to most debris disks, presenting a predominantly featureless spectrum, thought to arise from dust grains 10 μm–100 μm in size, with a small component of small silicate grains yielding a weak (10% over the continuum) 10 μm emission feature (*Reach et al.*, 2003). The analysis of the impact craters on the Long Duration Exposure Facility indicated that the mass distribution of the zodiacal dust peaks at $\sim$200 μm (*Love and Brownlee*, 1993). The reason why large dust grains are dominant is a direct result from P-R drag because smaller grains evolve more quickly and therefore are removed on shorter timescales than larger grains. However, for the Solar System, we only have information from the zodiacal cloud, i.e. the warmer component of the Solar System's debris disks, because the emission from the colder KB dust component is hidden by the inner cloud foreground.

In §4, we also mentioned that there seems to be a correlation between the presence of silicate features and large quantities of dust (due possibly to a recent dust-producing event). The Solar System, in its quiescent state, seems to be similar (in their lack of small silicate grains) to other debris disks that contain "normal" amounts of dust for their ages. But the Solar System went through periods of high activity, like the Late Heavy Bombardment, where dust production was orders of magnitude higher. Even though we do not know how the Solar System looked like during those spikes in dust production, the remarkable similarity between the spectra of the dusty disk around HD 69830 (a 2 Gyr solar type star) and comet C/1995 O1 (Hale-Bopp) (*Beichman et al.*, 2005b), may indicate that during those stages, the Solar System's dust disk could have also been similar to other debris disks experiencing similar spikes in their dust production.

7.3 Structure

The Solar System, being filled with interplanetary dust and harboring planets, is an ideal case to investigate the effect of the planets on the dynamics of the dust particles, and consequently on the structure of the debris disks. Dynamical models predict that the KB dust disk has a density enhancement in a ring-like structure between 35–50 AU, with some azimuthal variation due to the trapping into mean motion resonances with Neptune and the tendency of the trapped particles to avoid the resonance planet, creating a minimun density at Neptune's position (*Liou and Zook*, 1999; *Moro-Martín and Malhotra*, 2002; *Holmes et al.*, 2003; see chapter by *Liou and Kaufmann* in this book). The models also predict a depletion of dust inside 10 AU, due to gravitational scattering of dust particles by Jupiter and Saturn. However, the presence of this structure has not yet been observed (but there is clear evidence of the trapping of KBOs in resonance with Neptune, *Malhotra*, 1995; *Jewitt*, 1999; *Elliot et al.*, 2005).

As we mentioned above, the thermal emission from the colder KB dust is hidden by the much brighter inner zodiacal cloud foreground, which has been studied in detail by the $IRAS$, $COBE$ and ISO space telescopes (that could also map the spatial structure of the cloud, as their observing geometry changed throughout the year). These observations, together with numerical simulations, revealed that the Earth is embedded in an resonant circumsolar ring of asteroidal dust, with a 10% number density enhancement located in the Earth's wake, giving rise to the asymetry observed in the zodiacal emission (*Jackson and Zook*, 1989; *Dermott et al.*, 1994; *Reach et al.*, 1995). In addition, it was found that zodiacal cloud has a warp, as the plane of symmetry of the cloud depends on heliocentric distance (*Wyatt et al.*, 1999). This ring, the brightness asymmetry and the warp, indicate that even though the Solar System debris disk is radiatively-dominated, while the extra-solar debris disks observed so far are collisionally-dominated, there are some structural features that are common to both.

In terms of disk size, the comparison of the Solar System's dust disk with the handful of nearby spatially resolved debris disks observed to date indicates that the Solar System is small. This would be consistent with the Sun being born in an OB association, while kinematic studies show that most of the nearby spatially resolved debris disks formed in loosely populated Taurus-like associations (see discussion in §2.1). However, it may also be the result of an observational bias because so far we have been able to study large disks only. We have to wait until the next generation of interferometers come on line to be able to tell whether or not our Solar System debris disk is normal in its size.

8. FUTURE PROSPECTS

Debris disks are evidence that many stars are surrounded by dust-producing planetesimals, like the asteroids and KBOs in our Solar System. In some cases, they also provide evidence of the presence of larger bodies: first, because the production of dust requires the stirring of planetesimals, and the minimum mass for an object needed to start a collisional cascade is the mass of Pluto (see chapter by *Kenyon et al.* in this book); and second, because some debris disk show structural features that may be the result of gravitational perturbations by a Neptune to Jupiter-mass planet.

Due to limits in sensitivity, we are not yet able to detect debris disks with masses similar to that of our Solar System, but only those that are $>$100 times more massive. Observations are beginning to indicate that the solar and extra-solar debris disks may have evolved in broadly similar ways, in the sense that their dust production decays with time but is punctuated by short periods of increased dust production, possibly equivalent to the Late Heavy Bombardment. This offers a unique opportunity to use extra-solar debris disks to shed some light in how the Solar System might have looked in the past. Similarly, our knowledge of the Solar System is influencing our understanding of the types of processes which might be at play in the extra-solar debris disks. In the future, telescopes like $ALMA$, LBT, $JWST$, TPF and $SAFIR$ will be able to image the dust in planetary systems analogous to our own. This will allow to carry out large unbiased surveys sensitive down to the level of dust found in our own Solar System that will answer the question of whether or not our Solar System debris disk is common or rare. But very little information is known directly about the KB dust disk, in terms of its mass, its spatial structure and its composition, mainly because its thermal emission is overwhelmed by the much stronger signal from the inner zodiacal cloud. Any advance in understanding of the structure and evolution of the KB is directly relevant to our understanding of extra-solar planetary systems. And to that end, there is the need to carry out dust experiments on spacecraft traveling to the outer Solar System, like the one onboard $New\ Horizons$, and to perform careful modeling of the dynamical evolution of KB dust particles and their contribution to the Solar System debris disk that takes into account our increased knowledge of the KBOs.

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