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Size Distribution of Dust in the Disk of β Pictoris

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Abstract. Intensive studies of the β Pic dust disk, based on observational data from the visual to the far IR and mm, give a relatively good understanding of the global spatial dust distribution in the disk. In contrast, the size distribution of dust is poorly known—only some constraints on the grain sizes have been put so far. Assuming a continuous replenishment of larger grains from sources in the disk and a collisional production of smaller debris, and considering the dynamics of grains, we derive the size distribution of dust in a broad range from micron-sized grains to tiny nanometer-sized particles. We show that this dynamically justified size distribution explains the observed polarization and colors of the disk much better than commonly assumed single power-law distributions.

1. Introduction

Since the first *IRAS* observations attested to the so-called "Vega phenomenon", considerable study is being given to dust disks around main-sequence stars and, in particular, around β Pictoris. This has yielded a relatively good understanding of the global spatial distribution of dust in the disk (e.g., Artymowicz, Burrows, & Paresce 1989; Kalas & Jewitt 1995; Mouillet et al. 1997) and led to a number of conclusions about the chemical composition of the dust (Telesco & Knacke 1991; Aitken et al. 1993; Knacke et al. 1993; Artymowicz 1997), but its size distribution is as yet scantily known. Models derived from different observational data lead to somewhat controversial inferences (Table 1), especially concerning the content of small submicrometer grains.

Here we assess the size distribution in the β Pic disk from dynamical considerations and then use the derived size distribution to fit observational data. Assuming continuous replenishment of larger grains from sources in the disk and collisional production of smaller debris, we consider then the dynamics of grains under radiation pressure and stellar gravity forces. A more accurate model than that of Krivova, Krivov, & Mann (2000) is used to derive the size distribution of the dust over a wide range. To test the results against observational data, we analyze the polarization of the radiation scattered by dust grains, a valuable source of information about dust properties. We apply different shapes of the size distribution to model the observed spatial variation and wavelength dependence

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Table 1. Previously deduced sizes of the grains in the disk of β Pic

Type of data	Sizes	References
Far-IR + mm data	> 5–$10\ \mu$m	Chini et al. (1991) Zuckerman & Becklin (1993)
Gray colors	$>$ A few μm	Paresce & Burrows (1987) Lecavelier des Etangs et al. (1993)
Vis. + IR images	1–20 μm	Artymowicz et al. (1989)
10 μm sil. feature	$< 10\ \mu$m	Telesco & Knacke (1991)
	$\lesssim 2$–$3\ \mu$m	Aitken et al. (1993)
IR fluxes and scans + vis. data	$\sim 1\ \mu$m	Backman et al. (1992)
10 & 20 μm emission	Subμm	Telesco et al. (1988)
IR to mm data + 10 μm sil. feature	As in Comet Halley + extra-small grains	Li & Greenberg (1998)

of the polarization of the radiation of β Pic and show that the suggested size distribution gives better results than commonly used power-law distributions.

2. Dynamical Evolution of Dust Grains

2.1. Model

We assume the dust disk to consist of two dust populations which, borrowing the terminology from Solar System studies, may be called α- and β-meteoroids. The former are larger grains that move about the star in bound orbits, whereas the latter are smaller particles blown away from the star by stellar radiation pressure. The boundary between the two populations depends on the luminosity-to-mass ratio of the central star and the properties of dust grains. For β Pic and plausible compositions of grains in its disk, the boundary lies at a grain radius of $a_0 \approx 2$ to 3 μm (e.g., Artymowicz 1997), or the mass $m_0 \sim 10^{-10}$ g.

First we postulate the spatial and size distributions of α-meteoroids. We assume that the large grains in the disk are produced by a collisional cascade and the activity of comet-like bodies, so that the number density of α-meteoroids with sizes $[a, a+da]$ at a distance r from the star obeys the power law

$$n_\alpha(r,a)da = n(r)a^{-q}da, \tag{1}$$

with $q \approx 3.5$ being expected for both collisional (Dohnanyi 1969) and cometary (e.g., Greenberg & Hage 1990, Fulle et al. 1995) sources. The spatial part of the distribution $n(r)$ is taken to have the form (Artymowicz & Clampin 1997)

$$n(r) = n_0 \left[(r/r_m)^{-1} + (r/r_m)^{2.7}\right]^{-1}, \tag{2}$$

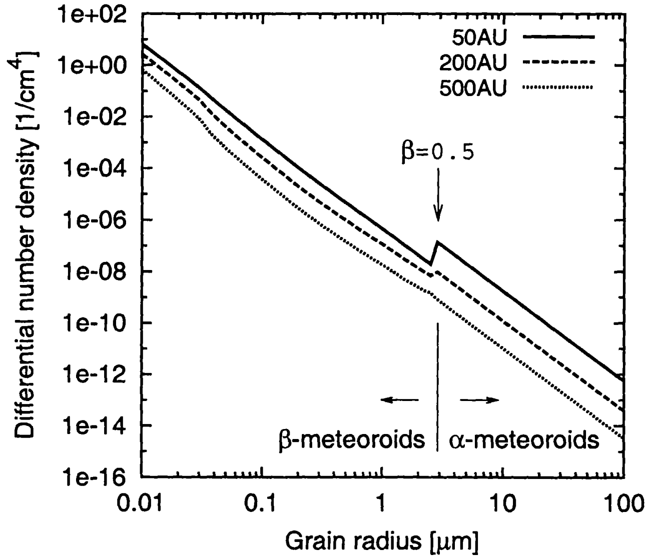

Figure 1. Size distributions of dust at different distances from the star.

where $r_m = 60$ AU and the normalizing constant n_0 is determined from the normal optical depth of the disk $\tau(r)$ given by Artymowicz & Clampin (1997), assuming a vertically uniform disk with the half-opening angle $\epsilon = 7°$.

Next, we assume that α-meteoroids create β-meteoroids through collisional fragmentation. The steady-state number density of β-meteoroids with sizes $[a, a + da]$ at a distance r from the star is

$$n_\beta(r,a)da = \frac{da}{r^2} \int_0^r r_0^2 \, \frac{dn^+}{dt}(r_0,a) \; v^{-1}(r_0,r,a) \; dr_0, \qquad (3)$$

where $dn^+/dt(r_0, a)$ is the number of β-meteoroids with sizes $[a, a+da]$ produced per unit time in a unit volume at a distance r inside the disk, and $v(r_0, r, a)$ is the velocity a β-meteoroid of radius a born at a distance r_0 attains at distance r. The β-meteoroid production rate is calculated from the collisional probabilities determined by (1) and from the impact mechanics of colliding particles (Krivov et al., in preparation). Thus a more accurate model is used as compared to Krivova et al. (2000), where all α-meteoroids serving as sources of β-meteoroids were assumed to have a "typical" size. The velocity of β-meteoroids is evaluated from the classical formulae of the "photo-Keplerian" problem.

2.2. Results

The computed size distributions at different distances from the star are depicted in Figure 1. The basic result is that the size distribution of larger grains cannot be simply extrapolated to smaller sizes: the grains with sizes just below the blowout limit are typically somewhat (but not strongly) depleted, and the slope of their size distribution may differ from that of the larger grains. Another result is that the contribution of smaller particles grows with the distance from the star. This is readily understandable: β-meteoroids are blown radially away from the star; thus the β-meteoroids produced at a certain distance from the star contribute to the number density at all larger distances.

3. Polarization and Colors

3.1. Model

To calculate polarization and colors, we represent the dust number density as

$$n(r,z,a) = n(r,a)\exp\left[-\left(\frac{z/r_6}{\zeta(r)}\right)^{\gamma}\right], \quad \zeta(r) = \zeta_6\left(\frac{r}{r_6}\right)^{\eta}, \tag{4}$$

where $n(r,a)$ is given by (1) for α-meteoroids and (3) for β-meteoroids, and the exponential term describes the dependence on z, the distance from the symmetry plane of the disk (Artymowicz et al. 1989; Kalas & Jewitt 1995). We take $\eta = 1.2$, $\gamma = 1.1$, $r_6 = 6''$, and $\zeta_6 = 0.05$, and assume the viewing angle to be $i = 4°$. The precise choice of the parameters describing the disk geometry is not crucial (Krivova et al. 1999, 2000). We use silicate (Laor & Draine 1993) as inferred from the 10 μm silicate feature (Aitken et al. 1993; Knacke et al. 1993) for Mie calculations of the particle scattering properties and also test other materials. An original numerical code is used to calculate the polarization scans at different wavelengths. The equations are given in Krivova et al. (2000).

3.2. Results

Polarization diagrams are predominantly determined by the dust grain sizes (see discussions in Voshchinnikov & Krügel 1999 and Krivova et al. 2000); this allows us to evaluate the sizes from an analysis of the polarimetric data. Dust composition and structure may only modify the derived values of the sizes, but the general shape of the size distribution still stands.

In Figure 2*a*, the polarization in the *UBVRIH* bands calculated for the derived size distribution and the traditional power-law one a^{-q} ($a_{\rm min} = 0.005$ μm, $a_{\rm max} = 100$ μm) is compared with observational data (Gledhill, Scarrott, & Wolstencroft 1991; Wolstencroft, Scarrott, & Gledhill 1995). For the power-law distribution, the index $q = 2.7$ provides a better, yet not satisfactory, agreement with the observational data, which means that small particles contribute less than in the case of the usually assumed $q = 3.5$ (cf. Voshchinnikov & Krügel 1999). For $q = 2.7$ the predicted colors of the disk, which are too blue in the case of $q = 3.5$, are a little bit redder than observed by Paresce & Burrows (1987), but within the observational errors.

Using the distribution derived in Section 2 gives much better results. The colors are also in a good agreement with observations. Still better agreement could be achieved if the sizes of the grains giving the major contribution to the cross-section are shifted to larger values ($\sim$ 5 to 15 μm). This is actually expected from a yet more accurate model (Krivov et al., in preparation).

Figure 2*b* shows the difference in the polarization in two wings. To explain the polarization in the NE wing one should increase the number density of small grains by $\approx$ 20–30 % as compared with the SW wing. There could be different mechanisms leading to such a difference in the sizes. One possibility is that the bombardment of the disk by interstellar dust particles (Artymowicz & Clampin 1997) under plausible conditions could produce more β-meteoroids in one wing (Krivova et al. 2000). The difference could also be explained within the "falling evaporating bodies" scenario under the presence of a planetary perturber (Lecavelier des Etangs, this volume, p. 308).

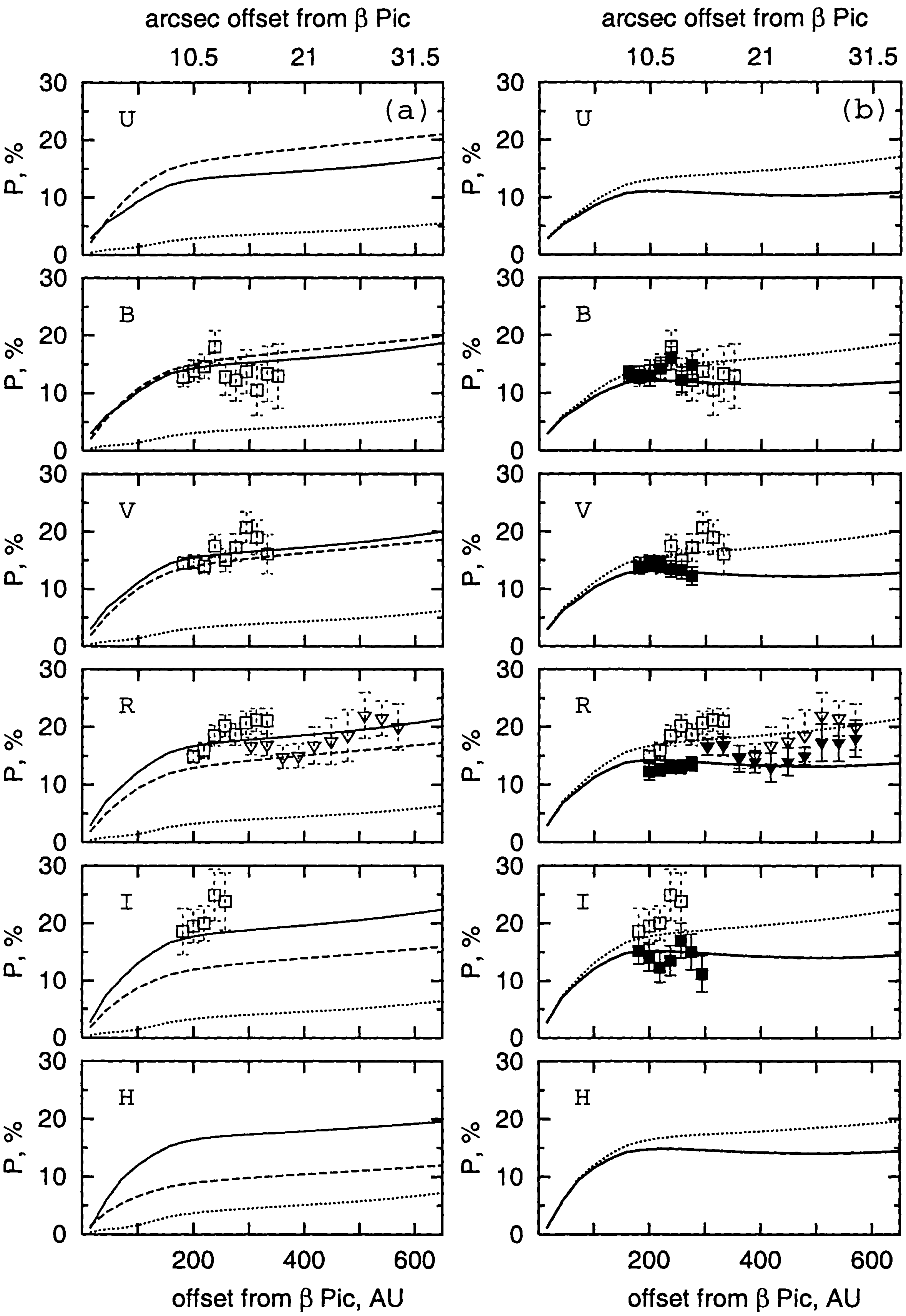

Figure 2. Modeled polarization of the disk of β Pic in *UBVRIH*. Symbols show the observed values from Gledhill et al. (1991, *triangles*) and Wolstencroft et al. (1995, *squares*). *a)* SW wing. *Dotted line*—standard power-law size distribution with the index $q = 3.5$; *dashed line*—the same with the index $q = 2.7$; *solid line*—our derived size distribution (Section 2). *b)* SW wing (*open symbols* for the data and *dotted curve* for the model results) and NE wing (*filled symbols* and *solid line*). About 20% "extra" β-meteoroids, as compared to the distribution in Figure 1, are present in the NE wing.

4. Conclusions

1. Our dynamical model suggests that the grains with sizes below about 2–3 μm are somewhat (but not strongly) depleted, and the slope of their size distribution differs slightly from that of the larger grains.
2. The suggested size distribution agrees well with the polarimetric and colorimetric observations.
3. Different polarizations in two wings can be explained if more small grains are present in the NE wing.

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