Gas in Dusty Debris Disks

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Abstract

The presence of gas in dusty debris disks around main-sequence stars is reviewed. We present new observational results for the most prominent representative of the class, viz. the southern naked-eye star β Pictoris. The spatial and spectral distribution of observed atomic lines from the disk around the star is reproducible by a Keplerian rotation model to a high degree of accuracy. The expected velocity dispersion due to radiation pressure in resonance lines is not observed. Modeling the motion of different atomic species under the influence of gravity, radiation pressure and gas friction leads to the conclusion that an underlying decelerating component must be present in the disk. This braking agent is most likely hydrogen, with inferred average densities $n_H > 10^6 \text{ cm}^{-3}$. This could support the observational result of Thi et al. (2001) which indicated the presence of appreciable amounts of H$_2$ around the star β Pic.

1 Introduction

One of the major highlights of the IRAS mission was the discovery of the ‘Vega-excess’ phenomenon exhibited by a number of main-sequence stars (Aumann et al. 1984), i.e. emission in excess over the stellar photospheric value at long wavelengths ($> \sim 10 \mu \text{m}$). Already from the very beginning it was recognised that this excess is re-emitted stellar radiation by a surrounding cloud of dust particles. The image of the southern Vega-excess star β Pic in the optical by Smith & Terrile (1984) confirmed the earlier notion that the spatial distribution of the dust is highly flattened, i.e. in a disk shaped configuration rather than in a spheroidal cloud. Recent reviews of β Pic and similar systems - the dusty debris disks - include those by Artymowicz (2000), Lagrange et al. (2000) and Zuckerman (2001).

1Collaborators on this project include Pawel Artymowicz, Alexis Brandeker, Göran Olofsson (Stockholm Observatory, Sweden), Malcolm Fridlund (ESA-ESTEC, The Netherlands) & Taku Takeuchi (University of California, Santa Cruz, USA). However, the responsibility for this article rests entirely with the author.
1.1 Dusty Debris Disk Evolution

Besides Vega ($\alpha$ Lyr) and $\beta$ Pic, other prominent members of the class are Fomalhaut ($\alpha$ PsA), $\varepsilon$ Eri and HR 4796A. The excess emission of these objects seems to outline an evolutionary trend (Spangler et al. 2001, Fig. 1), in the sense that the amount of emitting particulate matter in a given object declines with time. Yet younger objects would occupy the upper left corner of the diagram (with considerable spread due to increasing optical depth) and it seems reasonable to assume that the dusty debris disks (somehow) are linked to those of the pre-main-sequence (PMS) phase. PMS-disks, with ages $\lesssim 10$ Myr, are essentially gaseous and are believed to provide the material necessary for the formation of planetary systems (Calvet et al. 2000). Observed asymmetries and inhomogeneities in the dust emission from debris disks have been taken to provide evidence for dynamical signatures of disk-planet interaction, (e.g., Ozernoy et al. 2000, Augereau et al. 2001, Wyatt & Dent 2002, Kuchner & Holman 2003).

1.2 Planets in Dusty Debris Disks

Our knowledge regarding the incidence of known planets (gas giants) around debris disk stars is very limited. Heavy observational bias is at work here, though. Radial-velocity studies are biased toward relatively late spectral types, whereas the most prominent debris disk stars are of earlier spectral types. In addition, radial-velocity studies have focused on fairly old stars, whereas disks around stars much older than about 400 Myr would generally not have been picked up in the IRAS survey (Habing et al. 1999). Three planetary systems, discovered with the radial-velocity technique, have been claimed by Trilling et al. (2000) to possess dust disks. The observational evidence presented by Jayawardhana et al. (2002) (see also Schneider et al. 2001) argues strongly against any substantial amounts of dust around 55 Cnc, whereas the other two systems, viz. $\rho$ CrB and HD 210277, still need confirmation. Pantin et al. (2000) reported the detection of a circumstellar disk around $\iota$ Hor. However, this result has not yet been published in a refereed journal.

The circumstantial evidence for planet(s) around dusty debris stars is enormous. To give just a few examples, the case for Vega has been presented by Wilner et al. (2002), for Fomalhaut by Holland et al. (2003) and for $\beta$ Pic by Wahhaj et al. (2003). For the chromospherically active star $\varepsilon$ Eri, Hatzes et al. (2000) presented a rather noisy radial velocity curve (for more recent data, see http://exoplanets.org/esp/epseri/epseri.shtml) and the confirmation of the planet(s)
would need a longer baseline in time.

1.3 Widespread Gas in Dusty Debris Disks

If the evolutionary hypothesis is correct, then a similar apparent decrease in the gas content may be expected and one could hope to find objects being currently in a transitional phase between gas-rich PMS- and gas-poor debris disks. This could open up the possibility to directly witness the end phases of planet formation and the early stages of planetary system evolution. Appreciable amounts of gas could still be present in these systems.

Alternatively, in older systems, where the dust debris is most likely of more recent origin, the study of the dust production mechanism(s) could benefit from complementing observations of the accompanying gaseous components, as for example in the case of solar system comets (Cremonese et al. 2002).

In either of these scenarios, the detection of sharp spectral features originating from the gas would permit the direct observational study of the disk kinematics and provide input to theoretical models of the debris disk dynamics.

2 Searches for Molecular Gas

Recalling that the discoveries were made at IRAS wavelengths, it was clear already from the very beginning that the emitting dust grains had to be at relatively low temperatures (a few tens to some hundred Kelvin). The emission being optically thin, these observations led directly to estimates of the total amount of dust (particle sizes $\lesssim \lambda$) in these systems (Hildebrand 1983). Disregarding for a moment the many details which in reality enter these estimations such as, e.g., the correct description of the dust absorption coefficient(s) (Beckwith et al. 2000) - the mass is inversely proportional to this quantity - inferred lower limits to the dust mass are some fraction to some tens of a lunar mass ($M_{\text{Moon}}$). For comparison, the Minimum Mass Solar Nebula amounts to roughly $5 \times 10^4 M_{\text{Moon}}$, from which it is clear that, for any reasonable assumption about the local gas-to-dust mass ratio, any solar system type of planet formation must have been completed by the Vega excess stage.

If the gas-to-dust mass ratio in these systems were comparable to that of the interstellar medium (ISM, $\sim 160$), detectable amounts of (primarily molecular) gas could be expected. In fact, carbon monoxide (CO) has frequently been observed through disk absorption against the ultraviolet stellar continuum of $\beta$ Pic (Roberge
et al. 2000 and references therein). In an optical absorption study, Hobbs et al. (1985) put an upper limit on the amount of CH$^+$ in the $\beta$ Pic disk.

Emission line studies, mostly in the sub-/millimeter regime, have so far been essentially unsuccessful (Liseau 1999 and references therein). Molecules searched for in emission include CO, CS, SiO and HCO$^+$ from the gound and H$_2$O and O$_2$ (the SWAS Team) from space. In addition, the detection of rotational H$_2$ emission in the mid-infrared (ISO-SWS) from $\beta$ Pic has been reported (Thi et al. 2001), with an estimate of the total mass of the order of 50 $M_\odot$. However, Lecavelier des Etangs et al. (2001) were unable to confirm these amounts of H$_2$ through absorption measurements in the far ultraviolet (FUSE) and the matter seems at present inconclusive (but see below, Sect. 3.1.2).

Various explanations have been offered to explain the observed low levels of molecular concentration in dusty debris disks, particularly what regards CO, being ubiquitous in the ISM and in solar system comets. These include ‘abnormally’ low gas-to-dust mass ratios, ‘abnormally’ low gas phase CO abundances (relative to H$_2$), photodissociation of CO and, simply, non-existence (early dissipation through stellar wind and/or consumption during planet building). None of these explanations is flawless and the resolution of this issue will have to await future observational and theoretical improvements.

3 Searches for Atomic Gas

Observational studies of atomic gas, either ionised or neutral, in dusty debris disks have traditionally focused on line absorption in a very limited number of objects. Although very sensitive to column densities, these studies are generally incapable of pin-pointing the regions of line absorption along the line of sight. In the following, a number of observational studies are discussed, which were aiming at the detection of emission from atomic gas.

3.1 Atomic Gas Emission from the $\beta$ Pic Disk

The by-far best studied object among the dusty debris disks is the $\beta$ Pic system. The attempt to directly measure, through 21 cm line emission, the amount of atomic hydrogen gas was unsuccessful (Freudling et al. 1995). The presence of widespread ionised hydrogen in the disk is not expected and Balmer line emission has not been detected (Brandeker et al. 2002). Observations with the ISO-LWS may have detected feeble [C II] 157 $\mu$m emission toward $\beta$ Pic (Kamp et al. 2003).
Few details about the circumstellar disk could be learned from these spatially and spectrally under-resolved observations, though.

The resolution issue was greatly improved upon by using a large optical telescope, equipped with an Echelle spectrograph and a long slit, leading to the discovery of widespread sodium gas in the disk (Olofsson et al. 2001). These observations provided finally conclusive evidence that the star $\beta$ Pic is indeed surrounded by a disk in Keplerian rotation, seen nearly edge-on (Fig. 2).

Follow-up observations (Brandeker et al. 2003) covered the optical spectrum (0.3 to 1.1 $\mu$m) at greater resolving power and, in particular, covered a larger area with the spectrograph slit positioned both along and perpendicularly to the disk-midplane (Figs. 2 and 3). Projected slit widths were 6 AU and slit lengths 154 AU, covering the disk out to 300 AU in both the northeast (NE) and southwest (SW) parts of the disk. Perpendicular slits were positioned at approximately 60 AU and 120 AU on both sides from the star, extending to 80 AU on either side of the midplane (Fig. 3).

Nearly 80 emission lines from the disk were detected, all from non-volatile elements including Ca II, Cr I+II, Fe I, Na I, Ni I+II, Ti I+II. In addition, a dozen lines lack so far a clear identification. Neutral iron, with more than 50 strong lines, dominates the disk spectrum. Measurements of the line emission along the perpendicular slits revealed that the gas disk is not perfectly plane (Fig. 4). Inside $\pm3''$, the disk appears tilted at an angle of about 5°, very much the same as inferred for the dust disk by Heap et al. (2000). Further out, the gas disk is flaring at an opening angle of about 10° ($H/r \sim 0.2$).

The two disk halves display significant asymmetries and small scale structure in their line emission, as illustrated by NaI D$_2$ in Fig. 5. The NE disk extends much farther out, in fact to the limit of our observations (cf. Fig. 2). In contrast, further in, the SW side is brighter. These features can also be discerned in the dust disk, albeit at lower contrast (Heap et al. 2000).

### 3.1.1 The Kinematics of the Atomic Gas Disk

As a complete surprise came the observed small velocity dispersion of the line emission from the atomic disk (Olofsson et al. 2001). In the absence of a major component of volatile gases, an excess of some hundred of km s$^{-1}$ over the local Keplerian value of the radial velocity would be expected due to radiation pressure on the neutral sodium atoms. As different species will be differently sensitive to radiation pressure, their spectral lines should exhibit different widths. Below, the radiation pressure coefficient is calculated for various atoms/ions observed in the
For a single transition $i$, the radiation pressure coefficient $\beta_i$, expressing the relative importance of radiation pressure and gravity, can be written as

$$\beta_i = \frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{\pi r_e f_l \lambda^2 F_\lambda (R_\star)/c}{10^{\log g_\star} A_{\text{atom}}},$$

where the flux density $F_\lambda$ refers to the stellar photosphere at the wavelength $\lambda$ of the line and the gravity is given by the surface $\log g_\star$ and the atomic mass number $A_{\text{atom}}$ of the ion, expressed in amu, and where

$$\pi r_e f_l = \frac{1}{8 \pi} g_u \lambda^2 A_{\text{ul}}.$$

$r_e$ is the classical electron radius, $f_l$ the absorption oscillator strength and the other symbols have their usual meaning. For a particular atom/ion, the radiation pressure coefficient is $\beta = \sum_i \beta_i$. Both $F_{\text{grav}}$ and $F_{\text{rad}}$ are inverse square laws so that their ratio is independent of the distance to the star.

In Table II, $\beta$-values for a number of atoms/ions are presented. These are all for transitions from the ground, as the disk gas is too cool to maintain significant excitation in the higher states. For the photospheric spectrum the Next Generation Atmosphere Models were used (Hauschildt et al. 1999), which is shown in Fig. 6. Two values of $\beta$ are given per resonance line. $\beta_{\text{min}}$ corresponds to the scattering of a stellar photon by an atom which is essentially at rest (with respect to the radial velocity component), i.e. the source is the core of the photospheric absorption line. As the atom picks up speed, a greater number of source photons becomes available from the wing of the photospheric line and $\beta_{\text{max}}$ refers thus to the neighbouring stellar continuum. In addition, as we did not spin up the model atmosphere to the rotation velocity of the star, these two $\beta$ values represent truly strict limits to the realistic case. Obviously, the differences can be quite dramatic, as for e.g. the H and K lines of Ca II (Table II). In contrast, the photospheric Na D absorption is quite shallow and, hence, $\beta_{\text{min}} \sim \beta_{\text{max}}$ so that the sodium atoms should be sailing at their terminal speed at velocities much higher than what is actually observed (Olofsson et al. 2001, Brandeker et al. 2003).

### 3.1.2 The Dynamics of the Disk Gas

Also quite obvious from Table II is the fact that lines originating from different species and/or different ionisation stages should behave quite differently. For instance, the lines of singly ionised chromium should reflect only Keplerian rotation,
Table 1: Radiation pressure coefficients $^a \beta$ for the $\beta$ Pic gas disk; ions in alphabetical order

| Ion     | Vacuum Wavelength (Å) | $A_{ul}$ (s$^{-1}$) | $\beta^b_{\text{min}}$ | $\beta^b_{\text{max}}$ |
|---------|------------------------|---------------------|------------------------|------------------------|
| Ca I    | 4227.918               | 2.18e+8             | 35                     | 270                    |
| Sum (9)$^c$ |                      |                     | 35                     | 270                    |
| Ca II   | 3934.777               | 1.47e+8             | 2.0                    | 95                     |
|         | 3969.591               | 1.4 e+8             | 1.0                    | 34                     |
| Sum (4) |                        |                     | 3.1                    | 130                    |
| Cr I    | 3579.705               | 1.48e+8             | 3.8                    | 16                     |
|         | 3594.507               | 1.50e+8             | 3.1                    | 13                     |
| Sum (18)|                        |                     | 14                    | 69                     |
| Cr II   | 8002.280               | 1.0 e-1             | 1.e-7                  | 1.e-7                  |
| Sum (5) |                        |                     | 0                     | 0                      |
| Fe I    | 2484.021               | 4.9 e+8             | 0.16                   | 11                     |
|         | 3861.006               | 9.7 e+6             | 1.3                    | 20                     |
| Sum (40)|                        |                     | 3.7                    | 32                     |
| Fe II   | 2382.765               | 3.8 e+8             | 0.03                   | 7                      |
|         | 2600.173               | 2.2 e+8             | 0.4                    | 5                      |
| Sum (14)|                        |                     | 0.6                    | 16                     |
| H I     | 1215.6682              | 6.265e+8            | 3.e-5                  | 2.e-2                  |
|         | 1215.6736              | 6.265e+8            | 2.e-5                  | 1.e-2                  |
| Sum (10)|                        |                     | 0                     | 0                      |
| Na I    | 5891.583               | 6.22e+7             | 160                    | 170                    |
|         | 5897.558               | 6.18e+7             | 80                     | 83                     |
| Sum (32)|                        |                     | 240                    | 254                    |
| Ni I    | 2290.690               | 2.1 e+8             | 0.06                   | 2.3                    |
|         | 2320.747               | 6.9 e+8             | 0.06                   | 12                     |
| Sum (36)|                        |                     | 0.5                    | 20                     |
| Ni II   | 1751.910               | 4.8 e+7             | 0.06                   | 0.2                    |
| Sum (25)|                        |                     | 0                     | 0.2                    |
| Ti I    | 3636.499               | 8.04e+7             | 2.0                    | 10                     |
|         | 3982.887               | 3.76e+7             | 1.6                    | 10                     |
| Sum (40)|                        |                     | 14                    | 77                     |
| Ti II   | 3384.740               | 1.09e+8             | 3.0                    | 12                     |
| Sum (7) |                        |                     | 3.9                    | 19                     |

$^a$ NIST atomic data; model is $T_{\text{eff}} = 8000$ K, $\log g = 4.5$, $\log Z/Z_\odot = 0.0$ (Hauschildt et al. 1999).

$^b$ $\beta = F_{\text{rad}}/F_{\text{grav}}$ and $\text{min}$ and $\text{max}$ values refer to the central line absorption and neighbouring continuum, respectively.

$^c$ Number of ground state transitions for total $\beta$. 
whereas neutral chromium should possess a significant radial component. This is not observed (Brandeker et al. 2003). In fact, regardless of their $\beta$ value, none of the species shows significant radial velocity excess over the Keplerian value.

A possible explanation could be the existence of considerable amounts of, yet to be identified, ‘quiescent’ material, braking the radiatively accelerated gas to the observed relative velocities. An obvious candidate would be hydrogen, being hard to get at observationally. The star produces virtually no flux below the Lyman limit or at the Lyman transitions of H I (see Fig. 6). Any hydrogen gas would thus only follow the Keplerian rotation and be radially stationary and, as such, could act as the braking agent (see Table I).

We apply a simplified analysis, including gravity, radiation pressure and gas ‘friction’, to examine this possibility. The interaction of the gas with the dust particles in the disk is neglected (only big grains with $\beta \ll 1$ and strong coupling to the gas could decelerate the atoms). The equation of motion of the atom reads

$$m \frac{dv}{dt} = -F_{\text{grav}} + F_{\text{rad}} - F_{\text{fric}}. \quad (3)$$

Letting $F_{\text{rad}} = \beta F_{\text{grav}}$ and assuming $F_{\text{fric}} = C v$, this reduces to

$$m \frac{dv}{dt} = (\beta - 1) F_{\text{grav}} - C v. \quad (4)$$

The radial solution to Eq. 4 is

$$v = v_\infty + (v_0 - v_\infty) e^{-C t/m} \quad (5)$$

with $v_0 = v(t = t_0)$ and, as $t \to \infty$,

$$v_\infty = \frac{\beta - 1}{C} F_{\text{grav}}. \quad (6)$$

For collisions of neutrals with neutral hydrogen atoms, we approximate the friction coefficient (full momentum deposition) by

$$C_{\text{nn}} = \pi a_0^2 m_H n_H v_H = a_0^2 \left(8 \pi k m_H\right)^{1/2} T^{1/2} n_H, \quad (7)$$

where $a_0$ is the Bohr radius. For ions colliding with neutral hydrogen atoms, Beust et al. (1989) proposed (hyperbolic orbit approximation)

$$C_{\text{in}} = \pi b_0^2 m_H n_H v_H = \left(\pi \alpha m_H/e_0\right)^{1/2} q n_H, \quad (8)$$
where $b_0$ is the impact parameter, $\alpha_H$ is the polarisability of hydrogen and $q$ is the electric charge of the ion. The characteristic time scale to approach $v_\infty$ is given by the $e$-folding time

$$\tau = m/C .$$

(9)

For Eq. 6 to be valid $\tau$ needs to be shorter than the time scale for significant changes in the disk (e.g., $|dF_{\text{grav}}/F_{\text{grav}}| \sim 2 v_\infty \tau/r \ll 1$), a requirement which was verified a posteriori to be generally fulfilled.

In Fig. 7, the asymptotic velocity $v_\infty$ is shown as a function of the radial distance from the star, $r$, for three atomic species having different atomic masses and very different values of $\beta$ (Table I). The disk structure is approximated by power laws, e.g. $n \propto r^p$, where the density law was varied, but the same temperature distribution was used throughout [power law exponent $-0.3$ and normalisation at 26 AU, i.e. $T(26 \text{ AU}) = 110 \text{ K}$]. Density distributions are shown for three example values of $p$, i.e. $p = 0$ (constant density), $p = -1.5$ and $p = -2.5$ ('standard' density distribution).

For the neutral species $^{23}\text{Na I}$, an average value of $\beta = 250$ was used and in Fig. 7 the normalisation values at 26 AU of the hydrogen density [$n(26 \text{ AU})$ in cm$^{-3}$] are $10^6$ for $p = 0$, $10^7$ for $-1.5$ and $10^8$ for $-2.5$. As an illuminating example, for the ion $^{40}\text{Ca II}$, the minimum value $\beta_{\text{min}} = 3$ was selected and the corresponding $n(26 \text{ AU})$ are $10^{4.5}$ for $p = 0$ and $10^5$ for both $-1.5$ and $-2.5$. As the radiation pressure coefficient of $^{52}\text{Cr II}$ is merely a tiny $4 \times 10^{-7}$, only the constant density case [$n(26 \text{ AU}) = 10^5 \text{ cm}^{-3}$] is shown as an illustration.

Whatever the actual gas density distribution in the $\beta$ Pic disk might be, it is clear from these numerical experiments that average densities would need to be in excess of $10^6$ cm$^{-3}$ in order to meet the limits set by the observations: the observed spatial distribution of the line profiles are reproduced to within $0.1 \text{ km s}^{-1}$ by a Keplerian model (Brandeker et al. 2003). If this gas were roughly spherically distributed, as hinted at by the observations perpendicular to the disk, the total mass would be in the neighbourhood of $M_H \sim 0.02 r_{100}^3 \mu_2 n_6 M_{\text{Jupiter}}$ ($r_{100}$ is in units of 100 AU; $\mu_2$ is the molecular weight in units of one particle per two hydrogen nuclei; $n_6$ is $n_H$ in units of $10^6$ cm$^{-3}$). The implied column density of hydrogen $N_H \sim 2.5 \times 10^{21} n_6 r_{100} \text{ cm}^{-2}$ would suggest this gas to be molecular, as the upper limit on atomic hydrogen is a few times $10^{19}$ cm$^{-2}$ (Freudling et al. 1995). It follows that such an H$_2$ component would be consistent with the observations of Thi et al. (2001) for $r_{100} \sim 2$. Confirmation of these results by re-newed observations, with e.g. SIRTF, are thus eagerly awaited.
Significant amounts of H\(_2\) around \(\beta\) Pic are hard to reconcile with the absence of detectable H\(_2\) absorption along the line of sight toward the star, at the same time as CO absorption has clearly been detected. If real, the existence of such relatively large amounts of gas in the \(\beta\) Pic disk would have far reaching implications for the gas-dust dynamics and the evolution of the disk (Takeuchi & Artymowicz 2001). However, as already pointed out, this gas component would be insufficient to build an analogue to the solar system and may simply represent ‘left-overs’ from a recent planet formation epoch.

### 3.2 Search for Atomic gas in Other Systems

To this end, we have also searched the disks around HR 4796A and \(\varepsilon\) Eri for atomic gas. These searches have been unsuccessful. The reasons for this failure are possibly quite different, though. If the amount of gas would scale with the amount of dust, the dustier disk around HR 4796A should exhibit an even clearer gas signature than the \(\beta\) Pic disk. However, HR 4796A is nearly four times more distant and the scattering disk extends to less than one arcsec from the central star (Schneider et al. 1999), presenting a most unfavourable contrast case for ground based observations.

\(\varepsilon\) Eri on the other hand is more than six times closer to the Earth than \(\beta\) Pic and its circumstellar disk subtends several tens of arcsec in the sky (at sub-millimeter wavelengths). It should thus, in principle, be easier to observe. The disk contains merely one percent of dust compared to the \(\beta\) Pic disk (see also Fig. 1). Again, scaling the gas emission with the dust emission would imply two orders of magnitude lower intensities, which would have escaped detection at our present sensitivity.

### 4 Conclusions

Below, the main conclusions of this work are briefly summarised.

- Searches for molecular gas in dusty disks around main-sequence stars have so far been unsuccessful, with the possible exception of the \(\beta\) Pic system, toward which Thi et al. (2001) reported the discovery of substantial amounts of H\(_2\) gas.

- Searches for atomic gas in a few of these systems have resulted thus far in clear detections of line emission from the \(\beta\) Pic disk (Olofsson et al. 2001).
Follow-up observations revealed the presence of a large number of spectral lines from neutral and singly ionised non-volatile species (Brandeker et al. 2003).

- The results from spatio-spectral fitting of these lines are consistent with gas orbiting the star at Keplerian velocities. Deviations from Keplerian motion are less than 0.5 km s\(^{-1}\) at the 5\(\sigma\) level.

- The analysis of these motions invoking gravity, radiation pressure and gas friction on the atoms/ions indicates that some kind of decelerating material must be present in the disk.

- Identifying this braking agent with hydrogen gas leads to the conclusion that average hydrogen densities are \(n_H > 10^6\) cm\(^{-3}\) and that the hydrogen is most likely molecular.

- Without stretching parameters too far, this result could be in support of the result by Thi et al. (2001), i.e. that the present amount of gas around \(\beta\) Pic is of the order of 50 \(M_\odot\).

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Figure Captions

Fig. 1. The ratio of integrated excess to photospheric flux as a function of estimates of the stellar age. The most prominent Vega-excess stars are identified. Open circles refer to stellar members of a number of open clusters. The point for the Sun is a lower limit, as it traces only the fraction of the zodiacal dust inside the Kuiper Belt. Adapted from Spangler et al. (2001).

Fig. 2. Observations of the $\beta$ Pic disk in the NaI $D_2 \lambda 5890$ line (ESO, Chile). In the right panel of the **Left Figure**, the EMMI ($R \sim 60\,000$) observations with the 3.5 m NTT are shown (horizontal scale in km s$^{-1}$, vertical scale in AU). A model of the line emission from a disk in Keplerian rotation is shown to the left, whereas, in the middle, the model is shown degraded to the resolution of the observations, with white noise added and the central stellar spectrum removed (Olofsson et al. 2001). Follow-up observations with UVES ($R \sim 90\,000$) at the 8 m VLT, shown in the **Right Figure** to scale, largely improved on both the spectral and spatial resolution and coverage (Brandeker et al. 2003). Telluric $D_2$ emission is seen at $-30$ km s$^{-1}$ and the approaching southwest side is up (cf. Fig. 3).

Fig. 3. The slit positions of our VLT-UVES observations are shown superposed onto the HST-STIS image of the scattering dust disk (Heap et al. 2000) projected onto the sky. The width of the slit is 0\'\'3 and, during the observations, the seeing was in the range 0\'\'4 to 0\'\'6. The length of the slit, limited by the Echelle inter-order separation, is 8\". The observations along the disk were performed with overlapping slit positions.

Fig. 4. Scale heights of the gas disk in three emission lines (ground state transitions). The bars show the Full Width to Half Maximum of the line emission at four positions in the disk. $x$- and $y$-offsets, in arcsec, are relative to the star $\beta$ Pic and to the midplane of the scattering dust disk (Kalas & Jewitt 1995), respectively. For comparison, the dust disk (Heap et al. 2000) is shown to scale in the lower half of the figure.

Fig. 5. The spatial distribution of the NaI $D_2$ emission in the $\beta$ Pic disk, with the NE and SW disk halves identified (Brandeker et al. 2003). Error bars represent 1\$ of the quadratically summed photon noise of the line and off-line fluxes. Radial distances from the star are expressed in arcsec and integrated surface intensities in erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. The vertical dashed lines refer to the positions of the perpendicular slits.

Fig. 6. The UV spectrum of $\beta$ Pic. Continuum points are from FUSE and HST observations (archive data). Also shown are the results of HST-STIS observations of the NE- and SW-disk of $\beta$ Pic at 0\'6 distance from the star (archive data).
The line spectrum is based on a stellar model atmosphere (at 19.3 pc) with $T_{\text{eff}} = 8000$ K, $\log g = 4.5$ and $\log Z/Z_\odot = 0.0$ (Hauschildt et al. 1999); for the assumed $R = 1.75 R_\odot$, the luminosity of the star is $L = 11 L_\odot$. The ionisation edges of species discussed in the text are indicated by the vertical bars.

Fig. 7. The asymptotic velocity $v_\infty$ versus the radial distance $r$ from the star. For Na I (A = 23) an average $\beta = 250$ has been used, and the red curves are for $n(26 \text{AU}) = 10^6, 10^7$ and $10^8 \text{cm}^{-3}$ for $p = 0, -1.5$ and $-2.5$ (dotted, dashed and solid lines) respectively (see the text). For Ca II (A = 40) $\beta_{\text{min}} = 3$ has been applied as a strict lower limit to the radiation pressure coefficient (see Table 11). The blue curves are for $n(26 \text{AU}) = 10^{4.5} \text{cm}^{-3}$ for $p = 0$ and $10^5 \text{cm}^{-3}$ for both $p = -1.5$ and $-2.5$. For Cr II (A = 52), only the constant density case ($10^5 \text{cm}^{-3}$) is shown by the green curve. As this ion is insensitive to radiation pressure, relative velocities are negative. The 5σ upper limit to the observed excess velocities over Keplerian motion is shown by the purple horizontal line.
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