Planetary Material Around Main-Sequence Stars

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Main-sequence circumstellar dust systems like the IRAS-discovered prototypes Vega and β Pictoris have been found to be common, occurring around at least 15% of nearby field stars of types A-K. Defining characteristics of these objects include low dust luminosity and optical depth, small gas/dust mass ratio such that dust dynamics are approximately Keplerian, and short dust lifetimes relative to star ages. The dust is clearly "second generation", i.e. not primordial but released from larger parent bodies such as asteroids or comets. Recent images of some of these objects show them to be disks with central gaps about the size of the planetary region of our solar system, as had been inferred previously. High-resolution imaging has revealed fine structure in some of the disks, implying the influence of planet masses.

A few systems such as β Pic have circumstellar gas that also must be "second generation"; however, a general connection between circumstellar dust and gas in main-sequence systems is yet to be established. Observations and elaboration of models of β Pic's transient absorption line features have confirmed they can be explained in terms of infalling planetesimals. Planetesimals on star-grazing trajectories almost certainly imply the existence of planet-mass perturbers. It is reasonable to expect the same phenomenon to occur around other stars, especially younger ones, but interpretation of observations so far in these terms is not straightforward.

Stellar age estimates indicate that many of these disks are a few x 10^7 to a few x 10^8 yr old, corresponding to the hypothesized timespan for construction and heavy bombardment of planets in our solar system. The amount of dust appears to decrease with system age and theoretical calculations imply that internal processes completely dominate disk evolution relative to effects such as erosion by the ISM. Models of a postulated original massive Kuiper Belt and its collision debris production correspond in size and dust optical depth to the Vega / β Pic disks.

I. INTRODUCTION

We shall focus on observations and models of planetary systems in a late evolutionary stage when original optically thick protoplanetary disks have disappeared, planet-mass objects have formed, and remnant planetesimals are sources of "second generation" circumstellar (CS) dust and gas. Previous reviews regarding these objects are by Backman & Paresce (1993, hereafter BP93), Artymowicz (1997), Plets (1997a), Waelkens & Waters (1998), Lagrange (1998a), and Vidal-Madjar et al. (1998).

We suggest the following defining "Vega / β Pic-like" system characteristics that will be discussed immediately below:

1) bolometric $L_{dust}/L_* << 1$

2) M(dust+gas) $<< 0.01$ $M_\odot$ (the minimim-mass solar nebula)

3) dust dynamics not controlled by gas; $M_{gas} << 10$ M_{dust}

4) grain destruction times less than the age of the star.

Such cool, thin, nearly gas-less systems are generally harder to detect than the protoplanetary disks found in and near star-forming regions and thus are presently less well known and studied than their younger counterparts.

Criteria 1), 2), and 3) ensure that a massive protostellar disk is not present, the existing CS material is optically thin, most of the gas has condensed, dispersed, or is segregated from the dust, and solid particles are in Keplerian motion modified by radiation pressure (RP). Herbig Ae/Be (HAeBe) stars and classical T Tauri (TT) systems should be excluded by these criteria. In addition, criterion 3) requires that the grains are in orbit rather than condensing at cosmic abundances in winds and jets, and is meant to eliminate "shell" stars with CS gas envelopes but no measurable dust.

Criterion 4) is crucial, requiring that observed grains must be continuously replenished from reservoirs of larger objects and thus are second generation and not primordial. Inference of second generation *gas* around β Pic will be covered in section IV.B.2. It is important to point out that second generation material around a star indicates not only the existence of planetesimals but also of larger masses capable of sending small bodies into fragmenting collisions and star-grazing orbits to release dust and gas. Our solar system (SS) is an example of an old main-sequence (MS) system of second generation dust and gas. An external observer detecting the SS dust and active comet comae could thereby infer the existence of remnant planetesimals and their planetary perturbers.

Note that, despite the phrase "main sequence" in our chapter title, we prefer a definition of Vega / β Pic debris disk systems based on CS physical processes rather than the exact evolutionary state of the primary star. A star may or may not have reached MS status by the time its circumstellar disk is cleared of gas. Observations of pre-main-sequence (PMS) objects show that substantial protoplanetary disks generally disappear in less than 10 Myr (e.g. Strom et al. 1993). In comparison, ZAMS status is reached after 5/15 Myr for high/low-mass A stars and 30+ Myr for solar-mass stars. An age of 10 Myr might serve as a rough statistical dividing line between systems with dense gaseous protoplanetary disks and the more evolved, optically-thin planet-forming disks with which we are primarily concerned.

A modest number of CS dust systems have been found in the field at relatively large distances, e.g. HD 98800 (50 pc), HR 4796A (70 pc), HD 141569 (100 pc) and 51 Oph (130 pc), with ages less than a few x 10 Myr and guaranteed by selection effects to contain much more dust than in typical systems nearer to us. For lack of better terms we shall call these "old pre-MS" (OPMS) or "young MS" (YMS) stars. They are interesting because they represent the transition between PMS stars in star-forming regions and MS stars in the solar neighborhood. Such systems will be discussed in section V.B.

II. OBSERVATIONS

A. β Pictoris

A crucial bit of new information regarding this system is a revised distance from *Hipparcos* data of 19.28 $\pm$ 0.19 pc and hence an absolute V mag of 2.42 $\pm$ 0.03 (Crifo et al. 1997). This yields a bolometric luminosity for β Pic of 8.5 $L_\odot$, given an effective temperature of 8200 K (cf. previous value of about 6 $L_\odot$) with little or no inferred CS dust extinction.

Analysis of several photospheric lines (Ca II, Cr II, Fe II) seems to show that the star has solar composition in metallic elements (Lanz et al. 1995; Holweger et al. 1997) in contrast with previous claims. The implications of this will be discussed in the context of star ages and disk evolution (section III.A.2).

1. β Pictoris - Circumstellar Dust

High-signal/noise data optical images of β Pic's outer disk show five asymmetries at the few-percent level between the NE and SW wings (Kalas & Jewitt 1995): radial extent, surface brightness at a given radius, thickness at a given radius, and wing-tilt (position angle of the mid-plane), plus the so-called "butterfly" asymmetry in which disk thickness perpendicular to the mid-plane varies among the quadrants. The wing-tilt asymmetry can be explained by a combination of disk orientation and non-isotropic scattering phase function. The other surface brightness (dust density) asymmetries possibly reveal the dynamical influence of large masses in or near the disk.

High spatial resolution optical images ($\simeq$ 0.1 arcsec) obtained with AO techniques (Mouillet et al. 1997a) and HST (Burrows et al. 1995) trace the disk to within about 1 arcsec ($\simeq$ 20 AU) from the star. New

HST/STIS images (Heap et al. 1999; Fig. 1) reach in to r $\simeq$ 15 AU and constrain the vertical distribution of dust in the disk to have a sharp maximum at the disk midplane. The high spatial-resolution images also show an inner 3° warp (or asymmetric bulge) in the mid-plane relative to that of the outer disk. Both the disk thickness and the warp are most easily explained by the influence of planetary or substellar companions.

Lagage & Pantin (1994b) mapped the thermal emission at 10 μm from the disk in the region r < 100 AU for the first time and directly showed the central low-density "gap" or void. The disk position angle in those images is the same as the warped disk noticed later via scattered light at optical wavelengths. They also detected a large asymmetry in thermal-IR surface brightness between the inner disk wings (discussed further in section IV.A.1). Harvey et al. (1996) resolved the outer disk at 50 μm in KAO observations, obtaining results consistent with the IRAS scale size (Aumann 1991). Sub-mm photometry and an assumption of a plausible mass absorption coefficient led to an estimated total grain mass for the disk of 7 x 10^{23} kg ($\simeq$ 0.1 $M_\oplus$) (Zuckerman & Becklin 1993b).

The SCUBA camera at the *James Clerk Maxwell Telescope* produced sub-mm images of the β Pic disk. A prominent "blob" of emission is seen in those images at r $\simeq$ 30 arcsec (600 AU) (Holland et al. 1998; Fig. 2). The dust in the "blob" would need a net cross-section area comparable to all the dust in the rest of the disk if it is heated by the star; no other local heat source at that position is detected in the near-IR to a deep limit of K $\simeq$ +19.5 (Rosenthal et al. in prep.). It particular, it cannot be due to a brown dwarf or super-Jupiter.

IR aperture photometry at 2-13 μm plus spectrophotometric observations in the silicate bands (Knacke et al. 1993; Aitken et al. 1993) confirmed the previously detected silicate emission and inferred the presence of about 10^{-6} $M_\oplus$ of small ($\simeq$ 2 μm) grains within 30 AU of the star. The observed spectral feature has a significantly different shape from that of silicates in the ISM or around AGB and PMS stars but resembles that of solar system comets such as P/Halley containing partially crystalline silicates (Knacke et al. 1993).

2. β Pictoris - Circumstellar Gas

Spectroscopic monitoring of β Pic's gas (summarized in Lagrange 1995, 1998a) has continued to investigate the stable gas ring/disk lying within 1 AU of the star and to better characterize absorption-line variability.

HST observations (Vidal-Madjar et al. 1994; Lagrange et al. 1996) detected variability in lines of various ions. Recently, variability was also found in one neutral atomic species, C I (Jolly et al. in prep). Long campaigns of medium- and high-resolution (R = 3 x 10^4 to 10^5) spectroscopy from the ground and from space with the HST, as well as ultra-high resolution (R = 10^6) observations from the ground, revealed the presence of typical groupings of infall velocities of the Ca II lines. These groupings have velocites relative to the star of less than 10 km s^{-1} (very low-velocity features; VLVF), 10-30 km s^{-1} (low-velocity features; LVF), and $\geq$ 80 km s^{-1} (high-velocity features; HVF) (Lagrange et al. 1996; Beust et al. 1998; Petterson & Tobin 1999). LVF and HVF are also seen in UV lines. These velocity groupings are associated with different variability timescales: the higher the velocity, the shorter the timescale. The small number ($\leq$ 10%) of blueshifted events with respect to redshifted ones has been confirmed and the overall rate of events was estimated to be as much as a few hundred per year (Ferlet et al. 1993). The sizes of infalling clouds depend on the specific ion considered. The conditions in a typical infalling Ca II cloud are $n_e \geq 10^6$ cm^{-3} and $T_e \geq 10^4$ K.

About 15 ions and neutral species have been identified in the stable gas with HST (Lagrange et al. 1998b). Radio observations yield an upper limit to the H I content of $\leq$ 15 $M_\oplus$ and a ring gas/dust mass ratio estimated to be $\leq$ 10 (Freudling et al. 1995). Cold ($\simeq$ 20 K) molecular CO was also detected with HST (Vidal-Madjar et al. 1994; Jolly et al. 1998), although all attempts failed at radio wavelengths (Savoldini & Galletta 1993; Dent et al. 1995; Liseau & Artymowicz 1998). Most Ca II ions are probably located 0.3–1 AU from the star but the CO is located much further away ($\geq$ 10 AU; Jolly et al. 1998), possibly within the main dust disk.

3. Photometry

Small light variations ($\leq$ 0.06 mag) that occurred in 1981 were reported by Lecavelier et al. (1995). The β Pic light curve, carefully monitored during several years for photometric calibration purposes by the Swiss ESO telescope, showed a brightening of 0.06 mag lasting about 10 days followed by a central drop a few hours long and then a return to the long-term average value. These variations were tentatively attributed to a planet or a giant comet cloud (Lecavelier et al. 1997a; Lamers et al. 1997).

B. General Surveys for CS Dust, and Follow-Up Observations

Surveys of volume-limited stellar samples show that at least 15% of A-K MS stars have some far-IR dust excess with fractional dust luminosity ($f_d \equiv L_d/L_*$) greater than or equal to α Lyr's value of $\sim$ 2 x 10^{-5} (BP93; Plets 1997a [IRAS]; Dominik et al. 1998a [ISO]; Fajardo-Acosta et al. 1999 [ISO]). A few stars with f_d up to 10^{-2} were found. Even larger values ($f_d \simeq$ 0.1 or more) were measured for some B–A stars which are also emission-line stars and probably quite young. They evidently should be classified as PMS or OPMS stars (e.g. Sylvester et al. 1996; Dunkin et al. 1997b; Malfait et al. 1998), confirmed in some cases by ages derived from Hipparcos data (van den Ancker et al. 1998).

The selection of real MS stars is thus critical to the interpretation of surveys. Mannings & Barlow (1998) explicitly chose MS stars over about half the sky at $|b| \geq 10°$ from the Michigan Spectral Catalog of HD stars and found 70 new candidates with IR excess in the IRAS Faint Source Catalog. M-type MS stars could have dust disks as commonly as do stars of earlier spectral type, but their low luminosity makes detection of dust impossible at present around all but the closest systems. IRAS and ISO observations have revealed a few examples (Backman et al. 1998 and references therein; Fajardo-Acosta et al. 1999).

Photometric observations across a wide range of wavelengths constrained system SEDs and hence the disk properties (e.g. Sylvester et al. 1996; Sylvester and Skinner 1996; Sylvester et al. 1997; Fajardo-Acosta et al. 1998b). Complementary observations were made to better define the characteristics of the central stars (Dunkin et al. 1997a, 1997b). Waelkens et al. (1996) found spectroscopic signatures of dust composition in ISO SWS observations.

Dominik et al. (1998a), Becklin et al. (1998), Abraham et al. (1998) and Gaidos (1999) found evidence in IRAS and ISO data of evolution toward lower CS dust density with timescales of a few x 10^8 yr or less; these results will be discussed further in section III.B.3. Lynch & Russell (in preparation) searched for but found no warm (3.5-9 μm) excesses toward stars 51 Peg, 47 UMa, υ And, and τ Boo which have known or suspected planetary companions.

A coronographic optical imaging survey was performed on more than 50 MS stars and did not detect any disks (Kalas & Jewitt 1995) except around BD+31°643 (age $\leq 10^7$ yrs; Kalas & Jewitt 1997). These negative results are comparable to those of Smith et al. (1992). The general non-detection of optical disks, including even the prototype Vega and α PsA systems, could be attributed to a small scattering cross-section of CS dust (Kalas & Jewitt 1996), consistent with the IR SEDs, and does not require that the β Pic grains are substantially different from grains around other stars. Recently, disks were imaged at near-IR wavelengths around ρ^1 Cnc (a planet-bearing star resembling 51 Peg) and the OPMS star HD 141569 (sections II.D.4 and V.B, respectively).

C. General Surveys for CS Gas, and Follow-Up Observations

Stars found to have CS absorption lines similar to β Pic's were reobserved with the HST. HR 10, HR 2174 and 51 Oph exhibit narrow UV absorptions arising from excited levels indicating the presence of CS gas at distances greater than 15 R_* (Dunkin et al. 1997b; Lecavelier et al. 1997b). 51 Oph exhibits other spectroscopic similarities to β Pic that will be discussed in section V.B. Spectral monitoring of HR 10 (Welsh et al. 1998) confirmed variable redshifted absorptions (Lagrange-Henri et al. 1990) and moreover detected some blueshifted transients. The variability is interpreted as the result of comet evaporation, although no detailed models have been calculated as of this writing.

Other attempts to detect CS gas and/or spectroscopic variability were made in samples selected via IRAS (Cheng et al. 1992 and 1995) and IUE criteria (Grady et al. 1996a). A few stars were discovered to exhibit shell features, with 2 And also showing spectral variability in HST data (Cheng et al. 1997).

A survey for CO emission (Zuckerman et al. 1995b) around younger stars including some we label OPMS (section V.B) yielded upper limits (e.g. HR 4796A, HD 98800) or positive detections (e.g. HD 141569), leading the authors to conclude that gas in these systems dissipates on timescales shorter than about 10^7 years. This is consistent with the negative results of Lecavelier et al. (1998a) for CS gas from a spectroscopic survey of a large number of stars in the Ursa Major Stream (age $\simeq$ 300 Myr).

D. Observations of Individual Stars

1. Vega (α Lyrae)

Re-analysis of IRAS slow-scan observations produced a revised scale for the 60 μm dust emission of 35 arcsec diameter versus the previous 23 arcsec (van der Bliek et al. 1994). This indicates the dominant grains have characteristic sizes of order 10 μm rather than 100 μm and thus shorter lifetimes than previously calculated. Zuckerman & Becklin (1993b) estimated the minimum dust mass to be only 4 x 10^{22} kg from sub-mm observations. SCUBA sub-mm images (Holland et al. 1998; Fig. 2) show an emission peak that is not centered on the star position, but the offset is not much more than 1σ and is possibly an artifact. Atmosphere models and the very low $vsin(i)$ value indicate the star is viewed pole-on (Gray & Garrisson 1987), consistent with the nearly circular aspect of the 60 μm emission from dust.

Dent et al. (1995) failed to detect CO down to a column density limit of 1.6 x 10^{14} cm^{-2}. An upper limit of 10^{12} cm^{-2} had been placed previously on Ca II absorption (Hobbs 1988).

2. Fomalhaut (α Piscis Austrinus)

This disk was resolved by Harvey et al. (1996) at 50 and 90 μm. Fajardo-Acosta et al. (1997, 1998a) mapped the disk with ISO showing 60 μm emission extending about 30–80 arcsec (200–500 AU) from the star, attributed to approximately 10-μm-size grains radiating at T $\geq$ 50 K. The disk was mapped at sub-mm wavelengths (Holland et al. 1998; Fig. 2), clearly revealing a hollow central cavity. The position angle of the main axis of the ellipsoid is consistent among the SCUBA sub-mm images, ISO 60 μm maps, and slow-scan information from IRAS scan profiles (Gillett 1986).

No CS gas has been detected at optical, UV or radio wavelengths.

In particular, the reported detection of CS gas based on IUE data by Cheng et al. (1994) was not confirmed in HST spectra (Ferlet et al. 1995). Dent et al. (1995) set a CO upper limit of 2.4 x 10^{14} cm^{-2}.

3. ϵ Eridani

A SCUBA sub-mm image (Greaves et al. 1998; Fig. 2) of this dust disk around a very nearby cool MS star (3 pc, K2V) shows a definite ring and central clearing with a radius of about 30 AU. The size of the ring agrees with the scale derived from IRAS slow-scan observations (Aumann 1991). The sub-mm image shows significant azimuthal variations in the ring's surface brightness. Such asymmetries should be erased within a dust collision timescale of order 10^6 years. If real, they may provide evidence of either recent episodes of dust release or shepherding by larger bodies.

4. ρ^1 Cancri

This $\simeq$ 5 Gyr-old system is particularly interesting since it has both CS dust with modest fractional luminosity ($f_d \sim 5 \times 10^{-5}$) and at least one planet (a = 0.11 AU, M sin(i) = 0.84 M_{Jup}). ISO observations detected the disk at 60–90 μm, modeled as due to $\simeq$ 4 x 10^{-5} $M_\oplus$ of 10 μm dust grains lying between 35 and 60 AU from the star with a definite central cavity (Dominik et al. 1998b). Recently Trilling & Brown (1998) imaged the disk in scattered light at 2.3 μm (Fig. 3).

III. EVOLUTIONARY ISSUES

A. Stellar evolution

1. Ages of Stars - General

Reliable ages for field stars are still difficult to obtain, yet without ages for the MS CS dust and gas systems their place in stellar and planetary evolution cannot be ascertained. Stars in open clusters have supposedly well-determined ages but no post-ZAMS cluster is close enough for easy detection of CS dust by either IRAS or ISO (e.g. Backman et al. 1998). *Hipparcos* parallaxes should allow distance determinations that will challenge the quality of the stellar interior models upon which isochrones are based. One problem with isochrone ages is that they are bi-valued, i.e. a star occupies a position in an HR diagram above the ZAMS both before and after the ZAMS. Although the distinction between MS and giant stars is usually straightforward, the distinction between MS and PMS stars sometimes is not, and this determination is more difficult for earlier spectral types.

It is statistically unlikely that any of the stars within 25 pc (2x the volume containing β Pic) are much younger than a few x 10 Myr. This result applies generally for all spectral classes and can be derived by dividing the lifetime of a typical member of each class by the number of stars in that class within the volume considered. Discovery of a number of stars apparently younger than 10 Myr in the TW Hya association (Webb et al. 1998) supports the above argument as this group lies at d $\simeq$ 55 pc and thus in a 10x larger sample volume. Surveys of age indicators such as Li abundance and Ca II activity (e.g. Henry et al. 1996) show that the age histogram for nearby solar-type stars is approximately flat, with few objects younger than 10^8 yr.

2. Ages of Stars - Individual

Vega has a luminosity roughly 3 x L_{ZAMS} for its temperature. Comparison of its properties with evolutionary tracks for $M_* = 2.5$ $M_\odot$ (Palla & Stahler 1993; Bressan et al. 1993) indicate it could be either a PMS object with an age of about 2.5 Myr or a post-ZAMS object with an age of about 350 Myr. Holweger & Rentzsch-Holm (1995) have claimed that Vega's surface abundances indicate it is still accreting and therefore in a PMS stage. We prefer the post-ZAMS age for Vega based on: a) the previous argument about minimum plausible ages for nearby stars, b) the certain absence of G, K, and M stars as young as 2.5 Myr within 50 pc, and c) comparison of the detection likelihood implied by the two timescales.

The question of the age of β Pic produces the same type of controversy as for α Lyr. β Pic's luminosity was interpreted as either representing pre-ZAMS status with substantial extinction (Lanz et al. 1995) or post-ZAMS with different stellar parameters (Paresce 1991). Recent determinations (section II.B) that the star's luminosity is close to ZAMS and that its metallicity is approximately solar are still consistent with a wide range of possible ages from about 10^7 to a few x 10^8 yr.

An age estimate of 200 Myr for α PsA is obtained from the more easily determined age of its K4V proper-motion companion Gl 879 (Barrado y Navascues et al. 1997). An age of 800 Myr for ϵ Eri is found from recently recalibrated Ca II H+K activity indices (Henry et al. 1996).

B. Evolution of Dust and Dust Parent Bodies

Creation and destruction processes affecting MS CS solid material have been studied in some depth (BP93; Artymowicz 1994, 1997; Artymowicz & Clampin 1997). The timescale for loss of solids from each system, usually based on P-R drag and collisions as the two most readily calculable effects, is much shorter than the stellar age for all the prototype Vega / β Pic systems.

1. Radiation Pressure, Radial Motions, and Dust Avalanches

Radiation pressure will force some grains into eccentric orbits after release from parent bodies. The collision timescale including consideration of dust planar motions (eccentricities) as well as vertical motions (inclinations) is approximately $t_{coll} \simeq P_{orb}$ / (12 $\tau_\perp$) where P_{orb} is the local orbital period and $\tau_\perp$ is the local geometric optical depth perpendicular to the disk. This shortens t_{coll} relative to the value derived from vertical motions alone and strengthens the argument that observed grains must be replenished and not primordial.

Erosion of disk particles releases fine dust subject to radiative acceleration and ejection. Orbits will be hyperbolic for grains with a RP index $\beta \equiv F_{rad}/F_{grav} > 1/2$ if released from large parent bodies in circular orbits. These grains can impact other disk particles at high relative velocity and cause efficient cratering/breakup. Such a collision debris swarm should grow exponentially as the dust avalanche traverses the disk radially. Overall erosion rates much faster than implied by "normal" collisions occur if the dust disk exceeds a critical midplane radial optical depth roughly estimated to be about that of the β Pic disk (Artymowicz 1996). In denser disks the destruction rate grows exponentially with f_d.

2. Dust Quantity and Disk Evolution

The fact that at least 15% of nearby A, F, G, and K stars have far-IR dust excesses indicates that this phenomenon must extend at least in some cases over Gyr timescales. Nevertheless, a general decrease of f_d with age for PMS and MS objects is observed, discussed by Zuckerman & Becklin (1993b) and Holland et al. (1998). The similar A-type stars HR 4796A, β Pic, Fomalhaut, and Vega form a sequence of f_d decreasing monotonically from ages of 10 to 350 Myr (Fig. 4). Dominik et al. (1998a) and Becklin et al. (1998) both found evidence in ISO surveys of nearby field stars that the fraction with detectable far-IR excesses drops from about 50% to about 15% after 500 Myr. In apparent contradiction to these results, Abraham et al. 1998 claimed that only 1 of 9 stars in the Ursa Major Stream (age $\simeq$ 300 Myr) showed dust emission, but four of their ISO targets (all without far-IR excess) may not actually be members of the Stream (cf. Soderblom & Mayor 1993). Gaidos (1999) examined IRAS data on solar-type stars selected to be younger than 800 Myr based primarily on X-ray flux. He found detections and limits consistent with the amount of terrestrial-temperature dust predicted by a simple model of the SS heavy bombardment era.

Artymowicz (1994, 1996, 1997) argued that the dustiness of Vega-type (low-f_d) systems is self-limited by the dust avalanche process and proposed that gas-poor disks, in which gas drag is unimportant for dust kinematics, cannot be much dustier than β Pic (if geometrically similar). Systems with much larger f_d could be disks that have gas-controlled dynamics. The critical lower limit to the gas/dust mass ratio is calculated to be of order 10 and this amount of gas would be currently undetectable in most MS debris disks. That hypothesis may be strengthened by indications that the dustiness of IR-excess systems is bimodal (data collected in Artymowicz 1996). Only a few systems (e.g. β Pic, HR 4796A, HD 141569) are in the range $f_d = 10^{-3} - 10^{-2}$, whereas the neighboring logarithmic bins contain many more stars with lower (Vega-like) or higher values of f_d (stars generally known to be young PMS objects; cf. Dunkin et al. 1997b).

3. Interaction with the ISM: Nature versus Nurture

Hypotheses that interaction with ISM grains might be important in the evolution of Vega-like disks is supported by the discovery of streams of large ISM grains in the vicinity of Jupiter (Grün et al. 1994). Artymowicz & Clampin (1997), however, calculated that internal erosion should generally dominate in MS disks over the influence of ISM grains due to: a) the strong repulsive RP force exerted by luminous stars on absorbing sub-μm ISM grains, and b) high dust density in disks compared to the ISM. Only at the very outskirts of the prototype disks (radii exceeding $\simeq$ 400 AU) can the ISM bombardment be important, possibly capable of causing slight disk asymmetries.

IV. DISK MODELS AND INTERPRETATIONS

A. β Pictoris - Circumstellar Dust Models

1. Disk Morphology

If one assumes a single grain population (Artymowicz 1997), then current models do not easily fit both the scattered light images from HST/STIS (Heap et al. 1999) and the thermal-IR images of Lagage & Pantin (1994b) and Pantin et al. (1997). The thermal-IR data indicate that dust optical thickness peaks or reaches a plateau at 30–60 AU. Those IR images also show an asymmetry larger than a factor of 2 between the NE and SW wings' 12 μm thermal emission at those distances.

The visible STIS data, in contrast, match a larger gap with peak dust density near r $\simeq$ 120 AU and a much more symmetric distribution. The disk optical depth in a model of the scattered light by Artymowicz et al. (1999) equals: $\tau_\perp(\mathrm{r}) = 2\ \tau_m/\sqrt{(r/r_m)^{-2p} + (r/r_m)^{2q}}$, where r_m = 120 AU is a characteristic radius approximately coinciding with maximum $\tau_\perp(\mathrm{r}) \simeq 0.01$. The STIS data support $p = 2$ (i.e., $\tau_\perp \sim r^2$ near the star) and $q = 3$ (i.e., a steep fall-off, $\tau_\perp \sim r^{-3}$, at $r \geq r_m$). The significantly different sizes of the central gap deduced from scattered optical light versus thermal-IR data may imply two separate grain populations or one with radially varying physical and optical properties.

2. Dust Composition and Origin

The grey color in the visible and near-IR plus the silicate emission feature (section II.A.1) suggest a similarity of β Pic dust to cometary and interplanetary (zodical) dust in our system. Artymowicz (1997) showed that zodiacal light particles distributed as in the β Pic disk could also reproduce its observed linear polarization properties, implying a similar porosity or roughness of grain surfaces. On the other hand, the albedo of typical β Pic grains seems significantly higher than that of the typical SS particles, most of which scatter 10% or less of the visible sunlight. Based on models combining properties of the thermal and scattered radiation, the main β Pic disk has an albedo of $A \sim 0.3$-0.4 (Backman et al. 1992; Burrows et al. 1995) to $A > 0.5$ (Artymowicz et al. 1989). These observations are best explained by common mineral mixtures such as slightly darkened ices or bright silicates (Fe- and C-poor olivines and/or pyroxenes, e.g. Mg-rich pyroxenes with mass ratio Fe/(Mg+Fe) $\sim\leq 0.2$). While water ice is an important constituent of planetesimals, its vulnerability to potent UV photo-sputtering by β Pic , and its mechanical fragility, make it an unlikely material for the observed grains (Artymowicz 1994, 1997).

Collisions involving bodies up to the size of planetesimals, erosive grain impacts, and thermal evaporation of comet-like bodies are probably all effective in generating fresh dust in debris disks. The estimated overall dust grinding rate at the location of maximum dust density in β Pic's disk corresponds to a system destruction timescale of roughly 50 Myr, about 10^4 times longer than the disk replenishment time. This fits within the wide range of estimated ages for the star and is independent evidence that β Pic and its disk is not much older than 100 Myr. The total mass of the original β Pic planetesimal disk required for continuous dust replenishment is $\sim$ 100 $M_\oplus$ (Artymowicz 1997), of order that originally present in the SS (section VI.A).

Lecavelier et al. (1996), Lecavelier (1998b), and Li & Greenberg (1998) proposed disk models in which most of the dust is released by comet evaporation at only a few x 10 AU from the star but can be driven by RP to produce a wedge disk out to r > 1000 AU. The grains would spend most of their time at their respective apoapses so the outer disk would be relatively prominent. The evaporation of comets could also provide a source of the observed molecular CO column density.

B. β Pictoris - Circumstellar Gas Models

Comets as the origin of both the stable and variable gas are the only mechanism that has been successfully modeled.

1. FEB Models for Transient Absorption Features

The general idea for the FEBs is that the observed variable gas is due to evaporation of star-grazing comets (reviewed in Beust 1994). Dust released from active comets evaporates and produces the observed metallic gas which is subjected to RP, gravity, and collisions with the mostly neutral gas (H I, O I) around the comet. RP causes the size of the parabolic absorbing cloud (coma) to differ from one ion to another, ranging from $\leq$ 10% of the stellar diameter to larger than the star (Vidal-Madjar et al. 1994; for up-to-date values of the RP index β for various species see Lagrange et al. 1998b).

Simulations of individual events reproduce the variable features in terms of shape, velocities and depths (Fig. 5; Beust et al. 1998 and references therein). Typical distances of evaporations are respectively 30, 10-20, and ≤ 10 R_* for the VLV, LV and HV features, and evaporation rates are of order 3 x 10^7 kg/s, consistent with scaled values obtained from observations of small SS Kreutz-family (sungrazer) comets.

The FEB scenario explains the presence of highly ionized species as due to high pressure and temperature on the parabolic front (e.g. Beust & Tagger 1993, Mouillet and Lagrange 1995) although no full simulation including all the ionization processes has yet been completed. It may also explain via details of the comet dynamics (Beust & Lissauer 1994; see also, section IV.C) the puzzling observations that Ca II H is deeper than Ca II K (Lagrange et al. 1996) and that blueshifted variable features are rare (Crawford et al. 1998).

The simulations have difficulty reproducing the observed LVF timescales via the evaporation of a single body: the lines should be only detectable over a few hours, whereas actual events last significantly longer. One possible explanation is that we observe a "family" of bodies crossing the line of sight on close orbits, perhaps resembling the Comet Shoemaker-Levy 9 fragment train (Beust et al. 1996).

Beust et al. (1998) found that the mean motion resonance mechanism (section IV.C) proposed for propelling comets into the star implies that the comets' periastra undergo a gradual decrease until the comets start to evaporate and produce the observed variable absorptions. Comets of 1 km size can survive enough passages to produce the LVF at about 0.5 AU, but some comets must be $\simeq 10$ km in size to survive many more close passages before arriving at a few stellar radii where the HVF are produced.

2. FEB versus Shell Models for the Stable Gas

Observed species that suffer strong RP and do not have saturated lines are very unstable and must be continuously replaced. Similarly, the lifetime of CO to photo-dissociation is small. Thus, it is clear that gas must be continuously produced to resupply the observed stable component, near the star for the atomic gas and further away for CO.

Simulations of dynamics of gas released within 0.5 AU of the star and subjected to RP, gravity, and interaction with a ring of neutral gas at $\simeq 0.5$ AU reproduce the observed line depths and chemical abundances (Fig. 5; Lagrange et al. 1998b). The gas production rate needed to sustain the lines is $\simeq 3{\times}10^7$ kg/s. This neutral gas rate is compatible with the observed upper limits, in particular for H I, and is coincidentally similar to the estimated evaporation rate in an average FEB event (previous subsection).

Comet evaporation is a natural source of the atomic gas. The required evaporation rate is similar to that needed to explain the variable lines, and the number of comets necessary ($\simeq$ 1000/yr in all directions from the star) is plausible for a young system (Lagrange et al. 1998b). Also, this would explain the presence of CO through slow evaporation of comets at larger distances from the star (Lecavelier et al. 1996). The gas/dust ratio deduced from the CO abundance and lifetimes of the dust and gas appear to be consistent with both gas and dust being released by the same process (e.g. Jolly et al. 1998).

An alternate explanation of the stable gas as originating in a wind cannot be excluded but is unlikely. The gas production rate would correspond to a mass loss rate of about 10^{-16} $M_\odot$ /yr, compatible with an A-type stellar wind (Babel 1995). However, this model would imply that all stars, and in particular A-type stars having higher mass loss rates (e.g. Sirius, 10^{-12} $M_\odot$ /yr; Bertin et al. 1995), should also be surrounded by stable gas, but this is not the case. Also, the inferred presence in the stable ring of species like H I and O I that do not suffer much RP is inconsistent with a wind model.

Another explanation of the stable gas as a "shell structure" around the star seems inadequate. Maintaining gas in a hydrostatic shell suggests rotational support to balance the star's gravity. Although they are stable on dynamical timescales, such shells would be subject to viscosity effects causing both accretion onto the star and outward spreading. The lifetime of shells with radii less than 1 AU is expected to be shorter than 10^4 yr based on the Balbus-Hawley magnetic instability with viscosity parameter $\alpha \sim 0.01$.

C. Model Results - Indirect Evidence for Planets in Disks

The possibility that the Vega/β Pic disks are locations of ongoing or completed planet formation is one of the most exciting aspects of these systems. There are several indirect lines of evidence regarding the presence of massive bodies in or near some of these disks.

The SEDs of the prototype CS dust systems all imply transitions from outer high-density zones to inner low-density zones, but at at a wide range of temperatures such that ice sublimation is an unlikely explanation for all of them. A real possibility is that planets redirect grains (cf. Roques et al. 1994 for the case of β Pic) or consume grains as they drift via P-R drag toward central stars (cf. Liou et al. 1996 for the SS). α Lyr is an especially important case because its grain collision timescale is similar to or longer than the P-R drag timescale (e.g. BP93). The observed lack of hot grains around α Lyr implies that something must be eliminating the grains as they drift inward, or the inner zone would be filled in relatively rapidly.

Nothing short of planetary gravitational perturbations seems adequate to explain the FEB triggering mechanism in the β Pic system.

Possible mechanisms and their difficulties include: 1) close encounter with a single planet (Beust et al. 1991), requiring a planet on a highly eccentric orbit (but note that the 16 Cyg B and 70 Vir systems contain such objects); 2) the Kozai mechanism, as in the origin of the SS Kreutz-family comets (Bailey et al. 1992; Thomas & Morbidelli 1996); however, this would produce symmetric infall which is not observed; 3) secular resonance perturbation by a planet (Levison et al. 1995); this assumes a planetary configuration like our SS, but the mechanism is much less efficient for other possible planetary arrangements; 4) mean motion resonance, especially the 4:1 resonance, which seems to be an efficient and generic mechanism and one that can be an asymmetric source of star-grazing comets (Beust & Morbidelli 1996, 1998). Beust & Morbidelli (1998) also propose an additional Earth-mass planet to account for the rarely-observed blueshifted events.

The structure of the β Pic disk is the best understood of the prototypes due to high-resolution imaging. Burrows et al. (1995) have proposed that the gravitational perturbation of the disk by a massive companion (planet or brown dwarf) on an inclined orbit could explain a warp like that observed, reminiscent of previous work by Whitmire et al. (1988) regarding the outer disk. The simulations made by Mouillet et al. (1997b) showed that a physical warp at radii $\simeq$ 50 AU can be explained by a companion located between 1 and 20 AU from the star with a mass respectively between 10^{-2} and 10^{-5} $M_\star$ (6000 and 6 $M_\oplus$) for a system age of 200 Myr. Finally, the finite thickness of the β Pic disk (Artymowicz et al. 1989; Kalas & Jewitt 1995) implies that at least 1000-km objects must be embedded in the disk to maintain the requisite dynamical heating.

V. COMPARISONS WITH PRE-MS, MS, AND POST-MS SYSTEMS

A. PMS Stars and Possible FEBs

Young PMS stars (ages $\leq$ 1-10 Myr, depending on mass) exhibit strong IR excesses and spectral features indicating many characteristic differences from the Vega / β Pic disks: 1) the disk masses may be as high as 0.01 $M_\odot$ for HAeBe stars (Mannings and Sargent 1997; chapter by Natta et al.) and Class II TTs (Andre & Montmerle 1994); 2) accretion rates deduced from the SEDs are high: 10^{-8} to 10^{-6} $M_\odot$/yr for HAeBe stars and 10^{-9} to 10^{-7} $M_\odot$/yr for TT stars, many orders of magnitude larger than the gas accretion rate in β Pic; 3) winds and other gas ejection evident in PMS systems from blueshifted lines and P Cygni profiles are not observed in Vega/β Pic systems; 4) photometric variability with amplitude as high as several magnitudes is observed in UX Ori-type objects (see chapter by Natta et al.), substantially more than the possible sporadic variability of β Pic. For detailed descriptions of these PMS features see Herbst (1994) and Waelkens & Waters (1998) regarding TT stars and HAeBe stars, respectively.

A predictable evolutionary step in the dissipation of PMS disks is formation of kilometer-scale planetesimals (e.g. Lissauer 1993). Calculations indicate that resonant processes could have caused asteroid as well as comet infall to the sun (Farinella et al. 1994). It is therefore reasonable to expect asteroids and comets to be present around evolved PMS stars, creating at least some CS dust through collisions or evaporation and producing effects analogous to the β Pic FEB phenomenon. Whether FEB-generated spectral variability would be detectable in specific systems depends on: a) the efficiency of the process in producing strong-enough absorption lines, and b) the overall stellar activity: HAeBe stars usually exhibit strong, probably star-related variable spectral features such as P Cygni profiles that could mask FEB activity.

A number of HAeBe stars have been reported by Grady et al. (this volume) as exhibiting infall signatures superficially similar to those of β Pic. Those authors attribute this variability to FEB events at typical distances of 10 R_*, but this comparison should be regarded as tentative for examples based on a limited number of low-resolution, low-signal/noise IUE spectra. Also, in a number of cases, it is difficult to disentangle stellar activity from genuine FEB signatures. It is very important to note that for some of the PMS FEB candidate stars, e.g. AB Aur, variable spectral features have instead been attributed to differentially rotating and chromospherically driven winds or magnetically channeled accretion (Catala et al. 1993; Boehm & Catala 1995). There is also some evidence that the variability timescale is related to stellar rotation, supporting alternatives to FEB models. Therefore, the application of the FEB hypothesis to a large number of HAeBe stars (30%; Grady et al. 1996b) and the proposed relation between infall event frequency and stellar age should not be considered proven (but see also the chapter by Grady et al.)

A few stars (UX Ori, Grinin et al. 1994; HD 100546, Grady et al. 1997) show more convincing β Pic-like features, i.e. variable redshifted absorptions in metallic lines separable from features classically attributed to stellar activity. The variable features of ionized elements are similar to β Pic's in terms of shapes and velocity ranges, the infalling clouds have covering factors smaller than the stellar surface, and they contain over-ionized species (C IV, Al III). There are also some important differences: 1) variable lines are usually stronger, implying much more gas in the variable component than for β Pic; an estimate for the case of UX Ori gives about 10^{12} 3-meter bodies evaporating in less than 3 days at about 10 R_* (Grinin et al. 1996), i.e. more than 100x the mass in a typical β Pic event; 2) event rates are generally higher; 3) variability timescales seem to be longer, although data on short timescales are sparse; and 4) strong variable lines are observed in neutral species (e.g. Na I, Hα, C I) whereas β Pic, even though cooler, does not show detectable amounts of variable neutrals. Sorelli et al. (1996) showed for UX Ori-type stars that Na I absorption events can be reproduced with magnetic accretion as well as by comet evaporation provided the magnetic field is $\simeq$ 600 Gauss (below current detection limits).

A first attempt to apply the FEB simulations to a PMS FEB candidate, HD 100546, shows that it is difficult for an FEB model to successfully reproduce the observed depths of the variable lines because the high stellar luminosity means high RP on the ions. Also, these stars usually have robust stellar winds that will strongly interact with the evaporated material. Comet evaporation rates much higher than in β Pic are needed to reproduce this star's variable Mg II features observed with IUE (Lagrange and Beust 1999).

A further critical question is the relative frequency of blueshifted and redshifted features. One should expect to detect approximately as many blueshifted as redshifted events in a system without significant dynamical asymmetry. Grady et al. (this volume) attribute the general predominance of PMS redshifted events to complete evaporation of FEBs before periapsis. However, even around a late-B star a comet as large as P/Halley can be expected to easily survive periapsis passage at distances corresponding to velocities below about 100 km s^{-1}. Also, pre-periapsis destruction raises dynamical difficulties as the bodies are more likely to become star-grazers in a gradual way rather than at first passage (as mentioned in section IV.B.1). Finally, the marked dominance of redshifted over blueshifted transients in β Pic requires that we must be viewing the system with a special orientation. If an asymmetry toward redshifted transients is seen at low velocities in many systems, then FEBs cannot be the general explanation for the spectroscopic phenomena.

In conclusion, it is probable that FEB events are occurring around some PMS stars but their detection should not be as straightforward as in the case of β Pic. The interpretation of some HAeBe stars' variability as due to FEBs is questionable but a few show variable features convincingly similar to those of β Pic. The latter stars obviously deserve detailed monitoring and modeling for comparison with β Pic's spectroscopic variability.

B. Borderline Cases - OPMS and YMS Stars

These are stars evidently evolved beyond the TT/HAeBe stage but with denser dust disks than the Vega/β Pic prototypes, possibly including a significant gas component. These were designated "old PMS" = OPMS and "young MS" = YMS systems in section I.A.

1. HR 4796A

This A0V star at d = 67 pc has the highest IR disk fractional luminosity (5 x 10^{-3}) among MS A-type stars (Jura 1991; Jura et al. 1993). Spectroscopy of the nearer M-type companion (HR 4796B, r $\simeq$ 500 AU) gives an age estimate of 8–10 x 10^6 yr for HR 4796A assuming the stars are physically linked (Stauffer et al. 1995; Jura et al. 1998).

Jayawardhana et al. (1998) and Koerner et al. (1998) imaged a radially narrow disk at 10 and 20 μm oriented in the direction of component B, clearly visible in more recent near-IR HST/NICMOS images (Fig. 3; Schneider et al. 1999). The IR data sets are modeled by a ring of material around a central gap about 55 AU in radius, confirming Jura et al. (1995). Sparse dust in the gap at a temperature of 200–400 K is resolved. The outer disk seems surprisingly narrow, quite unlike the similarly dense β Pic disk which has been traced beyond r = 1000 AU. Dynamical model calculations are needed to see if the influence of the stellar companion is sufficient to truncate the disk at its outer edge or if nearer shepherding objects are required.

An upper limit of about 7 $M_{\oplus}$ of gas has been obtained from observations in molecular emission lines (Zuckerman et al. 1995b). As discussed above (section III.B.3), a gas mass exceeding the dust mass by less than an order of magnitude (presently undetectable; Zuckerman et al. 1997) could lengthen the dust destruction timescale enough to make it possible that the dust observed in this system is actually primordial. If gas dynamics are truly important there, the HR 4796A disk may be a very promising laboratory where distinctive spiral density waves and resonantly truncated disk edges could reveal the location(s) of the planet(s).

2. HD 141569

This A0 type star, located at about 100 pc, exhibits a fractional disk luminosity of f_d = 8 x 10^{-3}. van den Ancker et al. (1998) determined its age to be $\geq$ 10 Myr but it may be younger than that based on the strong Hα emission line (Dunkin et al. 1997b); it is usually classified as a HAeBe star. Recently, a disk (Fig. 3) was found around this object at near-IR wavelengths with HST/NICMOS by Silverstone et al. (1998) and Augereau et al. (1999). As in HR 4796A there is a ring of material around an apparent central gap, in this case with sizes Δr $\simeq$ 60 AU and r $\simeq$ 260 AU, respectively. Also, like HR 4796A, this star is a member of a double system, with a separation of about 700 AU.

3. HD 98800

This remarkable quadruple K-star system now has a good age determination of 10 Myr (5–20 Myr) based on its *Hipparcos* distance of 47 pc, indicating these stars are in a PMS but post-TT evolutionary stage (Soderblom et al. 1998).

The HD 98800 dust has a fractional luminosity of $f_d \simeq 0.1$ (Zuckerman & Becklin 1993a; Sylvester et al. 1996), approaching the maximum possible value for a flat or flared disk passively reprocessing stellar radiation. The stars are arranged as two spectroscopic binary systems separated by 0.8 arcsec (40 AU projected) near periapsis of a very eccentric (e = 0.993) orbit (Torres et al. 1995; Soderblom et al. 1996). Koerner et al. (in preparation) obtained 10 μm images showing that the dust is primarily around the B component of this system. Some of the dust is known to be at least mm-size from sub-mm and mm detections of the system (Sylvester & Skinner 1996).

The explanation for the high dust luminosity and, therefore, density could be any of the following or a combination: 1) enough of the original protoplanetary gas disk remains to preserve the dust from erosional avalanches; 2) an avalanche is in progress as we watch; 3) the close stellar encounter allows better heating of the outer parts of the disk or disks, substantially increasing the dust detectability; 4) the stellar encounter (possibly the first since the system formed) is disrupting a Kuiper Belt/Oort Cloud, causing massive collision rates, vaporization of planetesimals, and sudden release of grains. The latter possibility calls to mind the “Nemesis” hypothesis that explained supposed periodic mass extinctions on Earth by proposing the sun has a low-mass stellar companion producing comet showers at perihelion passages in a long-period eccentric orbit.

4. 51 Oph

Photometric and spectrophotometric data at 5-22 μm (Fajardo-Acosta et al. 1993) showed the presence of silicate emission attributed to grains smaller than 5 μm and with a total mass of silicates of 8 x 10^{-5} $M_\oplus$. The emission strength suggests that the typical grains around 51 Oph are larger and hotter than the ones around β Pic. The emission-feature mineralogy resembles that in β Pic and SS comets. Lagage & Pantin (1994a) did not resolve the 10 μm emission (FWHM = 0.9 arcsec), confirming that the dominant dust population is mostly closer to the star than in the β Pic system.

CS gas absorptions in a complex Ca II feature were confirmed through ultra-high resolution spectra (Crawford et al. 1997). The presence of highly ionized species (Grady & Silvis 1993; Lecavelier et al. 1997c) may be attributed to shock excitation in FEB comae. 51 Oph also shows cold C I lines with a column density of 5 x 10^{13} cm^{-2}(Lecavelier et al. 1997c). The short lifetime of C I indicates that species could be produced from photo-dissociation of CO released from comets.

C. λ Bootis, B-A Shell, and Post-MS Stars

Low metallicity proposed for β Pic (Paresce 1991) led King & Patten (1992) to associate β Pic with the (surface) metal-deficient A-type λ Boo stars, tentatively attributed to accretion of gas after gas-dust separation (Venn & Lambert 1990). Dunkin et al. (1997a) looked for λ Boo depletion patterns in a sample of A-type MS stars with high f_d values: only two showed subsolar metallicity, and they were not as strongly depleted as classical λ Boo stars. Comparison of a new list of λ Boo stars (Paunzen 1997) with IR excess stars from the catalogs of Mannings & Barlow (1998) and Oudmaijer et al. (1992) yields only a few stars in common. Thus, there seems to be no strong connection between either spectroscopic characteristics of λ Boo and β Pic-like stars or between λ Boo status and far-IR dust excesses.

The old classification of β Pic as a shell star led to consideration of a possible link between B-A stellar shells and IR excesses. Among the 17 MS A-shell stars presently known and detected in the IRAS Faint Source Catalog, 4 have 12 μm excess: β Pic, HR 9043, HR 3310 and HR 3989; the latter two stars are binaries. Cheng et al. (1991) found an IR excess for HR 10 using IRAS 1-dimensional coadds, and Fajardo-Acosta et al. (1998b) recently detected a 20 μm excess around HR 2174. This yields 6 stars out of 17 with detected IR excesses, which is a fraction not much larger than that for ordinary field A stars, although the small-number statistics do not allow clear conclusions. More sensitive IR photometric observations of a larger sample of A-type MS shell stars are needed.

Individual giant stars have been discovered with dust envelopes arguably connected to disks of planetary debris (Judge et al. 1987; Skinner et al. 1995 and Fekel et al. 1996). Searches were conducted in IRAS data for giant-luminosity descendants of MS stars to check whether far-IR excesses occur around them as often as around MS stars (Jura 1990; Zuckerman et al. 1995a; Plets 1997b). Their results were that far-IR dust excesses around ordinary red giants are significantly rarer than around their MS progenitors, indicating either that the disks decay substantially during the MS lifetimes of ordinary stars, or the rise in luminosity as stars leave the MS quickly destroys dust and dust parent bodies.

VI. COMPARISONS WITH OUR SOLAR SYSTEM

A. The Kuiper Belt

A hypothetical small-grain component of the Kuiper Belt (KB) could be the SS analog of the Vega/β Pic MS disks, especially if that structure originally contained more mass than it does at present. Although its existence has been inferred for many years, direct observations have only recently verified these speculations and begun to determine KB properties (see reviews by Weissman 1995; Weissman & Levison 1998; chapter by Farinella et al.). More than 90 large (100-300 km diameter) objects have been found so far in the KB at r = 30-50 AU and one object of this size class was discovered with a semi-major axis of 85 AU (Luu & Jewitt 1998; chapter by Jewitt and Luu). KB bodies with diameters in the few x 10 km size range are conjectured to be the source population for short-period comets. Objects of this size at about 40 AU have been reported in deep HST images (Cochran et al. 1995), but they await confirmation.

Model KBs consistent with these data and with IRAS and COBE limits on a cold component of the zodiacal emission (Backman et al. 1995; Stern 1996a; Teplitz et al. 1999; chapter by Farinella et al.) have grain populations orbiting at r = 30–100 AU in equilibrium between various removal processes and replenishment by collisions of a few x 0.1 $M_\oplus$ of comet nuclei. These models predict a fractional luminosity f_d in the range 10^{-7} to 10^{-6} for SS KB dust and show that dust $\tau_\perp$ just outside Neptune's orbit could be as much as an order of magnitude higher than at Earth's orbit without violating observational constraints due to warm foreground zodiacal dust. It is possible that HR 4796A, HD 141569, the known MS CS disks, and the SS have similar morphologies, i.e. outer disks or rings surrounding central regions of lower density that might correspond to planetary zones.

The amount of material observed or inferred in the known ("inner") KB falls far below the type of extrapolation (e.g. Tremaine 1989) that led Kuiper to hypothesize the existence of the Belt in the first place. In fact, Stern (1996b; 1997) and Kenyon & Luu (1998) have calculated that known large KB objects and Pluto-Charon could not have formed quickly enough, before Neptune grew large and over-stirred the KB velocity dispersion, unless the primordial inner KB had a mass of at least 10 $M_\oplus$. The density of collisionally-produced dust in such a disk would have resembled those in the prototype Vega and β Pic disks because the dust radiating area scales approximately with the square of the total mass of colliding parent bodies (falling short of that at higher densities because of grain-grain collisions). Such a massive original "inner" KB could evolve into a system like the present KB in the age of the SS (Davis and Farinella 1997; chapter by Farinella et al.).

B. Zodiacal Dust

Artymowicz (1997) discussed a number of similarities and differences between β Pic and SS zodiacal dust. Important contrasts include the facts that the SS dust disk: 1) appears geometrically several times thicker in the planetary region than the β Pic disk and may be more symmetric, 2) seems to contain more Fe and C in grains, and 3) has a slight negative radial gradient of mean albedo, whereas β Pic may have a positive gradient, and 4) has a characteristic grain size of a few x 10 μm versus a few x 1 μm for β Pic. These differences contrast with substantial similarities (section IV.A.2) and may simply reflect the earlier evolutionary stage of β Pic and/or some real compositional differences.

Of the prototype MS CS dust systems, only β Pic so far has detectable dust within the central gap, with model temperatures up to at least 350 K (Fajardo-Acosta et al. 1993). Upper limits on the amount of warm dust around other stars (e.g. Vega, Aumann et al. 1984) are generally high due to lack of spatial resolution and low contrast of dust flux to stellar photospheres at short IR wavelengths. The best IRAS photometric sensitivity at 12 and 25 μm to terrestrial-temperature dust around the nearest stars is several hundred times the optical depth in the SS zodiacal cloud. A few cases of warm CS MS dust have been found and studied recently by Fajardo-Acosta et al. (1998b) via mid-IR spectrophotometry. Mid-IR images of HR 4796A (Jayawardhana et al. 1998; Koerner et al. 1998) resolved a central warm dust population radiating at 200–400 K.

Detection of warm dust might be easiest in young systems during the 10^7-10^8 yr timescale expected for the formation of planets (Wetherill 1991; Lissauer 1993; Gaidos 1999) continuing into the long "end-game" of heavy bombardment. Grains produced by planetesimals with as little as 1% of the mass of the SS terrestrial planets could be easily detected from distances of tens of parsecs in the mid- and far-IR (Witteborn et al. 1982). This corresponds to the amount of interplanetary material estimated to have been present in the terrestrial zone a few x 0.1 Gyr after the formation of the SS.

Asymmetries and planetary wakes in exozodiacal clouds could be used to infer masses and locations of embedded planets (Dermott et al. 1998). Note, however, that the brightness of a 0.3 AU-diameter patch of the SS zodiacal cloud would approximately equal that of Earth at both visual and IR wavelengths; it is estimated that warm dust at more than about 10x SS density would challenge detectability of Earth-like planets via planned space-based mid-IR interferometers such as NASA's *Terrestrial Planet-Finder* (TPF; Beichman 1998). It is critical to such efforts that nearby stars be surveyed for terrestrial-temperature dust at sensitivities an order of magnitude below present limits.

VII. SUMMARY AND FUTURE PROSPECTS

The most important new results concerning the Vega/β Pic stars may be summarized as follows:

1) Vega/β Pic disks have been confirmed to be common; the true frequency of occurrence of solid material in orbit around normal stars may be much higher than the current detection sensitivity-limited estimate of roughly $\sim$ 15%.

2) There is evidence that the amount of dust, quantified by fractional dust luminosity f_d, decreases with age from PMS stars to MS stars.

3) The creation and evolution of Vega/β Pic disks is now understood theoretically to be governed primarily by internal processes such as collisions, radiation pressure, evaporation, and influence of possible planets, rather than by external effects such as erosion by the ISM.

4) Disks are now resolved around a few stars mainly via thermal-IR and sub-mm imaging, while optical/near-IR images providing higher spatial resolution allow examination of the fine structure of detectable disks. Imaging over a wide range of wavelengths is necessary to constrain the disks properties.

5) Central gaps, regions largely if not completely lacking dust, are observed to be normal. Structures at the edges of the gaps (sharp disk truncation, asymmetries, warps, waves) could be good indicators of the presence of planets.

6) Detailed models of the β Pic environment support the idea that planetesimals/comets and probably also larger bodies govern both the CS gas and dust. Dynamical models involving planets reproduce this disk's inner warp. Specific planetary configurations can explain the triggering of FEBs.

7) A few "borderline" cases have been identified, i.e. objects evolutionarily between PMS systems and Vega/β Pic disks. In such systems gas may still play an important role. The study of these objects is important since they trace a crucial transition in planetary system formation.

Newly available large (10 m) single aperture telescopes equipped with adaptive optics and observing at optical or thermal-IR wavelengths (10-20 μm) plus space observatories such as NGST will soon lead to more disk detections and also resolution of finer structures on scales of a few x 10^{-2} to 10^{-1} arcsec. Gaps created by Jovian planets around β Pic should be detectable in this regime. Long baseline ($\geq$ 100 m) optical-IR (ESO VLTI; Keck) or sub-mm (LSA/MMA) interferometers will give milli-arcsecond resolution, and their sensitivity is expected to be sufficient to study this type of disk. These observations will allow a better description of the individual systems and provide much tighter constraints on the orbits and masses of planets we infer to be present around β Pic, HR 4796A, and other similar systems. Access to a large number of disks will help constrain the evolutionary timescales involved in the formation and evolution of planetary systems.

Extensive spectroscopic searches for FEB events around stars with various ages will probably be performed in the next few years, as they give precious although indirect information regarding the dynamics of km-sized bodies and planets. This will help constrain in detail the processes involved in planetary system construction.

Finally, more direct detection of planets in these disks obviously would be of great importance. The radial velocity techniques are restricted for the moment to late-type stars. Other techniques such as photometric surveys will need to be used for the earlier-type stars. Some planned dedicated tools, e.g. dark-speckle (Labeyrie 1995) or very high-order adaptive optics (Angel 1994) might lead to planet imaging in the future.

Acknowledgements

A.-M. Lagrange thanks J. C. Augereau, H. Beust, J. Bouvier, D. Bockelee-Morvan, C. Catala, M. Gerbaldi, A. Lecavelier, F. Ménard, D. Mouillet, and J. Zorec for providing information and fruitful discussions. D. Backman thanks S. Fajardo-Acosta, P. Kalas, and M. Brown for discussions; L. Caroff and D. Goorvitch (NASA-Ames), C. Beichman (Caltech/IPAC), and R. Joseph (U.Hawaii/IRTF) for work space and hospitality during a research leave from F&M College; STScI GO grant 05885.02-94A for partial support; and E. Roberts for help editing this manuscript. P. Artymowicz thanks S. Heap and E. Pantin for joint discussions and the NFR (Swedish Nat. Sci. Res. Council) for generous research grants. Special thanks to A. Lecavelier, C. Dominik, P. Kalas, and S. Fajardo-Acosta for their reading of the draft manuscript, and to the referee M. Barlow for very helpful and constructive comments.

FIGURE CAPTIONS

Figure 1. HST/STIS coronagraphic visible-light image of the β Pic disk (Heap et al. 1999), which traced to within 15 AU of the star (middle panel). To more clearly show the asymmetric bulge out to about 100 AU the image was stretched 4x in the vertical direction and renormalized to the maximum flux in each CCD column.

Figure 2. SCUBA images of the disks around α PsA, α Lyr, β Pic, and ϵ Eri (Holland et al. 1998; Greaves et al. 1998).

Figure 3. Images of recently detected disks around stars of various ages and fractional disk luminosities.

Figure 4. f_d versus age for 4 stars of similar spectral type (see text).

Figure 5. a) Observed and simulated stable lines in the β Pic system; data from HST/GHRS. Left: observed Fe II lines arising from various low energy levels. Right: simulated spectra (see text). Note that in the observed data, redshifted absorptions are present in addition to the stable components; the former are not simulated (from Lagrange et al. 1998). b) Observed and simulated variable lines in the β Pic system. Left: observed Ca II K line, data from ESO/CAT: a low velocity absorption is seen in addition to the strong stable central absorption. Right: simulated Ca II K and H lines. The geometrical configuration of the comet is also shown (see text) (from Beust et al. 1994).

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