Structures in Dusty Disks

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Abstract. Optically thin dusty disks around Main Sequence stars consist of debris from catastrophic collisions or from low erosion of long-lived planetesimals. Resolved observations of dusty disks have systematically evidenced asymmetries and annular structures. It has been proposed that some of these structures could be signatures of undetected exoplanets. In this paper, I review and discuss currently proposed models to account for the observed structures. These include the impact of distant exoplanets and/or of stellar companions. The Solar System serves as a reference case for these approaches and similarities are pointed out along the paper as well as some limitations of current modeling efforts.

1. Extra-solar Dusty Disks

A major legacy of the IRAS and ISO missions is the identification of mid- and far-infrared excesses for a large fraction of nearby Main Sequence (MS) stars. The flux calibrator star Vega turned out to be representative of a class of MS stars surrounded by optically thin disks of cool solid material. It is now widely accepted that the Vega phenomenon likely represents a common stage in circumstellar disk evolution (Lagrange, Backman & Artymowicz 2000). This stage follows the dissipation of the initial massive gas disk which can support planetary formation. Early after the first IRAS results, Harper et al. (1984) concluded that because the observed grains are short-lived in the Vega disk, they are either collisional debris or ejected particles from evaporating exo-comets, implying in both cases a reservoir of large bodies generally referred to as planetesimals. Thanks to the continuous replenishment of the dust by the planetesimal disk, the dust disk can be sustained over hundreds, perhaps thousands, of Myr after the star has reached the MS. This process slowly erodes the planetesimal disk and the dust content of the disk is expected to decline with the star age as well. No clear picture of the decline of the disk fractional luminosity \( f_d = L_{IR}/L_\star \) with time has nevertheless been derived from the largest sample of debris disks studied so far, though a threshold \( f_d \) value fading with stellar age can be identified from the results of Decin et al. (2003). Observed dusty disks may also be affected by the presence of planetary embryos. They can stir up planetesimals through gravitational interaction thereby increasing the rate of collisions and resulting in stochastic brightness spikes of dust disks that may explain the observed large spread of \( f_d \) as a function of stellar age (Kenyon & Bromley 2002). Delayed stirring due to late planet formation has also been proposed by Dominik & Decin (2003) to explain this observed spread in \( f_d \) at a given stellar age.
The observed μm-sized grains around MS stars are but the tip of the iceberg of a size distribution that extends to planetesimal-sized bodies in extra-solar planetary debris disks. Dusty disks are a diagnostic for the presence of large solid bodies otherwise undetectable, including planets that can under certain conditions leave an imprint of their presence on the dust disk. Observed structures in dusty disks could therefore serve to reveal and characterize the mass and the orbital parameters of unseen planetary companions. Several studies have recently explored this attractive idea and have tried to constrain the distribution of the planetesimals and the properties of possible perturber(s) from the observations of the dust particles. I review in this paper current possible evidences for a link between observed structures in dusty disks and the presence of planets, starting with a brief summary of what we can learn from the dusty Solar System. The effect of stellar perturbers on planetesimal gas-free disks is also discussed. I finally emphasize on some theoretical and observational limitations.

2. Structures in the Dusty Solar System

2.1. The Zodiacal Cloud

IRAS satellite has revealed faint structures superimposed on the broad-scale background zodiacal cloud. Among these structures, dust bands inclined with respect to the ecliptic were evidenced by Low et al. (1984) and confirmed later with the COBE/DIRBE and ISOPHOT instruments in the mid-IR and in the visible from the ground. Low et al. (1984) suggest that the bands are collisional debris within the main asteroid belt between Mars and Jupiter rather than dust particles released by short period comets while other structures like narrow dust trails have a cometary origin. Some of these narrow trails don’t have identified parents and wide dust trails are still of unknown origin (Sykes & Walker 1992). The dust bands were thought to be associated with the three classical Hirayama asteroid families but it has been recently proposed that the Karin cluster and the Veritas family could be the only two sources of dust (Nesvorný et al. 2003). Nesvorný et al. (2003) moreover propose that the dust bands result from recent (5-8 Myr ago) collisional disruptions of multi-km sized bodies.

The similarities between Jupiter’s and the dust band particles’ inclinations and ascending nodes argue in favor of a dominant Jupiter influence on their dynamics (Dermott et al. 2001). The dusty Solar System carries other signatures of the gravitational perturbation of orbits of dust particles by the planets. The brightness enhancement of the zodiacal cloud in the Earth trailing direction relative to the leading direction can be explained by dust particles trapped into resonant orbits while approaching the Earth (Dermott et al. 1994). This resonant trapping results in an asymmetric (in azimuth) ring of particles with a cavity at the location of the Earth and a trailing dust cloud. The trapped particles responsible for the observed resonant ring are supposed to be mostly produced in the asteroid belt. They slowly spiral towards the Sun because of the Poynting-Robertson (PR) and the solar wind drag forces. The joint effect of the drag forces and of the gravitational perturbation of the planets could also explain other observed asymmetries in the zodiacal cloud. In the framework of the secular perturbation theory (Murray & Dermott 1999) and provided that the orbits of planets and grains are not coplanar, the variation in semi-major axis
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of the orbit of the dust particles directly translates in variation of the forced inclinations of the orbit of the grains that depend both on the grain size and on the heliocentric distance. The result is a warped zodiacal dust disk (Wyatt et al. 1999; Holmes 2002), most likely due to Jupiter and Saturn and which is indeed identified in the IRAS and COBE data sets (Deul & Wolstencroft 1988, Dermott et al. 1999). Similarly, the forced eccentricity of the dust particles due to Jupiter \((e = 0.05)\) provides a theoretical frame to explain the observed offset of the center of symmetry of the zodiacal cloud with respect to the Sun. But current models do not readily account for this offset (Holmes et al. 1998).

2.2. A Kuiper Dust Disk?

About \(10^5\) objects larger than 100 km are estimated to inhabit the classical Kuiper Belt (KB) outside Neptune with semi-major axis \(a\) between about 40 and 47 AU and with a total mass of about 0.1 \(M_\odot\) (Jewitt & Luu 2000). Whether the KB is in collisional equilibrium and produces observable dust is currently not known. According to Yamamoto & Mukai (1998), low erosion of KB objects (KBOs) by impacts of interstellar medium (ISM) dust particles could contribute to the production of grains in a dusty counterpart of the KB. An attempt to detect the thermal emission from the Kuiper dust disk from COBE data failed because of the dominant zodiacal contribution that could not be subtracted accurately enough (Holmes 2002). The existence of a Kuiper dust disk is therefore neither theoretically nor observationally established, though the Pioneer 10 and 11 spacecrafts sensitive to impacts caused by grains larger than 10 \(\mu m\) measured outside Saturn’s orbit a flux of grains coming from the KB at a rate consistent with the predictions of Yamamoto & Mukai (1998) (Landgraf et al. 2002).

A significant fraction (\(~10\%) of the KBOs are trapped in exterior mean motion resonances (MMRs) with Neptune. This includes the Plutinos which are KBOs residing in the 3:2 MMR at \(a \simeq 39.4\) AU. The spatial distribution of resonant objects has a specific azimuthally asymmetric structure that is a clear signature of the ongoing dynamical process (e.g. Malhotra 1996). Dust particles produced by collisional grinding of resonant objects or the trapping of grains produced by non-resonant objects but migrating inward due to PR drag could similarly harbor specific imprints that would indicate the presence of Neptune. The theoretical shape and the observability of a resonant Kuiper dust disk have been explored by Liou et al. (1996, 1999), Moro-Martín & Malhotra (2002) and Holmes et al. (2003) with the additional motive that identical structures observed in extra-solar dusty disks could serve to reveal the presence of exo-planets.

These studies show that only large grains stay long enough in the MMRs with Neptune to have a chance to produce detectable signatures. Large grains here means dust particles with \(\beta\) ratios smaller than about 0.1 (or grain radii larger than a few \(\mu m\)) where \(\beta\) is the ratio of radiation pressure to gravitation forces. Holmes et al. (2003) for instance considered the grains released by the Plutinos and addressed the question of their ability to remain trapped in the 3:2 MMR with Neptune by considering the action of PR drag, radiation pressure, the solar wind drag, the planetary gravitational perturbations but also the Lorentz force (since dust particles are supposed to be positively charged) and the drag force due to the neutral interstellar gas. They show that small grains produced
by the Plutinos with $\beta \geq 0.1$ have almost a zero probability to remain trapped in the 3:2 MMR with Neptune. The observability of contrasted structures in dusty disks produced by planetary perturbers therefore relies on the size-frequency (or $\beta$-frequency) of dust grains. For the KB, the size distribution is currently unknown while that of the zodiacal cloud shows a peak in particle radius at about 50–100 $\mu$m ($\beta < 5 \times 10^{-3}$) at a distance of 1 AU (Love & Brownlee 1993).

3. Observed Structures in Extra-Solar Dusty Systems

Only a sparse set of dusty disks around MS stars has been spatially resolved. Yet this sparse set should be considered as an impressive improvement compared to the situation a decade ago when the 10th IAP Astrophysics meeting on “Circumstellar Dust Disks and Planet Formation” was held in Paris (Proceedings edited by R. Ferlet & A. Vidal-Madjar). At that time $\beta$ Pic was the only system for which images were available. These images were revealing the disk-shaped and flat geometry of a system seen almost edge-on and very recent thermal images were suggestive of a clearing of the inner disk inaccessible in scattered light (Pantin & Lagage 1994).

Fig. 1 shows a montage of dusty disks firmly resolved so far around MS stars in age ascending order and Tab. 1 gives basic parameters for the stars and for the disks discussed in this paper. The three top panels of Fig. 1 display disks seen in scattered light using coronagraphic techniques to mask the central bright
Table 1. Resolved dusty disks from the youngest to the oldest. The Table includes basic stellar parameters, a typical distance \( R \) where the disk shows a density peak and a typical radial width (FWHM) around that distance, the observed inclination of the disk from pole-on, the typical spatial resolution at which it has been best resolved.

| Star Name | age [Myr] | \( d \) [pc] | Spectral Type | \( R \) [AU] | \( \Delta R \) [AU] | \( i \) [°] | Res. |
|-----------|-----------|--------------|--------------|-----------|--------------|--------|------|
| HD 141569 | 5±3       | 99           | B9.5V        | 200       | 45           | 55     | 5    |
| HR 4796   | 8±2       | 67           | A0V          | 70        | 12           | 73     | 4    |
| β Pic     | 12^{+8}_{-6} | 19.2       | A5V          | 90        | 80           | 90     | 1    |
| Fomalhaut | 150^{+200}_{-100} | 7.7       | A3V          | 155       | 60           | 70     | 58   |
| Vega      | 350^{+30}_{-30}  | 7.8       | A0V          | 100       | 40           | 5      | 110  |
| ε Eri     | 730±200   | 3.2         | K2V          | 65        | 30           | 30     | 45   |

The resolved dusty systems around MS stars display a wealth of structures: ring-shaped disks accompanied with gaps (all the systems), spiral structures and arcs (HD 141569), clumps or blobs (β Pic, ε Eri, Vega, Fomalhaut), offset asymmetries (HD 141569, HR 4796), warps or offset inclinations (β Pic, HR 4796?, Fomalhaut?). Most of these structures can be seen in Fig. 1. Some of the systems are moreover expected to possess exo-zodiacal dust populations, not observable on Fig. 1, which are deduced from spectral energy distribution modeling and/or mid-IR resolved observations (HR 4796, HD 141569, β Pic, Fomalhaut). An analogy with the structures described in Sec. 1 and 2 is tempting. Similar structures in the dusty Solar System are indeed related to the presence of the planets and the observed structures in extra-solar dusty disks have raised the idea that they could as well be due to yet undetected distant exoplanets in these systems (Sec. 4). It is interesting to note here that dusty disks have currently only been resolved around early type stars except ε Eri. Thus this approach is becoming an indirect but complementary method to direct searches for exoplanets by radial velocity and transit techniques that have mostly focused on nearby solar-type stars and are sensitive to short-period planets. It should also be noted that the two youngest systems (HR 4796 and HD 141569) are both very likely...
members of multiple stellar systems in which case planets may not be the only source of asymmetries in the dusty disks (Sec. 5).

4. The Planetary Hypothesis

Structures in dusty disks can be produced by resonant trapping of dust grains with a gravitational perturber like a planet. Such an explanation has been proposed for instance to explain the brightness asymmetry at $\lambda = 10\,\mu\text{m}$ between the two extensions of the edge-on $\beta$ Pic disk (Roques et al. 1994). Several authors have detailed the geometry of resonant signatures in a dusty disk (e.g. recent papers by Ozernoy et al. 2000, Kuchner & Holman 2003). Lobes, arcs and voids are features that can serve to locate and to characterize the type of dominant MMRs that depend in particular on the mass of the gravitational perturber (Fig. 2). These approaches have provided possible explanations to some of the observed structures in debris disks and observational tests have been proposed.

Resonant trapping with a planet can occur when the orbital period of the planet is $(p+q)/p$ times that of a bound particle where $p$ and $q$ are integers, $p > 0$ and $p+q \geq 1$. Kepler’s third law implies: 

$$a/a_p = \left[\frac{(p+q)}{p}\right]^{2/3} \times (1-\beta)^{1/3}$$

where $a$ and $a_p$ are the semi-major axis of the orbit of the particle and of the planet respectively and $\beta = F_{\text{rad}}/F_{\text{grav}}$. Thus the location of an external MMR ($q > 0$) moves inward with $\beta$. Each resonance has a libration width $\Delta a$ around $a$ that depends on the eccentricity $e$ of the particle and on the planet mass. In this libration zone, resonant orbits are stable (e.g. Malhotra 1996). But close to a planet the overlapping of adjacent resonances results in a chaotic region.

Dust particles trapped in an outer resonance receive energy from the inner planet and this energy can compensate the energy loss due to PR drag. This predicts that external MMRs will last longer than internal ones (Sicardy et al. 1993, Murray & Dermott 1999) and current studies of resonant structures
Table 2. Mass, semi-major axis and eccentricity of the predicted planets in the \( \epsilon \) Eri and Vega systems. The dominant MMRs are indicated as well as the expected orientation of the planet on the sky relative to the central star. The considered \( \beta \) values are also indicated. References: (1) Ozernoy et al.(2000), (2) Liou et al.(2000), (3) Quillen & Thorndike(2002), (4) Wilner et al.(2002), (5) Wyatt(2003).

| Star   | \( M_p \) [M\(_J\)] | \( a_p \) [AU] | \( e_p \) | MMRs       | \( \beta \) | orientation | Ref. |
|--------|----------------------|----------------|---------|------------|-------------|-------------|------|
| \( \epsilon \) Eri | 0.2 | 55–65 | 0 | 2:1, 3:2 | 0.002 | West | (1) |
| \( \epsilon \) Eri | 1 | 40 | 0.01 | 2:1, 3:2 | [0.002, 0.05] | (2) |
| \( \epsilon \) Eri | 0.084 | 40 | 0.3 | 3:2, 5:3 | 0.1 | North | (3) |
| Vega | 2 | 50–60 | 0 | (1+q):1 | 0.3 | NW | (1) |
| Vega | 3 | 40 | 0.6 | (1+q):1 | 0.01 | NW | (4) |
| Vega | 0.054 | 60–70 | 0 | 2:1, 3:2 | 0 | NW or SE | (5) |

in dusty disks have focused on MMRs with \( q > 0 \). This corresponds to a system with one planet and an outer belt of planetesimals and dust that, in turn, resembles the configuration of Neptune plus the KB in our Solar System (Sec. 2). Most models assume an unseen perturbing planet on a fixed orbit, though Wyatt (2003) considered the outward migration of a Neptune-like planet in the Vega system leading to an outer drift of the resonant structure with time. Two types of dust trapping are generally considered: particles produced in the MMRs by already trapped parent bodies (e.g. Wyatt 2003) or non-resonant particles migrating inward due to PR drag and trapped in external MMRs (e.g. Quillen & Thorndike 2002).

The results for \( \epsilon \) Eri and Vega are summarized in Table 2. Both systems require a planet with \( a_p \sim 40–70 \) AU and the models agree on the rough location of the planet in the Vega system. But the different approaches used to derive the parameters of the unseen planet, though some of them compare reasonably, do not readily converge toward an unique solution. General trends can nevertheless be drawn. The lumpy structure of the \( \epsilon \) Eri ring is generally better reproduced with a lower mass planet than for the case of Vega. The dominant resonances are the first order 2:1 and 3:2 external MMRs but the 5:3 could also contribute significantly. Dust trapping in these resonances results in arcs with asymmetric clumps qualitatively matching the four-lobed structure of the \( \epsilon \) Eri ring. The two-lobed structure of the Vega ring can be reproduced with a massive planet of a few Jupiter masses trapping dust particles in the \( (1+q):1 \) external MMRs. Wyatt (2003) could nevertheless reproduce the observations with a Neptune-like object (Fig. 2). The orbital periods of the planets being different from one model to another, the resonant patterns should accordingly revolve at different angular velocities. This provides an observational test to the models. For instance Ozernoy et al. (2000) predict \( \sim 0.7^\circ/\text{year} \) for the \( \epsilon \) Eri structures whereas Quillen & Thorndike (2002) predict \( \sim 1.3^\circ/\text{year} \).

Long-term planetary perturbations can also affect the structure of a disk but, contrary to MMRs, they do not depend on the precise location of the
perturber on its orbit. The edge-on $\beta$ Pic disk shows vertical deformations that can primarily be explained by a planet on an orbit inclined by a few degrees with respect to the initial midplane of the disk. The precession of planetesimal orbits forces the parent bodies of the observed dust grains to become coplanar with the planet orbit. The precession frequency $\omega_p$ decreases with the distance from the central star. The vertical deformation propagates outwards with time $t$ and stops approximately at the distance for which $|\omega_p^{-1}t|$ is $\sim 1$. With an assumed age of 20 Myr, a $1 M_{\text{Jup}}$ planet at 10 AU does produce a warp at $\sim 70$ AU as observed in the $\beta$ Pic system (Mouillet et al. 1997). The observable position of the warp shifts only slightly outward when a size distribution of particles, their dynamics and their optical properties are taken into account instead of an unique population of planetesimals (Augereau et al. 2001). Due to radiation pressure the smallest bound grains with $\beta$ larger than $\sim 0.15$ are placed on orbits with significant $e$ values. They spend a large fraction of their orbital time close to their apoastron far from the ring of planetesimals where they originate from. These small grains not only fill the outer regions of the disk and produce a surface brightness consistent with the observations as expected, but they also produce a vertical asymmetry at several hundreds of AU that is a dusty counterpart of the planetesimal warp. In this model the large-scale vertical (“butterfly”) asymmetry at hundreds of AU is related to the presence of a planet at $\sim 10$ AU and requires a colliding planetesimal ring peaked at about 90 AU (Tab. 1).

5. Stellar Perturbers

The three youngest systems shown in Fig. 1 could have been affected by stellar companions. The sharply defined ring around HR 4796 for instance shows a faint brightness asymmetry in thermal emission (at $\lambda \sim 20 \mu m$) and in scattered light which could be due to the perturbation of the disk by a close M companion thought to be bound. Provided that this stellar companion, located at a projected distance of 517 AU from HR 4796, is on an eccentric orbit ($e \sim 0.13$), the dust particles suffer a small but sufficient forced eccentricity. The result is a ring of dust offset from the central star and a brightness enhancement of the dust near the forced pericenter of the perturbed disk (Wyatt et al. 1999).

The secular perturbation of the HD 141569 disk by the two stellar M companions also provides an explanation for some of the observed asymmetries and for the size of the disk. Assuming that at least one of the companions is bound with HD 141569 and on a sufficiently eccentric orbit, it excites a spiral density wave which qualitatively matches the observed asymmetric ring of dust particles in the outer regions of the disk (at $\sim 325$ AU) after the perturbers have only completed $\sim 10$ orbital revolutions (Fig. 3, Augereau & Papaloizou, 2004a). This corresponds to a disk evolution timescale of a few Myr if $e$ is between 0.7 and 0.9 with the derived pericenter distance of 930 AU. In that approach the wide dark lane between the two asymmetric rings at 200 AU and 325 AU is not regarded as a depleted region which would suggest a mechanism to clean up the dust disk in that region. Rather the two asymmetric rings are considered as two independent coherent over-densities produced by perturbers: the stellar companions for the outermost structure and probably substellar object(s) for the inner ring.
Passing stars could also leave an imprint on a disk. According to Kalas et al. (2000), the \( \beta \) Pic disk could have recently experienced a low relative velocity encounter with a 0.5 M\(_\odot\) star on a low-inclination and parabolic orbit. Such a stellar flyby produces near to the periastron of the stellar perturber, at about 700 AU from the central star, a transient spiral structure that collapses in eccentric ring-like density concentrations in \( \sim 0.1 \) Myr. The concentrations, when seen edge-on, coincide with the positions of faint features that appear in one of the two extensions of the disk at distances between 500 and 785 AU from the star when a smooth scattered light disk model is subtracted from the observations. The length asymmetry of the disk can also be reproduced. If the flyby is not coplanar, the model proposed by Kalas et al. (2000) provides an alternative explanation to the vertical (warp and butterfly) asymmetries in the disk (see also Sec. 4). No convincing candidate star in the neighborhood of \( \beta \) Pic has been identified so far which presently makes this approach unlikely.

6. Current Modeling Limitations and Alternative Approaches

Several models currently proposed to reproduce the observed structures in dusty disks rely on the trapping of particles in MMRs with a planet in collision-less systems or in systems where the collision timescale of particles is larger than their resident timescale in a MMR. Too frequent collisions could dissolve structures. Lecavelier et al. (1996) have shown that resonant structures in the \( \beta \) Pic disk are observable at a few tens of AU if the surface density remains below a critical value that translates into a maximal vertical optical thickness of a few \( 10^{-4} \). Holmes et al. (2003), addressing the question of the observability of a Plutino dust disk, clearly show that contrasted structures only appear for large particles (small \( \beta \) values) since their dispersion in semi-major axis after a collision remains generally smaller than the libration amplitude of the resonance. As a consequence images dominated by particles with large \( \beta \) values should hardly show resonant structures.

The situation may be worsened by the effect of the radiation pressure. The trapping of a dust particle in an external MMR results in a raising of its
eccentricity on a characteristic timescale that drops with $\beta$ (Liou & Zook 1997). Thus $e$ raises faster with $\beta$. In other words, radiation pressure can speed up the ejection of a particle from a MMR if $e$ can reach the critical maximum value of the eccentricity allowed in that resonance (Weidenschilling & Jackson 1993). The sharpness of resonant features therefore critically depends on $\beta$ and, in turn, on the grain size distribution in the disk. Recent studies have shown that the size distribution resulting from collisions in a disk with a lower cutoff size (due for instance to radiation pressure) could depart significantly from the theoretical collisional equilibrium distribution described by the classical $-3.5$ power law (e.g. Thébault et al. 2003 and ref. therein). The size-strength law of solid bodies for describing collisions is moreover badly constrained. Finally, the contribution of evaporating comet-like bodies to dust disks is also not known.

Several processes not discussed here could also affect structures in dusty disks. As indicated in Sec. 2.2, impacts from ISM grains could contribute to the production of dust in the Solar System and may have the ability to erase any signature of a planet in the outer Solar System (Moro-Martín & Malhotra 2002). This effect could nevertheless be negligible for earlier-type stars (A-F) because of the relatively strong radiation pressure (Artyomowicz & Clampin, 1997). Stellar wind and stellar magnetic field can also be considered. Interplanetary dust particles for instance are charged by the emission of photoelectrons due to solar UV and to solar wind ions (Kempf et al. 2001). The Lorentz force may not be negligible for the smallest and closest particles (e.g. Barge et al. 1982, Fahr et al. 1995). The temporal and spatial variations of $\vec{B}$ in the Solar System have been shown to affect the orbits of charged dust particles by causing a random walk in semi-major axis and a dispersion in inclination and a precession of nodes. Stochastic collisions are another potential source of asymmetries in disks. It has been shown nevertheless that the clumps in the Fomalhaut disk are unlikely due to that mechanism (Wyatt & Dent 2002). Alternatively, gas-dust coupling can structure the youngest disks when the gas is not yet entirely dissipated (Takeuchi & Artyomowicz, 2001). Gas in Keplerian rotation has indeed been observed in the HD 141569 and $\beta$ Pic systems (Augereau et al. 2004b, Brandeker et al. 2004).

7. Future Prospects

Inferring the presence of planets from structures in dusty disks presently suffers from a major problem: the set of spatially resolved dusty disks is still sparse. But it is noteworthy that well marked asymmetries and annular shapes have been systematically observed. Therefore detecting unseen planetary companions from perturbed disks geometries is a promising approach while it remains in its infancy mostly because of observational limitations.

The three oldest systems for instance (Fig. 1) have only been resolved at very low spatial resolution, blurring possible fine structures produced by embedded planets. Two different millimeter interferometers, sensitive to higher spatial frequency structures than the sub-mm SCUBA images, could resolve two lobes in the Vega disk but curiously the lobes do not properly match each other (Koerner et al. 2001, Wilner et al. 2002). Future instruments like CARMA and ALMA for instance will have access to optically thin disks that are borderline targets for current millimeter interferometers and will be able to provide constraints on the
residual gas. The direct search for planets around stars with debris disks has to this date not yet resulted in any detection and no such debris disk has been resolved so far around those stars for which giant planets were detected by radial velocity techniques. The $\epsilon$ Eri system (Fig. 1) is an exception since it could host a Jupiter-mass planet (Hatzes et al. 2000). Presumed detections of disks around stars with known planets have been claimed but almost all of them are awaiting a confirmation or have been invalidated by follow-up observations (e.g. 55 Cnc, Schneider et al. 2001b).

The handful of resolved disks also contrasts with the number of expected debris disks in the solar neighborhood: 20% on average and up to 40% for A type stars (Habing et al. 2001). These statistics and the time-dependant evolution of the disk luminosity will be revisited soon with the Spitzer Space Telescope. These observations will provide a valuable database for the search of faint extended and structured emissions around MS stars with future high resolution and high contrast instruments on ground-based telescopes (e.g. VLT/Planet-Finder) and on-board the JWST. By constraining the dust content and the structure of the dusty disks, these observations will also help to prepare future missions such as TPF/Darwin that aim at directly detecting Earth-like planets.

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