Dust in young solar systems

Natalia A. Krivova [a,b]

[a]Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany

[b] Astronomical Institute, St. Petersburg University, 198504 St. Petersburg, Russia

Recent spectacular discoveries of extrasolar planets and circumstellar discs around main-sequence stars have offered a fertile ground for comparative studies of these objects and of the Solar System. There is no question that the planets and discs are manifestations of the same phenomenon called a "solar system", even though the detection of planets around stars with discs is as yet hampered by observational limitations. In this review we concentrate on the main- and pre-main-sequence stars with circumstellar discs representing younger analogues of the Solar System. The emphasis is placed on the dust component of the discs. Properties of the dust, its spatial distribution and some physical processes in which it is involved are covered. Some general evolutionary tendencies are also touched upon.

1. DISCS AND/OR PLANETS?

The origin of the Solar System is one of the oldest and still one of the most fascinating problems of astronomy. Real impetus to the research was given in the 1980s when IRAS observations evidenced the presence of dust around a few main-sequence (MS) stars (Aumann et al., 1984; Gillett, 1986) and the disc of β Pic was imaged by Smith & Terrile (1984). The next wave of interest to the problem was driven by recent discoveries of planets around other solar-type stars (Mayor & Queloz, 1995; Butler & Marcy, 1996; Marcy & Butler, 1996; Butler et al., 1997; Marcy et al., 1997; see Marcy & Butler, 2000 and Marcy et al., 2000 for recent reviews). These intriguing discoveries have given us an opportunity to look at our Solar System from the outside and, in addition, at its past. Whereas the first offers a clearer view into the global properties of a dust disc, the latter provides insight into the process of the system's formation.

The presence of dusty discs around stars during the planet formation stage is required by all plausible theories (e.g., Lissauer, 1993). Being a by-product of the star formation, discs make an excellent reservoir of the material for the formation of planets and smaller bodies. "Discs, then, are the thread connecting protostars and planets" (Beckwith & Sargent, 1993). The bulk of the material left over after star formation is completed disappears by the time when the planetary system is formed. The remainder is present mostly in a solid form. The Edgeworth-Kuiper Belt (EKB; Jewitt & Luu, 1993; 1995; 2000) provides a vivid illustration of that. Further abundant evidence is found that at some evolutionary stages discs and planets may coexist:

1. The giant gas planets are thought to be formed rapidly, with a solid core being developed in $\lesssim 10^6$ yr and accretion of a massive gaseous envelope being accomplished in $\sim 10^7$ yr (Zuckerman, 1994 and references therein). This is less than the ages of typical disc systems.
2. Decreasing with time, the masses of discs even around "old" pre-main-sequence (PMS) stars are typically still higher than $0.01 M_\odot$ (Beckwith et al., 1990; Beckwith & Sargent, 1993; Mannings, 1994; Henning et al., 1998) — a minimum mass required for planet formation in a system (e.g., Lissauer, 1993). At the same time the total masses of circumstellar material around main-sequence stars are much less (Yamashita et al., 1993; Zuckerman & Becklin, 1993; Zuckerman et al., 1995; Holland et al., 1998; Walker & Heinrichsen, 2000, among others) evidencing that planets, if any, must already have been formed there.
3. A low amount of gas around MS stars is another argument in favour of the already completed planet formation (e.g., Yamashita et al., 1993; Dent et al., 1995; Zuckerman et al., 1995; Holweger et al., 1999; Liseau, 1999; Greaves et al., 2000a). When compared to the standard gas to dust ratio (≈ 100), the gas is typically depleted by a factor of up to $100 - 1000$.
4. Inner depletion zones in the discs of MS stars (see Sect. 3.1) are also thought to be a sequel of the presence of a planet.

Because of many observational restrictions the Solar System was for a long time the only example showing a co-existence both of planets and a disc. Improved observational techniques, however, made it possible to image even tenuous debris discs around nearby stars. As a result, three other solar-type stars known to be orbited by a planetary-mass companion (55 Cnc, ρ CrB and HD 210277) were recently found to also possess discs (Trilling & Brown, 1998; Trilling et al., 2000).

Nevertheless, the discs as tenuous as our EKB dust disc are still beyond the observational limitations (Trilling et al., 2000), so that the discs accessible to observations and study are typically more massive and younger than the EKB. That is why we direct our attention now to these younger analogues of the Solar System (see Fig. 1). By this the group of so-called Vega-type systems is typically meant. First recognized as a separate class of objects by IRAS observations, they have been intensively studied during the last 15 years. The four famous IRAS prototypes — β Pic, Vega, Fomalhaut and ε Eri — belong to this class. Generally speaking, the group includes all MS stars surrounded by dust discs. In this sense, our Solar System may also be considered as a Vega-type system.

The discs are not, however, something that suddenly develops when the star reaches the main sequence. Just the opposite: young stars deeply embedded in residues of the protostellar clouds gradually get free of the remnant material, the clearing being particularly effective in the inner parts. This primordial material is lost from the interior of the shells well before the stars reach the main sequence (e.g., Backman & Paresce, 1993; Il'in & Voshchinnikov, 1993). The discs around older stars, inevitably evidenced by different observational data, are thus second-generation, or debris, discs. They are maintained by a collisional cascade of dust grains released by comets and/or planetesimals (Sect. 3.3). It is clear now, that circumstellar shells of the "oldest" PMS stars, though somewhat more extended and dense than the discs in Vega-type systems, are actually of the same nature. So by "young solar systems" we mean here systems, in which a MS or PMS star older than a few Myr is surrounded by *debris* dust material.

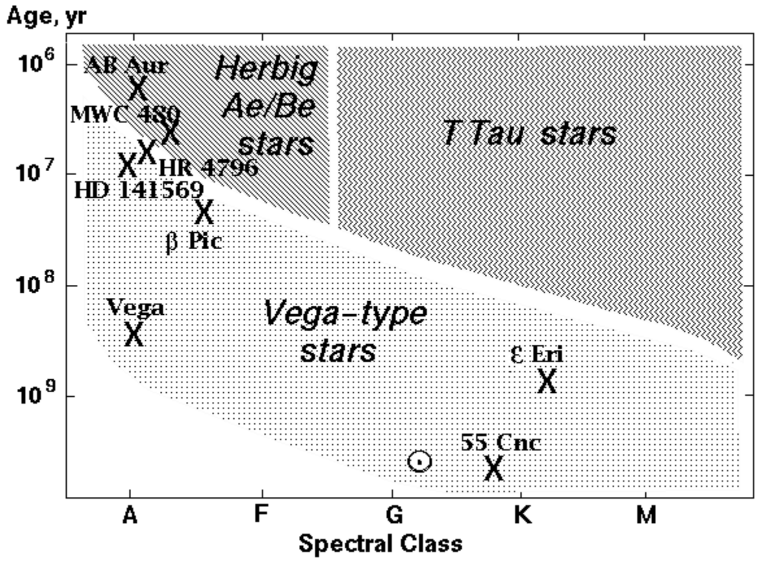

Figure 1. Classification of "young solar systems"

2. CIRCUMSTELLAR DUST: OBSERVATIONAL MANIFESTATIONS

The presence of dust around MS stars was first indicated by the mid- and far-*IR excesses* detected by IRAS for four sources (Aumann et al., 1984; Gillett, 1986). Later on the excesses were found for many other MS stars (e.g., Aumann, 1985; Backman & Gillett, 1987; Walker & Wolstencroft, 1988; Aumann & Probst, 1991; Stencel & Backman, 1991; Cheng et al., 1992). The excesses are typically seen in far-IR, although in a few cases mid-IR emission is also detectable. The younger the system, the larger is the excess in the mid-IR, and PMS objects show strong emission already in the near-IR. Up till now thermal emission of dust has remained the main criterion for the selection of Vega-type candidates (Mannings & Barlow, 1998; Fajardo-Acosta et al., 1999; Decin et al., 2000).

Spectroscopic observations in the IR region provide another good means of studying circumstellar dust. Whereas warmed dust emits mostly in the continuum, warm silicate particles produce also the well-known $10\,\mu$m emission feature which is observed in many dusty objects (see Sect. 3.2 for more details). The presence of silicates in crystalline form is also evidenced by emission features in the $20-70\,\mu$m region (Waelkens et al., 1996; Malfait et al., 1998; Waelkens et al., 1998; van den Ancker et al., 2000). A family of emission bands ($3.29\,\mu$m and associated $3.4-3.6\,\mu$m features, $6.2, 7.7, 8.6$ and $11.3\,\mu$m) from small carbon-rich particles, generally attributed to polycyclic aromatic hydrocarbons (PAHs), is also often observed (Brooke et al., 1993; Sylvester et al., 1996; Waelkens et al., 1996; Malfait et al., 1998; van den Ancker et al., 2000; Walker & Heinrichsen, 2000).

It is well known that small dust particles are also effective absorbers and scatterers of stellar radiation. The amount of dust around Vega-type stars is, however, insufficient to cause observable circumstellar *extinction.* The optical depth of the discs is always much less than unity even in the visual. A crude measure of the optical depth is offered by the fractional luminosity of dust relative to the star L_{IR}/L_* (see, e.g., Backman & Paresce, 1993). For Vega-type stars, it is commonly less than 10^{-2} (see Table 1). Being dustier (which is well seen from comparison of the ages and values L_{IR}/L_*), younger (PMS) objects have, on average, more material along the line of sight, so that the circumstellar extinction is observable. Note, that the material around PMS stars may not be confined to a flat disc, but rather to a more extended envelope (see discussions by Pezzuto et al., 1997; Waters & Waelkens, 1998; Miroshnichenko et al., 1999).

Circumstellar dust also shows up in the observed *polarization* of stellar light. To cite an example, an optical polarimetrical monitoring of 18 Vega-type and post-T Tau stars undertaken by Oudmaijer et al. (2000) has shown that the radiation of 15 of them was polarized. In Fig. 2 the observed polarization of Vega-type stars and their precursors is plotted as a function of the observed fractional luminosity of dust. The tendency is clear: the integral polarization of star-disc systems is proportional to the disc optical depths. It is also proportional to the albedo of dust particles and depends on the inclination angle of the disc with respect to the line of sight (Krivova et al., 1999, 2000). This should and does introduce some dispersion into the observed values. For the oldest objects with tenuous discs, the integral polarization is, unfortunately, very low and close to the detection limits, which makes the study difficult. Further uncertainty is introduced by the interstellar component of the polarization. Fortunately, in the case of Vega-type systems this component is normally not large, as the objects are fairly close. Obtaining polarization maps instead of measuring the integral polarization may be more advantageous, as in this case, polarization in an optically thin disc is independent of the (typically poorly known) optical depth and is predominantly determined by the dust properties.

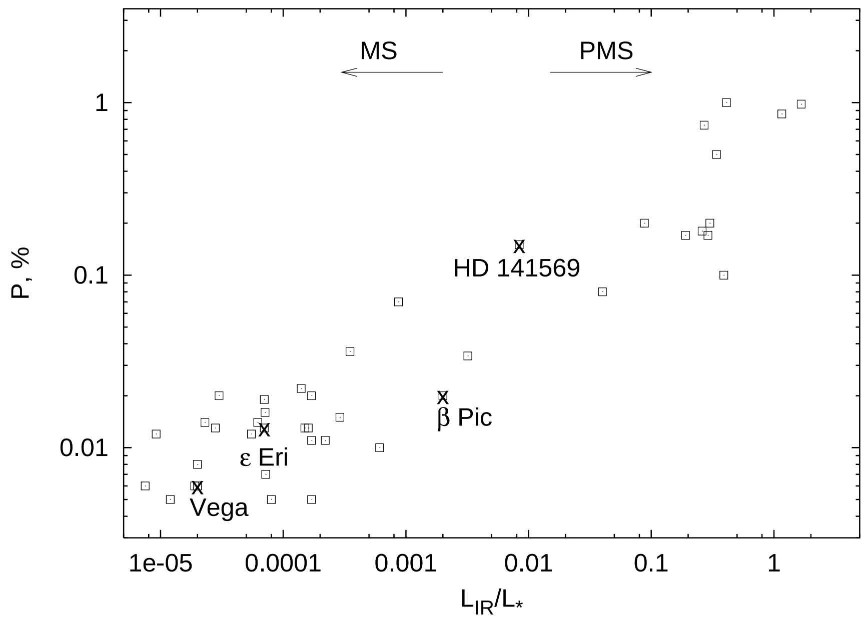

Figure 2. Polarization vs. L_{IR}/L_* for Vega-type and “old” PMS stars

Table 1
Characteristics of discs around some PMS and MS stars

Star	*Sp*	*Age, Myr*	L_{IR}/L_*	M_g/M_d	α^a	R_i^b, *AU*	*Images*^{c}	*References*
Sun	G2	4500	$\sim 10^{-7}$	$\lesssim 1$	~3–4?	~30	–	22,28,45
55 Cnc	G8	5000	7×10^{-5}		~4	13–35	nIR	3,21,49
ε Eri	K2	500-1000	10^{-4}	$\lesssim 0.1$	ring	35	smm	2,7,13,29,53
Vega	A0	300 ± 200	2×10^{-5}	$\lesssim 0.1$			smm	2,4,7,18,53
α PsA	A3	200 ± 100	8×10^{-5}	$\lesssim 0.15$		60	fIR,mm smm	2,4,7,8,18,29,46,53
β Pic	A5	10–100	2×10^{-3}	$\lesssim 0.1$	~3	~ 60	diff	5,7,11,16,18,23,26, 27,29,34,37,39,43
HD 141569	B9.5	$\gtrsim 10$	8×10^{-3}		ring	~ 150	n,mIR	1,9,47,50,52
HR 4796A	A0	8 ± 2	5×10^{-3}	$\lesssim 30$	ring	~ 50	n,mIR	14,20,24,42,44,48,54
HD 100546	B9	~ 10	$\gtrsim 0.1$	~ 100	$\sim 3-4$	< 40	nIR	17,19,36,38,50
MWC 480	A2	6		100^d	$\sim 7/4$	$(-)^e$	mm	30,31,36
WW Vul	A0-3	4 ± 2	0.27	100^d	~1.5	$(-)^e$	–	6,10,25,36,41
BF Ori	A0-5	2.3 ± 1	0.29	100^d	~1.5	$(-)^e$	–	15,25,36,41
AB Aur	A0	2 ± 1	0.54	100^d	~1	$(-,^e$ $< 150)$	diff	12,30,32,33,35,40,47 50,51

Notes:
$^a\alpha$ is the index of the power-law mid-plane density distribution outside the depletion zone;
^bR_i is the size of the inner depletion zone;
^{c} nIR, mIR, and fIR — near-, mid-, and far-IR, respectively; (s)mm — (sub)millimetre;
^{d} no data available indicating non-standard ratio;
^{e} the absence of the inner depletion zone is inferred from the spectral energy distribution.

References:
[1] Augereau et al. (1999); [2] Backman & Paresce (1993); [3] Baliunas et al. (1997); [4] Barrado y Navascues (1999); [5] Barrado y Navascues et al. (1999); [6] Berdiugin et al. (1992); [7] Dent et al. (1995); [8] Fajardo-Acosta et al. (1997); [9] Fisher et al. (2000); [10] Friedemann et al. (1993); [11] Golimowski et al. (1993); [12] Grady et al. (1999); [13] Greaves et al. (1998); [14] Greaves et al. (2000b); [15] Grinin et al. (1989); [16] Heap et al. (2000); [17] Henning et al. (1998); [18] Holland et al. (1998); [19] Hu et al. (1989); [20] Jayawardhana et al. (1998); [21] Jayawardhana et al. (2000); [22] Jewitt & Luu (1995); [23] Kalas & Jewitt (1995); [24] Koerner et al. (1998); [25] Krivova & Il'in (1997); [26] Lagage & Pantin (1994); [27] Lecavelier des Etangs et al. (1993); [28] Levison and Duncan (1997); [29] Liseau (1999); [30] Mannings & Sargent (1997); [31] Mannings et al. (1997); [32] Marsh et al. (1995); [33] Millan-Gabet et al. (1999); [34] Mouillet et al. (1997a); [35] Nakajima & Golimowski (1995); [36] Natta et al. (1997); [37] Pantin et al. (1997); [38] Pantin et al. (2000); [39] Paresce & Burrows (1987); [40] Pezzuto et al. (1997); [41] Rostopchina (1999); [42] Schneider et al. (1999); [43] Smith & Terrile (1984); [44] Stauffer et al. (1995); [45] Stern (1996); [46] Stern et al. (1994); [47] Sylvester et al. (1996); [48] Telesco et al. (2000); [49] Trilling & Brown (1998); [50] van den Ancker et al. (1998); [51] Voshchinnikov et al. (1996); [52] Weinberger et al. (1999); [53] Yamashita et al. (1993); [54] Zuckerman et al. (1995)

Imaging is, of course, a direct and the best way to probe circumstellar dust — both in thermal emission in the IR and in the scattered stellar light in the visual (including polarization maps). Indisputable leader among the systems with available "portraits" is β Pic. Being one of the closest and with the favourable edge-on orientation, it is still dense enough to be imaged at different wavelengths from optical (Smith & Terrile, 1984; Paresce & Burrows, 1987; Gledhill et al., 1991; Golimowski et al., 1993; Lecavelier des Etangs et al., 1993; Kalas & Jewitt, 1995; Kalas et al., 2000) through near- (Mouillet et al., 1997a) and mid-IR (Telesco et al., 1988; Lagage & Pantin, 1994) to the submillimetre region (Holland et al., 1998). A number of other Vega-type sources have been recently imaged in different wavelength regions (see, e.g., Skinner et al., 1995; Kalas & Jewitt, 1997; Guild et al., 1999; Trilling et al., 2000; Silber et al., 2000 and Table 1). The discs/shells of PMS stars are dustier, which should make them easier to detect. These objects are, however, more distant, so that it is commonly not an easy matter to resolve an "old" PMS system, either.

3. THEORETICAL INTERPRETATIONS

3.1. Structure of the discs

Yet before first images of Vega-type systems were obtained it had become clear that the observed excess emission in the IR stems from circumstellar dust grains rather than from other sources like free-free emission, background IS cirrus, cool companions, etc. (Aumann et al., 1984, see also Backman & Paresce, 1993). Already first coronograph images of **$\boldsymbol{\beta}$ Pic** showed a clear disc-like circumstellar structure. Explanations alternative to the dust disc — equatorial mass loss or bipolar outflows from a pre- or post-main-sequence object — were quickly ruled out (see Backman & Paresce, 1993; Artymowicz, 1994 for details). A set of subsequent images of β Pic resulted in a relatively good understanding of the global spatial distribution of dust in the disc. Not going into details (which can be found in other reviews centred on this intriguing object — e.g., Backman & Paresce, 1993; Artymowicz, 1994; Lagrange-Henri, 1995; Artymowicz, 1997), we outline here the main ideas.

The disc seen nearly edge-on extends outward to more than 1000 AU (Smith & Terrile, 1987; Kalas & Jewitt, 1995). The material is confined within the half-opening angle $\sim 7°$ (Artymowicz et al., 1989) and the mid-plane number density of dust particles falls off approximately as r^{-3} (Kalas & Jewitt, 1995, and references therein). At about 100 AU, however, the radial density distribution changes its profile (Golimowski et al., 1993; Lagage & Pantin, 1994; Kalas & Jewitt, 1995; Mouillet et al., 1997a; Heap et al., 2000). Within this zone the number density increases much slower, so that the normal optical depth remains constant or even drops slightly. Two wings of the disc are substantially asymmetric. By analyzing their own and other observations, Kalas & Jewitt (1995) identified in the disc of β Pic five types of asymmetry. These comprise a general brightness/radial extension asymmetry of two wings, their width asymmetry, and warp-like disc asymmetries, some of which are especially pronounced in the inner parts of the disc (Burrows et al., 1995; Heap et al., 2000).

The *asymmetries* are also seen in the discs of some **other stars** (e.g., Greaves et al., 1998; Holland et al., 1998; Telesco et al., 2000) attracting considerable interest as a presumed manifestation of planets orbiting these stars. Whereas the warps and local asymmetries are, most probably, really the signatures of the alleged planets (Burrows et al., 1995; Mouillet et al., 1997b; Heap et al., 2000), the global brightness asymmetries may also be due to other mechanisms. The difference by about 20% observed in the brightness and polarization of the two wings of β Pic is well explained by slightly different size distributions (Krivova et al., 2000). Such a difference could, under plausible conditions, be put down to interactions of the circumstellar particles with interstellar dust grains (Lissauer & Griffith, 1989; Artymowicz & Clampin, 1997; Krivova et al., 2000). On the other hand, the difference in the sizes may be attributed to the action of a planet, too. Lecavelier des Etangs et al. (1996) suggests that, if the planetary orbit is slightly eccentric, it would cause alignment of periastrons of comets/planetesimals at larger distances from the star and therefore a non-axisymmetric dust production and distribution in the disc. Krivov et al. (2000) point out another possible mechanism: as small dust particles are blown away by stellar radiation pressure, their enhanced collisional production in the regions where the disc parent bodies are trapped in planetary resonances would lead to an overabundance of hyperbolic grains in the adjacent outer parts of the disc.

The so-called *inner depletion zones* are another widely present feature of Vega-type systems, also attributed to the presumed planets. Apart from β Pic, the depletion zones are found in all cases when the disc around a MS or transitive-aged star is resolved — see Table 1. Many other MS stars with circumstellar discs have low near- and mid-IR fluxes, yet detectable emission at 60 and 100 μm. It is very difficult to explain such a distribution of energy unless the regions close to the stellar photospheres are devoid of dust particles. The gaps apparently occur more frequently in stars older than 10 Myr, indicating a clearing with age (Skrutskie et al. 1990). The inner parts of younger systems are not yet accessible to observations. But the spectral energy distribution suggests that the inner gaps are not yet formed and the inner boundary of the dust discs/shells is determined by dust grain sublimation (e.g., Friedemann et al., 1995; Krivova & Il'in, 1997; Miroshnichenko et al., 1997; Reimann et al., 1997). For a few T Tau stars, however, the spectral energy distribution shows an evidence of the gaps (Marsh & Mahoney, 1992, 1993).

The *density profile* is not established in great detail for stars other than β Pic. It is clear, however, that the radial density slope for MS objects is typically much steeper than for young stars with discs/shells (cf. values of α in Table 1). In some cases, as for HD 141569 or HR 4796A (Augereau et al., 1999; Weinberger et al., 1999; Schneider et al., 1999; Telesco et al., 2000), the discs have an abruptly bounded ring structure with intensity falling off fast both inwards and outwards.

3.2. Dust properties

In comparison with the dust distribution and structure of the discs, the properties of dust particles are much more difficult to find out. Nevertheless, some constraints can be placed, especially when a combination of different observational data, like in the case of β Pic, is available.

Chemical composition. IR and optical data considered in combination allow an estimation of the mean albedo of dust particles. For β Pic it appears to be rather high — 0.5 ± 0.2 (see Artymowicz, 1997 for a discussion) thereby ruling out such materials as carbonaceous species, pure metals and iron-rich minerals. A similar value (about 0.4) is derived for HD 141569 (Weinberger et al., 1999). Comparison of spectrophotometric data of β Pic with laboratory reflectance spectra together with the albedo restrictions led

Artymowicz et al. (1989) to the conclusion that the particles are likely to be composed of magnesium-dominated (i.e. iron-poor) olivines and pyroxenes or astronomical ices (H_2O, CO_2, NH_3, CH_4) with a small admixture of carbonaceous compounds. Spectroscopic observations of other Vega-type and younger systems imply essentially akin composition — silicates, typically magnesium-rich, small carbon particles (PAHs), iron oxide and crystalline water ice (e.g., Hanner et al., 1995, 1998; Sylvester et al., 1996; Waelkens et al., 1996; Malfait et al., 1998; van den Ancker et al., 2000; Walker & Heinrichsen, 2000).

Spectrophotometry in the $10\,\mu$m spectral region has shown that silicates are indeed important constituents of dust in the disc of β Pic (Telesco & Knacke, 1991; Knacke et al., 1993; Aitken et al., 1993). The silicate feature is quite similar to those in some Solar System comets with characteristic features (e.g., secondary peak at $11.3\,\mu$m) of crystalline silicates and differs significantly from those in very young stars. A similar profile of the feature is observed in some other cases, including intermediate-stage (post-Herbig Ae/Be) objects (Fajardo-Acosta et al., 1993; Sylvester et al., 1996; Waelkens et al., 1996; Malfait et al., 1998; Sitko et al., 1999a). The presence of crystalline silicates in the discs is corroborated by emission features in the $20-70\,\mu$m region (Waelkens et al., 1996; Malfait et al., 1998; Waelkens et al., 1998; van den Ancker et al., 2000). This suggests that the dust was reprocessed and supports the idea that the cometary bodies resupply the grains to the discs. For yet younger, PMS, objects, however, the spectral structure due to cristalline material is typically not seen, implying probably amorphous materials (Sitko et al., 1994; Hanner et al., 1995, 1998; Sitko et al., 1999b).

Size distribution. Another important characteristic of dust grains in the discs is their size distribution. The results obtained in the case of β Pic by different authors differ somewhat and at the first glance seem even somewhat controversial. First of all, the grey colours of the disc (Paresce & Burrows, 1987; Lecavelier des Etangs et al., 1993) are indicative of big particles — bigger than a few micron. Even larger sizes are suggested by far-IR and millimetre data (Chini et al., 1991; Zuckerman & Becklin, 1993). To account for both IR and optical observations together, the major contribution to the cross section should be given by grains about $1-20\,\mu$m in size (Artymowicz et al., 1989), though an additional population of hotter and smaller grains is required by some models (e.g., Telesco et al., 1988; Backman et al., 1992). Micron-sized grains are also responsible for the observed silicate emission feature (Knacke et al., 1993; Aitken et al., 1993). Though grain collisions should really supply the disc with small grains, particles smaller than $\sim 2\,\mu$m should be quickly swept out of the disc by stellar radiation pressure (Artymowicz, 1988).

A detailed consideration of polarimetric data available for β Pic (Krivova et al., 2000) shows, that there is, in fact, no contradiction in these data. The observed spatial distribution and the wavelength dependence of the polarization together with the disc colours can only be explained if particles in a wide size range are present in the disc with grains smaller than $\sim 3-10\,\mu$m in size being somewhat depleted, though still of importance. This general shape of the size distribution is confirmed by a model of the dynamical evolution of circumstellar dust grains — it is a result of the joint action of the particle collisions and stellar radiation pressure (Krivova et al., 2000; Krivov et al., 2000). A detailed dynamical modelling (Krivov et al., 2000) implies that the overall distribution has basically three different slopes. The slope is steeper, with the power-law exponent close to 3.5 typical of collision-governed systems, for grains smaller than the blowout limit and for big grains (tens of microns and bigger). For intermediate-sized particles prone not only to mutual collisions, but also to the destructive impacts of small grains streaming outwards, there is a gentle dip in the distribution. A similar shape of the distribution has long been known for the Zodiacal Cloud (Grün et al., 1985), although the distribution is set by different mechanisms.

As principally the same mechanisms of dust production and removal act in discs of other MS stars, the general shape of the size distribution is expected to be similar. Indeed, though the presence of large grains ($\gtrsim 5{-}20\,\mu$m) is inferred by observational data for many stars (see, e.g., Chini et al., 1990; Backman & Paresce, 1993; Zuckerman & Becklin, 1993; Greaves et al., 1998; Jayawardhana et al., 2000), evidence of smaller hotter grains also exists (e.g., Skinner et al., 1992, 1995; Fajardo-Acosta et al., 1993; Sylvester & Skinner, 1996; Augereau et al., 1999; Wyatt et al., 1999; Telesco et al., 2000; Fisher et al., 2000; Silber et al., 2000). In younger and dustier systems, collisions should be very intensive, so that the depletion of smaller grains could be much less pronounced. On the other hand, the interaction of the dust particles with gas, which is not depleted in young systems, can dampen down the relative velocities of the grains, decreasing the probability of catastrophic collisions.

We are still in the dark about the *structure* of circumstellar dust grains. If, as is commonly believed, the particles in the discs are really of cometary origin (Sect. 3.3), then the aggregate structure proposed by Li & Greenberg (1998) is a good probability. Fluffy aggregates in this model are made up of primitive interstellar dust particles consisting of a silicate core and an organic refractory mantle. An additional ice mantle could cover the grains in the outer region of the disc. Such a model provides a good fit to the $10\,\mu$m silicate feature and the continuum emission from near-IR to millimetre observed in the case of β Pic (Li & Greenberg, 1998). An extremely high porosity of the aggregates (consisting of more than 95% of vacuum) suggested by the authors seems, however, to be in conflict with the observed high level of the polarization (Krivova et al., 2000; see also Krivova & Il'in, 2000).

3.3. Dust sources and sinks

It was quickly realized that dust particles in the discs around MS stars can not be left over after the star formation. Particles, the presence of which is indicated by different observational data, should be destroyed or removed from the discs by stellar radiation pressure, grain-grain collisions and sublimation of grains (e.g., Backman & Paresce, 1993). Other possible, though less crucial, sinks of dust include sweeping up by larger bodies, destruction due to impacts of interstellar particles, sputtering due to the stellar wind. This implies that the particles must be continuously replenished. By analogy with the Solar System, Weissman (1984) suggested that the dust material could be supplied by large bodies, like comets or planetesimals. Further observational evidence was found in support of this idea called Falling and Orbiting Evaporating Bodies (FEBs, OEBs) scenario (Ferlet et al., 1987; Beust et al., 1989, 1998; Lecavelier des Etangs et al., 1996).
1. Spectroscopic observation of β Pic in the visible and UV revealed strong variations of the circumstellar absorption lines Ca II, Mg II, Al III, C IV and others (see Lagrange et al., 1987; Lagrange-Henri et al., 1989; Beust et al., 1989 and later works of this group for more details). The lines are almost always red-shifted and the variations are sporadic,

which was interpreted as the result of vaporization of large bodies falling towards the star. The phenomenon was later observed for many other stars, including PMS ones (e.g., Grady et al., 1996; Grinin et al., 1996a; Cheng et al., 1997; Lecavelier des Etangs et al., 1997; Welsh et al., 1998). Moreover, spectroscopic monitoring by Grady (2000) revealed red-shifted absorption lines in 17 of 18 programme MS and PMS stars.
2. Identification of the stable CO and C I circumstellar features in β Pic implies that the disc is continuously replenished with these gaseous species (Vidal-Madjar et al., 1994). A permanent or quasi-permanent source of gas is attested by stable circumstellar lines of many other elements (Lagrange et al., 1998). The source should have standard abundances in refractory elements and the FEBs scenario provides a natural explanation of this.
3. A similarity of the profile of the $10\,\mu$m silicate emission feature in β Pic and some Solar Sytem comets discussed above indicates that the dust in the disc may be a product of the comet disruptions.
4. The hypothesis of planetesimals as the replenishing source of dust in circumstellar discs is implicitly supported by the existence of trans-Neptunian objects believed to be a primordial population left over after the formation of the planetary system (Jewitt & Luu, 1995, 2000).
5. The so-called UX Ori phenomenon — irregular brightness dimmings accompanied by an increase of the polarization and a blueing of the object observed for many PMS stars — is believed to be another manifestation of large comet-like bodies or planatesimals moving around the stars (e.g., Grinin, 1988; Grinin et al., 1996b).

It should be mentioned that comet-like bodies or planetesimals produce mainly large dust particles (Davis & Ryan, 1990; Sykes et al., 1986) which then supply smaller grains to the disc through their collisional fragmentation (see Krivov et al., 2000).

4. DUST IN MULTIPLE SYSTEMS

Observations show that at least half of all stars are members of multiple systems (Leinert et al., 1993). Let us, therefore, touch briefly on such systems (detailed reviews can be found in Lubow & Artymowicz, 2000; Mathieu et al., 2000). The discs in binaries occur in two principal types: circumbinary (GG Tau, DQ Tau, UZ Tau E, UY Aur, HD 98800, BD+31 643) and circumstellar (HR 4796A, T Tau N, GG Tau, UZ Tau W) (Jensen & Mathieu, 1997; Mathieu et al., 2000, and references therein). UZ Tau and GG Tau make intriguing examples of systems, in which both types of discs are found (Jensen et al., 1996a; Guilloteau et al., 1999).

There are also planets found in binaries — 16 Cyg B, 55 Cnc, τ Boo (Butler et al., 1997; Cochran et al., 1997). It is well known that three-body stellar systems are unstable and tend to eject the lowest mass object (e.g., Standish, 1972; Monaghan, 1976; Mikkola & Valtonen, 1986). Benest (1996, 1998) found that stable planetary orbits exist up to distances from each star of about half the binary's periastron separation. Stable circumbinary orbits also exist, when the semimajor axis, measured in units of the binary's semimajor axis, is larger than 2 (Holman & Wiegert, 1999). Planets migrating to larger distances should be ejected from the system.

The gravitational field of close companion(s) perturbs also the orbits of dust particles. The orbits are unstable at circumstellar distances of the same order as the component separation in a multiple star system. Therefore discs in such systems are expected to be truncated (on the outside of circumstellar discs and on the inside of circumbinary discs) by tidal interactions (Lin & Papaloizou, 1993; Artymowicz & Lubow, 1994). A decrease in the disc mass is then expected in systems with a separation smaller than the size of a typical disc. Indeed, from millimetre observations discs in close binary systems (the separation is less than $\sim 100\,\mathrm{AU}$) were found to be substantially less massive than the discs around single stars or in wide systems (e.g., Beckwith et al., 1990; Jensen et al., 1994, 1996b; Osterloh & Beckwith, 1995; Dutrey et al., 1996). In some cases evidence also exists of a tidal truncation of a circumstellar disc (Stapelfeldt et al., 1998; Jayawardhana et al., 1998; Guilloteau et al., 1999; Schneider et al., 1999) and of a dynamically cleared central region in a circumbinary disc (Dutrey et al., 1994; Jensen & Mathieu, 1997; Kalas & Jewitt, 1997; Koerner et al., 2000). At the same time, for the survival times of the discs, no significant difference between singles and binaries was found (Simon & Prato, 1995).

5. CONCLUDING REMARK

Recent discoveries of (i) circumstellar discs around main-sequence, and particularly, around solar-type stars, (ii) extrasolar planets, particularly those in star-disc systems, and (iii) the EKB have shown that the "solar system" phenomenon is not unique. We still do not know how typical our Solar System as it exists is. A detection of an Earth-mass planet outside the Solar System would undeniably be exciting, which makes planet-hunting a popular field of exploration. At the same time, information of no little significance can be gleaned from observations of circumstellar dust. The more so, as the dust is much easier to observe than the planets: whereas the masses of the observable discs in Vega-type systems are estimated to be less than the Earth's mass (e.g., Zuckerman & Becklin, 1993; Yamashita et al., 1993; Dent et al., 1995; Holland et al., 1998; Walker & Heinrichsen, 2000), planets of such masses are far beyond the detection limits. Of course, the physical processes and the dust properties in circumstellar discs are not easy to understand, and here our knowledge of the Solar System could be very helpful. In turn, the overall distribution of the material, particularly in the outer parts of the discs, is now much better known for other systems. Representing different evolutionary stages, other systems provide also a good test of the theory of the formation of the Solar System. So, to better understand the essence of the circumstellar discs, the extrasolar planets and the EKB in themselves and the planetary formation process as a whole, we must combine our efforts in these, as yet rather individual, areas.

Acknowledgements. I wish to thank D. Backman, V. B. Il'in, A. V. Krivov, A. Lecavelier des Etangs, and I. Mann for interesting and fruitful discussions and encouragement and J. A. M. McDonnell and I. P. Williams for the invitation that initiated this review.

REFERENCES

Aitken, D., Moore, T., Roche, P. et al., 1993, MNRAS 265, L41
Artymowicz, P., 1988, ApJL 335, L79
Artymowicz, P., 1994, in Circumstellar Dust Disks and Planet Formation, ed. R. Ferlet & A. Vidal-Madjar (Gif-sur-Yvette: Frontières), 47

Artymowicz, P., 1997, Ann. Rev. Earth & Planet. Sci. 25, 175
Artymowicz, P., Burrows, C. & Paresce, F., 1989, ApJ 337, 494
Artymowicz, P. & Clampin, M., 1997, ApJ 490, 863
Artymowicz, P. & Lubow, S. H., 1994, ApJ 421, 651
Augereau, J. C., Lagrange, A.-M., Mouillet, D. & Ménard, F., 1999, A&A 350, L51
Aumann, H. H., 1985, PASP 97, 885
Aumann, H. H., Beichman, C. A., Gillett, F. C. et al., 1984, ApJL 278, L23
Aumann, H. H. & Probst, R. G., 1991, ApJ 368, 264
Backman, D. E. & Gillett, F. C., 1987, in Cool Stars, Stellar Systems, and the Sun, ed. J. L. Linsky & R. E. Stencel (Lect. Notes in Phys. 291; Berlin: Springer), 340
Backman, D. E. & Paresce, F., 1993, in Protostars and Planets III, ed. E. H. Levy, J. I. Lunine & M.S. Matthews (Tucson: Univ. Arizona Press), 1253
Backman, D. E., Witteborn, F. C. & Gillett, F. C., 1992, ApJ 385, 670
Baliunas, S. L., Henry, G. W., Donahue, R. A. et al., 1997, ApJL 474, L119
Barrado y Navascues, D., 1999, Ap&SS 263, 235
Barrado y Navascues, D., Stauffer, J. R., Song, I. & Caillault, J. P., 1999, ApJL 520, L123
Beckwith, S. V. W. & Sargent, A. I., 1993, in Protostars and Planets III, ed. E. H. Levy, J. I. Lunine & M.S. Matthews (Tucson: Univ. Arizona Press), 521
Beckwith, S. V. W., Sargent, A. I., Chini, R. S. & Guesten, R., 1990, AJ 99, 924
Benest, D., 1996, A&A 314, 983
Benest, D., 1998, A&A 332, 1147
Berdiugin, A. V., Grinin, V. P. & Minikulov, N. H., 1992, Izv. Krym. Astrofiz. Obs. 86, 69
Beust, H., Lagrange, A.-M., Crawford, I. A. et al., 1998, A&A 338, 1015
Beust, H., Lagrange-Henri, A.-M., Vidal-Madjar, A. & Ferlet, R., 1989, A&A 223, 304
Brooke, T., Tokunaga, A. & Strom, S., 1993, AJ 106, 656
Burrows, C. J., Krist, J. E., Stapelfeldt, K. R. et al., 1995, BAAS 187, 3205
Butler, R. P. & Marcy, G. W., 1996, ApJL 464, L153
Butler, R. P., Marcy, G. W., Williams, E. et al., 1997, ApJL 474, L115
Cheng, K. P., Bruhweiler, F. C., Kondo, Y. & Grady, C. A., 1992, ApJL 396, L83
Cheng, K. P., Bruhweiler, F. C. & Neff, J. E., 1997, ApJ 481, 866
Chini, R., Krügel, E. & Kreysa, E., 1990, A&A 227, L5
Chini, R., Krügel, E., Kreysa, E. et al., 1991, A&A 252, 220
Cochran, W. D., Hatzes, A. P., Butler, R. P. & Marcy, G. W., 1997, ApJ 483, 457
Davis, D. R. & Ryan, E. V., 1990, Icarus 83, 156
Decin, G., Dominik, C., Malfait, K. et al., 2000, A&A 357, 533
Dent, W. R. F., Greaves, J. S., Mannings, V. et al., 1995, MNRAS 277, L25
Dutrey, A., Guilloteau, S., Duvert, G. et al., 1996, A&A 309, 493
Dutrey, A., Guilloteau, S. & Simon, M., 1994, A&A 286, 149
Fajardo-Acosta, S. B., Stencel, R. E. & Backman, D. E., 1997, ApJL 487, L151
Fajardo-Acosta, S. B., Stencel, R. E., Backman, D. E. & Thakur, N., 1999, ApJ 520, 215
Fajardo-Acosta, S. B., Telesco, C. M. & Knacke, R. F., 1993, ApJL 417, L33

Ferlet, R., Vidal-Madjar, A. & Hobbs, L. M., 1987, A&A 185, 267
Fisher, R. S., Telesco, C. M., Piña et al., 2000, ApJL 532, L141
Friedemann, C., Gürtler, J. & Reimann, H. G., 1995, A&A 300, 269
Friedemann, C., Reimann, H. G., Gürtler, J. & Toth, V., 1993, A&A 277, 184
Gillett, F. C., 1986, in Light on Dark Matter (Noordwijk: Dordrecht), 61
Gledhill, T. M., Scarrott, S. M. & Wolstencroft, R. D., 1991, MNRAS 252, 50
Golimowski, D. A., Durrance, S. T. & Clampin, M., 1993, ApJL 411, L41
Grady, C. A., 2000, in Disks, Planetesimals and Planets, ed. F. Garzon & T. J. Mahoney (ASP Conf. Ser.), in press
Grady, C. A., Perez, M. R., Talavera, A. et al., 1996, A&AS 120, 157
Grady, C. A., Woodgate, B., Bruhweiler, F. C. et al., 1999, ApJL 523, L151
Greaves, J. S., Coulson, I. M. & Holland, W. S., 2000a, MNRAS 312, L1
Greaves, J. S., Holland, W. S., Moriarty-Schieven, G. et al., 1998, ApJL 506, L133
Greaves, J. S., Mannings, V. & Holland, W. S., 2000b, Icarus 143, 155
Grinin, V. P., 1988, Astron. Lett. 14, 27
Grinin, V. P., Kiselev, N. N. & Minikulov, N. K., 1989, Sov. Astron. Lett. 15, 448
Grinin, V. P., Kozlova, O. V., Thé, P. S. & Rostopchina, A. N., 1996a, A&A 309, 474
Grinin, V. P., Natta, A. & Tambovtseva, L., 1996b, A&A 313, 857
Grün, E., Zook, H. A., Fechtig, H. & Giese, R. H., 1985, Icarus 62, 244
Guild, T. B., Koerner, D. W. & Sargent, A. I., 1999, BAAS 195, 2503
Guilloteau, S., Dutrey, A. & Simon, M., 1999, A&A 348, 570
Hanner, M. S., Brooke, T. Y. & Tokunaga, A. T., 1995, ApJ 438, 250
Hanner, M. S., Brooke, T. Y. & Tokunaga, A. T., 1998, ApJ 502, 871
Heap, S. R., Lindler, D. J., Lanz, T. M. et al., 2000, ApJ 539, 435
Henning, T., Burkert, A., Launhardt, R. et al., 1998, A&A 336
Holland, W. S., Greaves, J. S., Zuckerman, B. et al., 1998, Nature 392, 788
Holman, M. J. & Wiegert, P. A., 1999, AJ 117, 621
Holweger, H., Hempel, M. & Kamp, I., 1999, A&A 350, 603
Hu, J. Y., Thé, P. S. & De Winter, D., 1989, A&A 208, 213
Il'in, V. B. & Voshchinnikov, N. V., 1993, Astron. Rep. 37, 362
Jayawardhana, R., Fisher, S., Hartmann, L. et al., 1998, ApJL 503, L79
Jayawardhana, R., Holland, W. S., Greaves, J. S. et al., 2000, ApJ 536, 425
Jensen, E. L. N., Koerner, D. W. & Mathieu, R. D., 1996a, AJ 111, 2431
Jensen, E. L. N. & Mathieu, R. D., 1997, AJ 114, 301
Jensen, E. L. N., Mathieu, R. D. & Fuller, G. A., 1994, ApJL 429, L29
Jensen, E. L. N., Mathieu, R. D. & Fuller, G. A., 1996b, ApJ 458, 312
Jewitt, D. & Luu, J., 1993, Nature 362, 730
Jewitt, D. & Luu, J., 1995, Ap&SS 223, 164
Jewitt, D. C. & Luu, J. X., 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss & S. S. Russell (Tucson: Univ. Arizona Press), 1201
Kalas, P. & Jewitt, D., 1995, AJ 110, 794
Kalas, P. & Jewitt, D., 1997, Nature 386, 52
Kalas, P., Larwood, J., Smith, B. A. & Schultz, A., 2000, ApJL 530, L133
Knacke, R. F., Fajardo-Acosta, S. B., Telesco, C. M. et al., 1993, ApJ 418, 440
Koerner, D. W., Jensen, E. L. N., Cruz, K. L. et al., 2000, ApJL 533, L37

Koerner, D. W., Ressler, M. E., Werner, M. W. & Backman, D. E., 1998, ApJL 503, L83
Krivov, A. V., Mann, I. & Krivova, N. A., 2000, A&A, in press
Krivova, N. A. & Il'in, V. B., 1997, Astron. Lett. 23, 791
Krivova, N. A. & Il'in, V. B., 2000, Icarus 143, 159
Krivova, N. A., Krivov, A. V. & Mann, I., 2000, ApJ 539, 424
Krivova, N. A., Mann, I. & Krivov, A. V., 1999, in Meteoroids 1998, ed. W. J. Baggaley & V. Porubčan, (Astron. Inst. Slovak Acad. Sci., Bratislava), 291
Lagage, P. & Pantin, E., 1994, Nature 369, 628
Lagrange, A.-M., Beust, H., Mouillet, D. et al., 1998, A&A 330, 1091
Lagrange, A.-M., Ferlet, R. & Vidal-Madjar, A., 1987, A&A 173, 289
Lagrange-Henri, A.-M., 1995, Ap&SS 223, 19
Lagrange-Henri, A.-M., Beust, H., Ferlet, R. & Vidal-Madjar, A., 1989, A&A 215, L5
Lecavelier des Etangs, A., Deleuil, M., Vidal-Madjar, A. et al., 1997, A&A 325, 228
Lecavelier des Etangs, A., Perrin, G., Ferlet, R. et al., 1993, A&A 274, 877
Lecavelier des Etangs, A., Vidal-Madjar, A. & Ferlet, R., 1996, A&A 307, 542
Leinert, C., Zinnecker, H., Weitzel, N. et al., 1993, A&A 278, 129
Levison, H. F. and Duncan, M. J., 1997, Icarus 127, 13
Li, A. & Greenberg, J. M., 1998, A&A 331, 291
Lin, D. N. C. & Papaloizou, J. C. B., 1993, in Protostars and Planets III, ed. E. H. Levy, J. I. Lunine & M.S. Matthews (Tucson: Univ. Arizona Press), 749
Liseau, R., 1999, A&A 348, 133
Lissauer, J. J., 1993, ARA&A 31, 129
Lissauer, J. J. & Griffith, C. A., 1989, ApJ 340, 468
Lubow, S. H. & Artymowicz, P., 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss & S. S. Russell (Tucson: Univ. Arizona Press), 731
Malfait, K., Waelkens, C., Waters, L. B. F. M. et al., 1998, A&A 332, L25
Mannings, V., 1994, MNRAS 271, 587
Mannings, V. & Barlow, M. J., 1998, ApJ 497, 330
Mannings, V., Koerner, D. W. & Sargent, A. I., 1997, Nature 388, 555
Mannings, V. & Sargent, A. I., 1997, ApJ 490, 792
Marcy, G. W. & Butler, R. P., 1996, ApJL 464, L147
Marcy, G. W. & Butler, R. P., 2000, PASP 112, 137
Marcy, G. W., Butler, R. P., Williams, E. et al., 1997, ApJ 481, 926
Marcy, G. W., Cochran, W. D. & Mayor, M., 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss & S. S. Russell (Tucson: Univ. Arizona Press), 1285
Marsh, K. A. & Mahoney, M. J., 1992, ApJL 395, L115
Marsh, K. A. & Mahoney, M. J., 1993, ApJL 405, L71
Marsh, K. A., van Cleve, J. E., Mahoney, M. J. et al., 1995, ApJ 451, 777
Mathieu, R. D., Ghez, A. M., Jensen, E. L. N. & Simon, M., 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss & S. S. Russell (Tucson: Univ. Arizona Press), 703
Mayor, M. & Queloz, D., 1995, Nature 378, 355
Mikkola, S. & Valtonen, M. J., 1986, MNRAS 223, 269
Millan-Gabet, R., Schloerb, F. P., Traub, W. A. et al., 1999, ApJL 513, L131

Miroshnichenko, A., Ivezić, Ž. & Elitzur, M., 1997, ApJL 475, L41
Miroshnichenko, A., Ivezić, Ž., Vinković, D. & Elitzur, M., 1999, ApJL 520, L115
Monaghan, J. J., 1976, MNRAS 176, 63
Mouillet, D., Lagrange, A.-M., Beuzit, J.-L. & Renaud, N., 1997a, A&A 324, 1083
Mouillet, D., Larwood, J. D., Papaloizou, J. C. B., and Lagrange, A.-M., 1997b, MNRAS 292, 896
Nakajima, T. & Golimowski, D. A., 1995, AJ 109, 1181
Natta, A., Grinin, V. P., Mannings, V. & Ungerechts, H., 1997, ApJ 491, 885
Osterloh, M. & Beckwith, S. V. W., 1995, ApJ 439, 288
Oudmaijer, R., Davies, J. & EXPORT-team, 2000, in Disks, Planetesimals and Planets, ed. F. Garzon & T. J. Mahoney (ASP Conf. Ser.), in press
Pantin, E., Lagage, P. O. & Artymowicz, P., 1997, A&A 327, 1123
Pantin, E., Lagage, P. O. & Waelkens, C., 2000, in Disks, Planetesimals and Planets, ed. F. Garzon & T. J. Mahoney (ASP Conf. Ser.), in press
Paresce, F. & Burrows, C., 1987, ApJL 319, L23
Pezzuto, S., Strafella, F. & Lorenzetti, D., 1997, ApJ 485, 290
Reimann, H. G., Gürtler, J., Friedemann, C. & Käufl, H. U., 1997, A&A 326, 271
Rostopchina, A. N., 1999, Astron. Rep. 43, 113
Schneider, G., Smith, B. A., Becklin, E. E. et al., 1999, ApJL 513, L127
Silber, J., Gledhill, T., Duchêne, G. & Ménard, F., 2000, ApJL 536, L89
Simon, M. & Prato, L., 1995, ApJ 450, 824
Sitko, M. L., Grady, C. A., Hanner, M. H. et al., 1994, in Circumstellar Dust Disks and Planet Formation, ed. R. Ferlet & A. Vidal-Madjar (Gif-sur-Yvette: Frontières), 389
Sitko, M. L., Grady, C. A., Lynch, D. K. et al., 1999a, ApJ 510, 408
Sitko, M. L., Lynch, D. K., Russell, R. W. & Grady, C. A., 1999b, BAAS 195, 7806
Skinner, C. J., Barlow, M. J. & Justtanont, K., 1992, MNRAS 255, 31P
Skinner, S., Brown, A. & Dent, W. R. F., 1995, Ap&SS 224, 555
Smith, B. A. & Terrile, R. J., 1984, Science 226, 1421
Smith, B. A. & Terrile, R. J., 1987, BAAS 19, 829
Standish, E. M., 1972, A&A 21, 185
Stapelfeldt, K. R., Krist, J. E., Menard, F. et al., 1998, ApJL 502, L65
Stauffer, J. R., Hartmann, L. W. & Barrado y Navascues, D., 1995, ApJ 454, 910
Stencel, R. E. & Backman, D. E., 1991, ApJS 75, 905
Stern, S. A., 1996, A&A 310, 999
Stern, S. A., Festou, M. C. & Weintraub, D. A., 1994, Nature 368, 312
Sykes, M. V., Lebofsky, L. A., Hunten, D. M. & Low, F., 1986, Science 232, 1115
Sylvester, R. J. & Skinner, C. J., 1996, MNRAS 283, 457
Sylvester, R. J., Skinner, C. J., Barlow, M. J. & Mannings, V., 1996, MNRAS 279, 915
Telesco, C. M., Decher, R., Becklin, E. E. & Wolstencroft, R. D., 1988, Nature 335, 51
Telesco, C. M., Fisher, R. S., Pinã, R. K. et al., 2000, ApJ 530, 329
Telesco, C. M. & Knacke, R. F., 1991, ApJL 372, L29
Trilling, D. E. & Brown, R. H., 1998, Nature 395, 775

Trilling, D. E., Brown, R. H. & Rivkin, A. S., 2000, ApJ 529, 499
van den Ancker, M. E., Bouwman, J., Wesselius, P. R. et al., 2000, A&A 357, 325
van den Ancker, M. E., de Winter, D. & Tjin A Djie, H. R. E., 1998, A&A 330, 145
Vidal-Madjar, A., Lagrange-Henri, A.-M., Feldman, P. D. et al., 1994, A&A 290, 245
Voshchinnikov, N. V., Molster, F. J. & Thé, P. S., 1996, A&A 312, 243
Waelkens, C., Malfait, K. & Waters, L. B. F. M., 1998, Ap&SS 255, 25
Waelkens, C., Waters, L. B. F. M., De Graauw, M. S. et al., 1996, A&A 315, L245
Walker, H. J. & Heinrichsen, I., 2000, Icarus 143, 147
Walker, H. J. & Wolstencroft, R. D., 1988, PASP 100, 1509
Waters, L. B. F. M. & Waelkens, C., 1998, ARA&A 36, 233
Weinberger, A. J., Becklin, E. E., Schneider, G. et al., 1999, ApJL 525, L53
Weissman, P. R., 1984, Science 224, 987
Welsh, B. Y., Craig, N., Crawford, I. A. & Price, R. J., 1998, A&A 338, 674
Wyatt, M. C., Dermott, S. F., Telesco, C. M. et al., 1999, ApJ 527, 918
Yamashita, T., Handa, T., Omodaka, T. et al., 1993, ApJL 402, L65
Zuckerman, B., 1994, in Circumstellar Dust Disks and Planet Formation, ed. R. Ferlet & A. Vidal-Madjar (Gif-sur-Yvette: Frontières), 131
Zuckerman, B. & Becklin, E. E., 1993, ApJ 414, 793
Zuckerman, B., Forveille, T. & Kastner, J. H., 1995, Nature 373, 494