# Polarization of the Zodiacal cloud and other Solar system-type debris disks

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**Abstract.** We calculate the linear polarization of solar radiation scattered by the Zodiacal dust cloud as seen from large heliocentric distances. We then discuss the dependence of polarization on the spatial distribution and optical properties of the interplanetary dust grains, and estimate possibilities of further constraining these on the base of future polarimetric measurements from outside the Solar system. This approach is extended to debris disks around other stars, namely, to the $\beta$ Pic disk. Our preliminary results show that the profile of scattered intensity and polarization scans observed for $\beta$ Pic can be satisfactorily fitted with Solar system-like radial and angular distributions of dust, assuming scattering properties of dust to be also similar to those retrieved from Zodiacal light observations.

**Key words:** Zodiacal cloud – circumstellar dust disks – $\beta$ Pic – polarization

## 1. Motivation

Measurements of polarization are an important tool for studies of dust in different environments, such as the Solar system, interstellar clouds and circumstellar shells. In this paper we present model calculations of polarization and discuss their possible applications to two types of dust complexes: *(i)* the Zodiacal cloud and *(ii)* debris disks around main-sequence stars.

*Solar system – a look from outside.* Observations of the Solar system dust cloud were mainly done from the Earth or the Earth's orbit and also by spacecraft from 0.3 AU to $\approx$ 5 AU. Based on previous data, we estimate the polarization of the Zodiacal dust cloud as seen from outside the Solar system. We examine the dependence of polarization on the spatial distribution and optical properties of the interplanetary dust, and therefore estimate possibilities of further constraining these on the base of polarimetric measurements which could be made by future deep-space missions. A further aspect of this study is the comparison of the Solar system dust cloud to dust clouds around other stars.

*Debris disks of main-sequence stars.* Recent extensive observational studies of dust disks of main-sequence stars, which in many respects resemble that of the Sun, have raised the question of whether observations of scattered light and its polarization would reveal the spatial distributions of dust and properties of

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the dust particles in these systems. We try to answer this question by applying the present knowledge of dust in our Solar system to a model calculation of the expected polarization.

## 2. Model

We consider different dust spatial distributions that essentially consist of a main component of dust concentrated to the ecliptic and an optional isotropic component (models a–h of Giese et al., 1986 — see Fig. 1, left panel). The radial variation of number density is assumed proportional to $r^{-(1.0 \div 1.3)}$ and extended outward to the Kuiper belt region.

We use the polarization and scattering functions derived *empirically* from Zodiacal light measurements. The typical single particle polarization increases from zero for the forward scattering to a maximum of 30–35% for a scattering angle $\theta \sim 80°$ and then decreases (Weiß-Wrana, 1983). The scattering properties are described by an empirical volume scattering function (Mann, 1992).

An original numerical code is used to calculate the spatial intensity and polarization distributions (maps) of an axially-symmetric, optically thin (single-scattering) circumstellar dust shell, which could be measured from a distant point at an arbitrary viewing angle $\varphi$.

## 3. Total polarization

The total polarization[1] of the Zodiacal cloud for different cloud models (a, c, g and h of Giese et al., 1986) and its dependence on the viewing angle are shown in Fig. 1. Within the certain geometries considered here the polarization of the cloud seen "edge-on" is almost independent of the dust spatial distribution. At the same time, the polarization of a disk observed at $\varphi \sim 30°$–$60°$ is sensitive to the presence of an isotropic component which depolarizes the radiation. We can therefore conclude that measurements from a spacecraft at ecliptic latitudes of 30° to 60° would be the most beneficial to specify the geometry of the cloud.

Computations with a polarization function typical of smaller, interstellar dust grains (with maximum values up to 100% at $\theta \approx 90°$) show that the absolute value of polarization degree for all viewing angles increases with the value of the single particle maximum polarization, whereas a significant influence of the exact slope of the single particle polarization curve on the result is not expected.

[1]The total polarization of an object "star+shell" $P = (I_\perp - I_\parallel)/(I_\perp + I_\parallel + I_*) < (\tau \cdot \Lambda)/(\tau \cdot \Lambda + 1)$, where $\tau$ is optical depth and $\Lambda$ is albedo, is extremely low in the case of faint dust shells. E.g. for $\beta$ Pic ($\tau$ <0.1 in visual), the expected total polarization (due to dust scattering only) is substantially less than 0.1%. Thus, spatially unresolved polarization could be measured only with a coronograph technique, i.e. after removing direct stellar radiation component $I_*$. Here, "total polarization" is used in this sense.

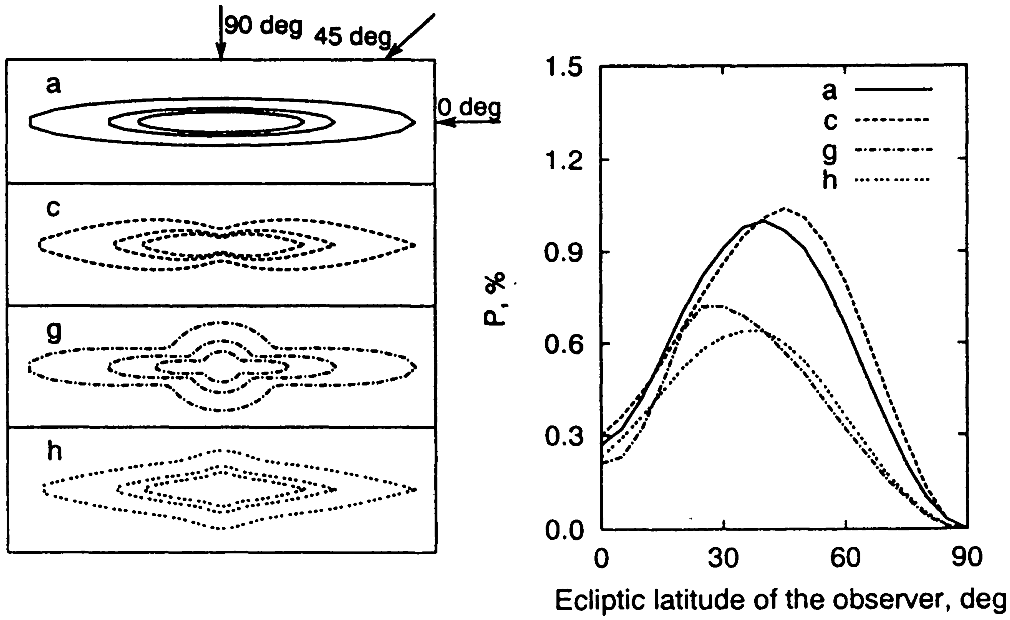


**Figure 1.** Total polarization of the Zodiacal cloud as a function of the viewing angle (right) for different cloud models (a, c, g, h of Giese et al., 1986, left).

## 4. Polarization maps

*Application to Zodiacal cloud.* We have calculated polarization maps and scans of the Zodiacal cloud as could be observed by a distant observer at different viewing angles $\varphi$ for different geometries of the cloud shown in Fig. 1. We found the maps and scans to be almost independent of the considered geometries of the dust distribution. The polarization in the inner parts of the shells grows distinctly with $\varphi$. As a result, a fairly steep gradient within the field of view which is expected for polarization maps at $\varphi = 0°$ (from 5% to 35%) tends to flatten for higher viewing angles (20% to 35% for $\varphi = 90°$) showing a smaller difference of polarization for inner and outer parts of the shells.

*Application to $\beta$ Pic.* Optical polarization measurements for the disk around $\beta$ Pic were made by Gledhill et al. (1991) in R band and by Wolstencroft et al. (1995) in BVRI. In all cases the polarization is almost constant between 15″ and 30″ (290–570 AU for the distance 19 pc — Crifo et al., 1997).

Figure 2 shows the observational results in R band (upper panel) and some model results (V band, lower panel). Three models considered are: (1) a disk with an opening angle 14° (Artymowicz et al., 1990), inner dust-free zone radius $R_i = 40$ AU (Lagage & Pantin, 1994), exponent of radial slope $\nu = 1.3$ as an average expected for the Solar system; (2) the same disk except that $R_i = 1$ AU and $\nu = 2.7$ as suggested by Li & Greenberg (1998) from consideration of the IR to millimeter emission; (3) the same as (2), but for angular density distribution like in "c" model of Giese et al. (1986). The dust properties were the same as in Zodiacal cloud. As seen from Fig. 2, all the models are in conformity with the general trend of the observations, though the better agreement is achieved

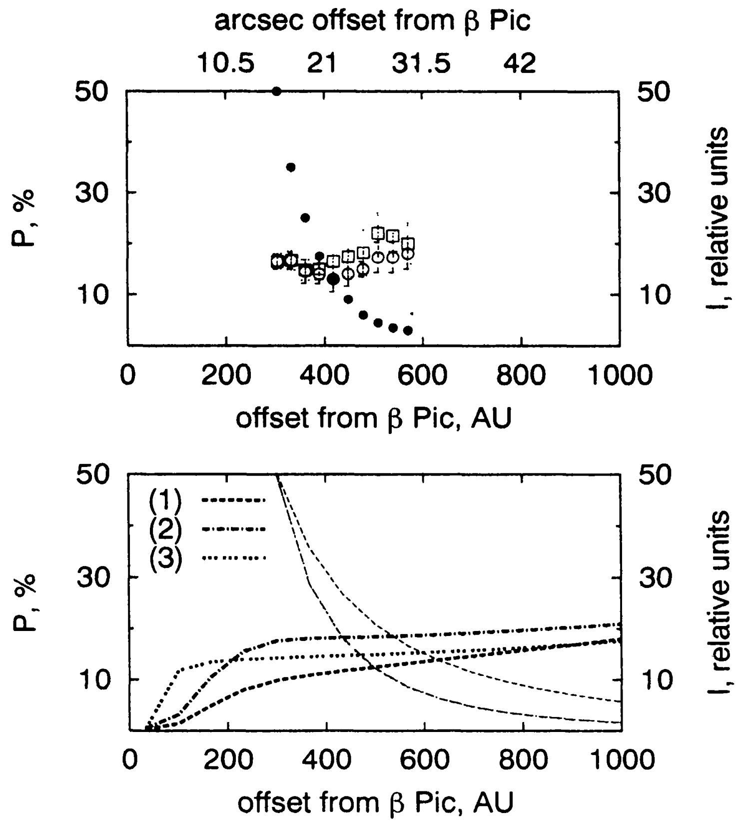


**Figure 2.** Polarization and intensity scans for the $\beta$ Pic disk: observations (Gledhill et al., 1991; top) and model (bottom). Bold lines and open symbols show polarization distribution, thin lines and filled symbols — normalized intensity. See text for details.

with the spatial distribution of Li & Greenberg (1998). The exponent of radial slope $\nu$ therewith controls the intensity distribution slope, while $R_i$ and angular density distribution specify the polarization profile.

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