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Zodiacal Cloud Complexes

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We discuss some aspects of the study of the Zodiacal cloud based on brightness observations. The discussion of optical properties as well as the spatial distribution of the dust cloud show that the description of the dust cloud as a homogeneous cloud is reasonable for the regions near the Earth orbit, but fails in the description of the dust in the inner solar system. The reasons for this are that different components of the dust cloud may have different types of orbital evolution depending on the parameters of their initial orbits. Also the collisional evolution of dust in the inner solar system may have some influence. As far as perspectives for future observations are concerned, the study of Doppler shifts of the Fraunhofer lines in the Zodiacal light will provide further knowledge about the orbital distribution of dust particles, as well as advanced infrared observations will help towards a better understanding of the outer solar system dust cloud beyond the asteroid belt.

1. Introduction

Small bodies in our solar system cover a broad size range from asteroids and comets to dust particles of micrometer size and below. Brightness observations do mainly cover a range of particles of 1 to 100 micron in size, i.e. the so-called Zodiacal dust particles, first observed in the brightness of the Zodiacal light. The dust particles mainly originate from the collisional evolution of bigger, meteoritic particles that are produced by the activity of comets and the collisional evolution of asteroids. As opposed to the bigger particles, the lifetime of the dust particles is limited not only by their collisional evolution but also by the Poynting-Robertson effect which causes their slow drift towards the Sun. We will discuss previous results about the optical properties and the spatial distribution of the Zodiacal dust and show the limits of these dust cloud models. Then we will shortly discuss attempts of a multi-component description of the Zodiacal dust cloud. As perspectives for future investigations, we will mention the Doppler shift of Fraunhofer lines in the Zodiacal light as well as the observational investigation of the outer solar system dust cloud.

2. Brightness Inversion and Optical Properties

Brightness observations yield a good data set of the visible Zodiacal light brightness from about 30° elongation from the Sun out to the Gegenschein (see Dumont, 1976; Leinert *et al.*, 1977; Levasseur-Regourd and Dumont, 1980) as well as infrared observations, usually at elongations larger than 60° from the Sun (Hauser *et al.*, 1984; Reach *et al.*, 1996; Matsumoto *et al.*, 1996). The observed brightness of the Zodiacal light results from the integrated signal from the volume elements in space along the line of sight (LOS). The brightness depends on the spatial distribution of the dust in the solar system and on the scattering (or thermal emission) properties per volume element. A common method of data analysis applies forward calculations of the line of sight integral under reasonable assumptions about particle properties and spatial distribution. Detailed descriptions of the line of sight integrals have been given before (see Dumont, 1973; Röser and Staude, 1978; Giese *et al.*, 1986). Also the average scattering properties of particles have been directly inverted from the brightness integral in some cases (see for instance Levasseur-Regourd and Dumont, 1980; Lamy and Perrin, 1986). At this point we want to concentrate on the average optical properties that can be derived from the observed brightness.

The brightness integral includes a volume scattering function VSF(θ, r), which describes the brightness component that is seen of a given spatial volume along the line of sight at a given solar distance r (cf. Dumont, 1973; Hong, 1985; Perrin and Lamy, 1989); in the case of thermal emission the VSF is replaced with a volume emission function, VEF (see below). Both the VSF and the VEF denote the average differential cross section $d\sigma/d\Omega$ of particles per volume element for the process in question and include the spatial variation of particle number density. The VSF includes a spatial variation of number density as well as a spectral variation of scattering properties and a change of the size distribution with solar distance r. It is defined as:

$$\mathrm{VSF}(r,\theta) = \int_{\alpha_1}^{\alpha_2} \frac{d\sigma}{d\Omega}(\theta, r, \alpha) \cdot \frac{dn}{d\alpha} d\alpha, \tag{1}$$

where α denotes the size parameter $\alpha = 2\pi s/\lambda$, s is the particle size and λ the wavelength of scattered light. The discussion of average optical properties implies the simplification of Eq. (1) to the product

$$\mathrm{VSF}(r,\theta) = n'(r)\langle G\rangle A_p(r,\theta). \tag{2}$$

In this relation $n'(r)$ is the number density of optical efficient particles and G is the geometric cross section of the particles. The geometric albedo A_p is usually defined at back scattering

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$\theta = 180°$ (Hanner *et al.*, 1981) but in this case is given as a function of scattering angle, θ. Brackets denote average values. A constant size distribution with solar distance r would keep the average geometric cross section constant. From that we can derive the change of the average geometric albedo of particles, when assuming a certain run of number density n'.

$$n'(r) = n'(r_o)(r/r_o)^{-\nu}, \tag{3}$$

$$A_p(r) = A_p(r_o)(r/r_o)^{-\mu}, \quad \nu + \mu = \mu^*. \tag{4}$$

We stress that n' may not be identical to the average number density of particles in interplanetary space n, which would result from integration over the whole size spectrum of particles, but n' is only the average number density of optically effective particles. Also the VEF can be given in terms of global properties:

$$\mathrm{VEF}(r) = \langle n' \rangle (r) \langle G \rangle E(r). \tag{5}$$

This combination of geometric cross-section G, number density n' and albedo $A_p(r)$, respectively emissivity $E(r)$ in the VSF and in the VEF causes an ambiguity in the brightness inversion. A discussion of particle properties based on brightness observations reduces Eq. (1) to the product of average values given in Eq. (2). It should also be noted that the inversions are based on the assumption that the dust cloud is homogeneous.

Whereas the description of the dust properties at about 1 AU distance from the Sun that are based on the assumption of a homogeneous dust cloud yields reasonable results, the view changes for a description of the dust near the Sun. When assuming for instance an increase of the dust albedo with solar distance r according to a radial power law with exponent 0.25, as was suggested from Zodiacal light analysis (Kneißel and Mann, 1991) the values get very high for the near solar dust. Even more, the polarization of dust in the inner solar system is still puzzling. As far as the polarization models are concerned, there is certainly need for better data in the near solar region (see Kimura and Mann, this issue), which are hopefully provided with the measurements of the LASCO coronagraph on SOHO (see Brueckner *et al.*, 1995). However, the fact that the extrapolation of optical properties in the inner solar system gives unreasonable results, questions the application of a homogeneous dust cloud model. This leads to a further consideration of the spatial and orbital distribution of the particles.

3. Models of the Spatial Distribution

As mentioned before, the spatial distribution of the dust cloud can be derived from brightness data. In a further step the inversion of the number density distribution (first introduced by Haug, 1958) leads to the distribution of orbital elements. The Zodiacal dust is concentrated towards the invariable plane of the solar system, however observers report that the symmetry plane is slightly tilted (see for instance Leinert *et al.*, 1980; James *et al.*, 1997; Ishiguro *et al.*, this issue). Although local structures are observed, the rotational symmetry of the overall dust cloud with respect to an axis through the Sun is confirmed by observations. In terms of the orbital evolution it can be explained by the randomization of the orbital parameters argument of the pericenter and of the ascending node under gravitational perturbations. The rotational symmetric number density distribution is given as a function of solar distance r and helio-ecliptic latitude $\beta_\odot$. The separation of these two components is usually applied and is based on the assumption that the forces acting on the particles do only have a radial dependence. Transformed into orbital parameters this means that the distribution of inclinations (derived from the latitudinal dependent part of the number density distribution), does not change. A closer look at the acting forces, will show that this separation of the two components is not valid (see Scherer and Fahr, this issue) in a second order attempt. But for an analysis of the overall structure of the dust cloud, it is certainly sufficient to apply the separation of the radial dependence and the latitudinal dependence in the dust cloud distribution.

The spatial distribution of dust was derived from brightness data by several authors (see for instance Leinert *et al.*, 1977; Lumme and Bowell, 1985; Murdock and Price, 1985; Giese *et al.*, 1986; Good *et al.*, 1986) and later on the distribution of orbital elements was given for several Zodiacal cloud models (see Kneißel, 1988). The concentration of the dust cloud towards the ecliptic plane yields a maximum in the distribution of orbital elements at small inclinations. Some models of the Zodiacal cloud point to the existence of dust in retrograde motion around the Sun, however a direct information of whether the particles are in prograde or retrograde motion around the Sun cannot be derived from brightness observations.

The radial distribution of the number density is connected to the deceleration of particles due to the Poynting-Robertson effect. The spatial distribution of dust particles is often described with an exponent ν close to 1. This radial slope of the number density distribution can be explained with particles in orbits with low eccentricity. However this approach depends on a constant size distribution and assumes that the same dust population contributes to the scattering at different solar distances, as mentioned above.

4. Sources of the Dust Cloud

There are different estimates for the contribution of comets, respectively asteroids to the interplanetary dust cloud. Based on the calculation of collisional effects, Dermott *et al.* (1994) give a value of about 30% of the dust at 1 AU to result from asteroids. According to Fechtig (1989), the near ecliptic dust cloud consists of about 1/3 of cometary dust and 2/3 of asteroidal dust. The latter estimate is mainly based on the analysis of the impact directions of particles and the material bulk density derived from Helios in situ measurements. However, both estimates are given for the region close to the Earth orbit.

The dust cloud composition varies in space and may also vary with particle size. The study of near solar dust properties, for instance indicates properties that are better explained with a predominant component of cometary material rather than asteroidal material (see Mann *et al.*, 1994). For the case of the outer solar system, the ULYSSES measurements show the existence of a large component of interstellar dust (Grün *et al.*, 1994). Furthermore, the observation of dust disks around main sequence stars and the observation of Kuiper belt objects initiated the discussion about a possible compo-

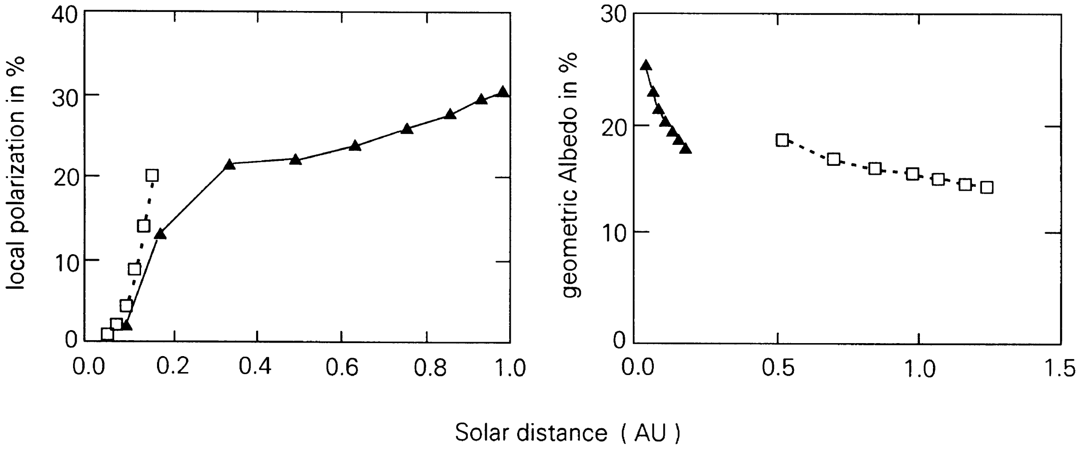

Fig. 1. Average polarization (left hand side) and average geometric albedo at 90° scattering angle (right hand side) of interplanetary dust close to the ecliptic plane derived from Zodiacal light and F-corona data (from Mann, 1997).

nent of Kuiper belt dust particles in the outer solar system (see for instance Backman and Paresce, 1993).

5. Two Component Description of the Dust Cloud

The application of a homogeneous dust cloud model has several limitations, as comes clear in the previous discussion. The comparison of different models of the Zodiacal cloud had led to the suggestion of a two component dust cloud (Kneißel and Mann, 1991), which consists of asteroidal particles in regions near the ecliptic and particles from long period comets in an isotropic distribution. The alteration of the cometary component was assumed to cause an increase of the average brightness of the particles in the dust cloud. However, the resulting change of the particles properties that would fit the observed brightness results (see Fig. 1), would be especially drastic near the Sun and could not be explained with findings about single particle scattering properties.

A more recent attempt assumes that the difference between the two components in the dust cloud is rather explained by a different type of spatial distribution (due to the fact that particles that are produced by long period comets are on orbits with high eccentricity and produce a steep increase of the number density when decelerated from Poynting-Robertson effect) than by different particle properties (see Mann, 1995). As shown in Fig. 2, the deceleration of particles due to the Poynting-Robertson effect causes a decrease of the orbital eccentricity. Assuming the deceleration of particles with an initial eccentricity of 0.99, these will stay in an elliptic orbit for most of their lifetime. Particles which start with an eccentricity of 0.60 will be in circular orbits for a significant amount of their lifetime. Although the assumption of the initial semi major axis of the orbits is a little artificial the figure shows the tendency that particles from short period comets may reach almost circular orbits, whereas the fragments from long period comets may stay in high eccentricity orbits. The resulting radial slope of the number density distribution would be $n \propto r^{-1}$ for the case of the circular orbits and $r^{-2.5}$ for the case of unbound orbits. This indicates that the variation of the dust cloud composition due to the different orbital dynamics is possible, if not to say probable.

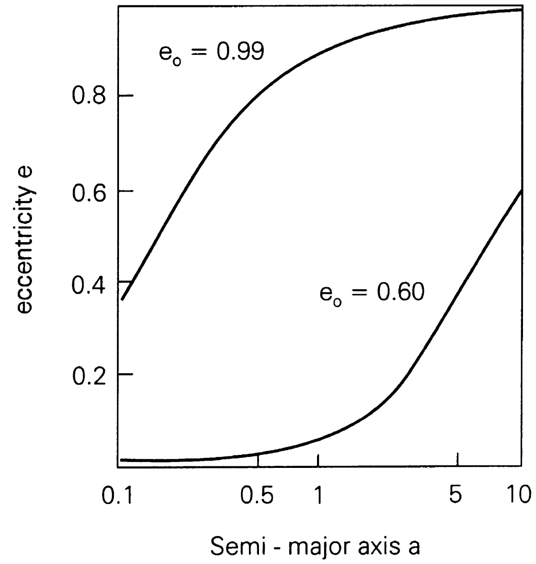

Fig. 2. The eccentricity e of orbits with an initial eccentricity $e_o = 0.99$, respectively $e_o = 0.60$ under deceleration from the Poynting-Robertson effect (see Wyatt and Whipple, 1950), given as a function of semimajor axes. The initial semimajor axis is 10 AU (from Mann and Grün, 1995).

In addition to this effect, a further collisional evolution of particles inside the Earth's orbit can change the dust cloud composition as well as the size distribution (see Ishimoto, this issue).

Also an empirical model has been developed by Divine (1993) in order to give a description of the dust cloud based on different dust experiments, brightness observations and radar observations. This model consists of 5 different components, which however, are mainly describing the regions outside the Earth orbit. Only two components have a significant contribution in the inner solar system. The components in the Divine model partly lack a physical explanation. Nevertheless, this attempt shows the difficulties that arise in the comparison of different type of experimental results, such as in-situ experiments and brightness observations.

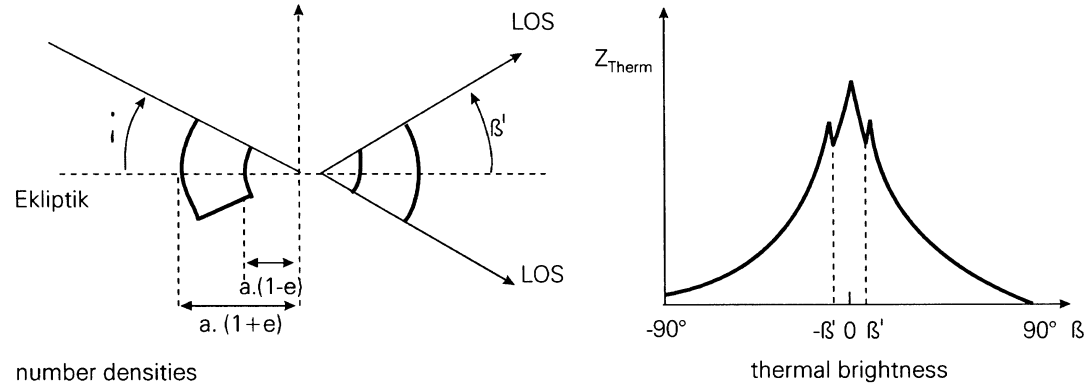

Fig. 3. Explanation of the IRAS dust bands. The left hand side shows the number density distribution in a perpendicular cut through the ecliptic plane. Dust particles released from an asteroidal collision form a dust swarm of similar semi major axes, eccentricities and inclinations. The arguments of perihelia and ascending nodes are randomized from gravitational perturbations and the swarm forms a doughnut-shapes dust torus of the inner extension $a(1-e)$ and the outer extension $a(1+e)$. As seen in observations from the Earth's orbit, the integrated signal has a small enhancement at the elongation beta, where the line of sight crosses the edges of this dust torus (right hand side).

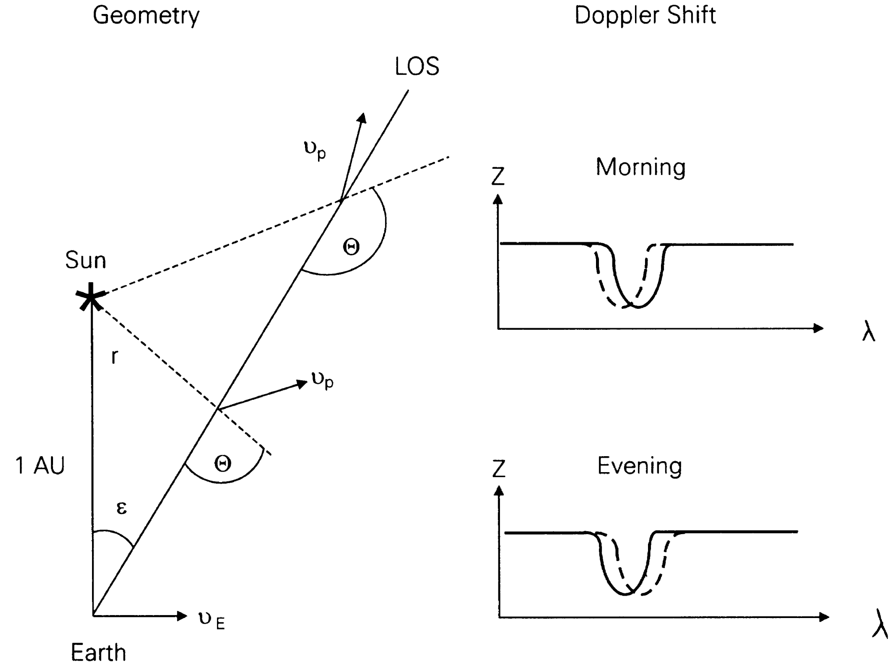

Fig. 4. Doppler shift of Fraunhofer lines in the Zodiacal light: the Fraunhofer lines of the solar spectrum are shifted due to 1. the relative velocity between the Sun and the dust particles moving with v_{p} relative to the Sun and 2. due to the relative velocity between the dust particles and the observer on Earth moving with v_{E} relative to the Sun.

6. Brightness vs. in-situ Results

We will briefly discuss the IRAS dust bands as an example for observational results and their comparison to in-situ results. The dust bands (see Fig. 3) were first noticed in the IRAS infrared Zodiacal emission data as symmetrically placed enhancements of the brightness and later on explained by an enhanced number density of grains with certain orbital parameters (Dermott *et al.*, 1984; Sykes and Greenberg, 1986). An opportunity for impact measurements was given with the dust measurements on the Ulysses and Galileo spacecraft, which passed the asteroid belt during the last 5 years (see Grün *et al.*, 1994). However, there was no indication for an enhanced flux rate onto the dust detectors when the spacecraft passed these dust band regions. After calculation of the detection probabilities based on the geometry of the detector and the orbit of the dust particles, this led to an upper estimate of the density of small particles in the dust bands. This may indicate that the production of dust particles, connected to the dust bands is relatively low, compared to the total amount of dust produced in the asteroid

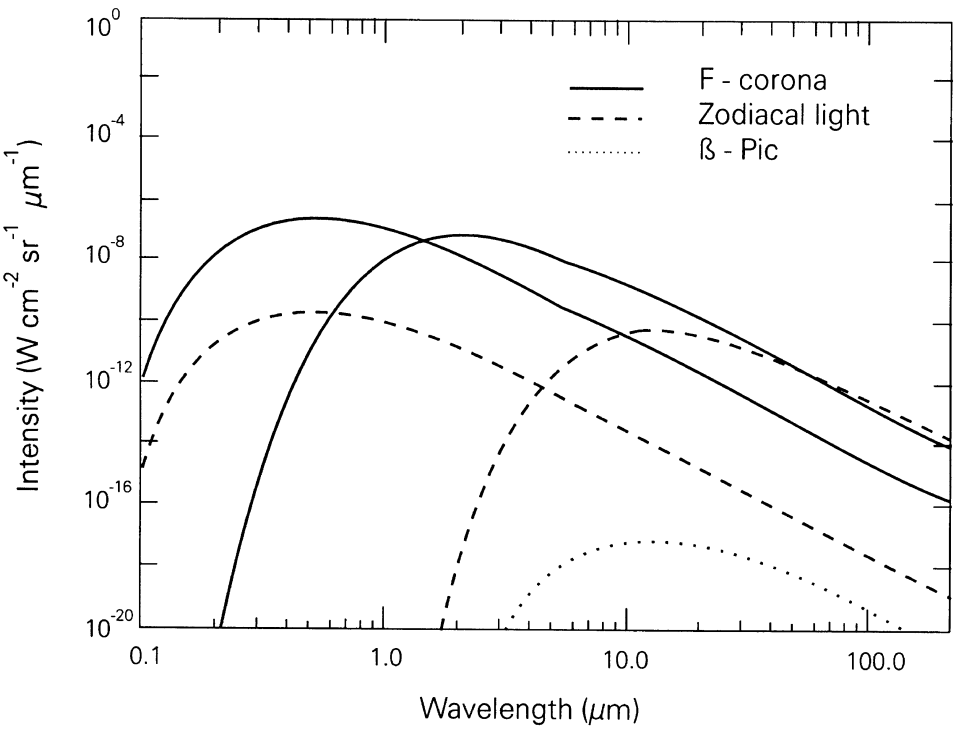

Fig. 5. Thermal emission and scattered light intensities of Zodiacal light at 90° elongation, of the solar F-corona at 1° elongation and of the β Pictoris dust shell.

belt (see Mann *et al.*, 1996). Based on the assumption that the dust bands are produced from the single destruction of a 100 km sized object, the production rate would amount to 10^{10} g/year, which is small compared to a required dust production in the order of 10^{14} g/year, which would be required keep the mass budget of the Zodiacal dust cloud in a steady state. At this point a further study of the formation and the evolution of dust bands would be worthwhile. This comparison shows, however how a dust feature that has noticeable effect on the thermal emission brightness, may not be significant in the size range, that is covered with in-situ experiments (and vice versa local dust streams, observed with in-situ experiments are not detected with observations).

7. Future Perspectives

7.1 Doppler shift measurements

As was mentioned before, brightness observations give a good overview of the structure of the overall dust cloud, but do only partly reveal its orbital distribution. The comparison of brightness observations and impact experiments on the other hand, yields the problem that usually the latter do not describe the size range that is covered with the brightness observations. Impact experiments also yield the problem of correct extrapolation from the local flux to overall orbital distributions. At this point Doppler shift measurements could help to understand the dust dynamics of particles in the same size range as the size of the particles that produce the Zodiacal light brightness is and also could cover a wider spatial range in the dust cloud. The Fraunhofer lines of the solar spectrum are shifted due to 1. the relative velocity between the Sun and the moving dust particles and 2. due to the relative velocity between the dust particles and the observer on Earth (see Fig. 4). The final Doppler shift is given from the different velocity directions of the particles in a given volume in space and the integration along the line of sight of the observer (see Mukai and Mann, 1993). Several attempts have been made to determine the Doppler shifts in the Zodiacal light (Fried, 1978; East and Reay, 1984), however the results are partly contradictory so far, presumably due to observational problems. As was pointed out by Clarke (1996) the analysis of the Doppler shift measurements would benefit from polarization measurements performed at the same time.

7.2 Measurements of the outer solar system cloud

Figure 5 shows the thermal emission and scattered light intensities of Zodiacal light at 90° elongation, of the solar F-corona at 1° elongation and of the β Pictoris dust shell. This indicates that the detection of dust components in the outer solar system would especially benefit from observations in the infrared regime, since the cool dust in the outer solar system would have its peak brightness at larger wavelength (see Mann, 1996). The figure also indicates that the thermal emission around β Pictoris is observed at longer wavelength than the Zodiacal dust thermal emission and hence corresponds to a cooler dust cloud that is more comparable to regions of the Kuiper belt in our solar system. Hence the study of the outer solar system dust cloud yields interesting opportunities for a comparison to other circumstellar systems. The outer solar system dust cloud may consist of fragments from long period comets (see Mann and Grün, 1995), particles from interstellar space or even fragments from Kuiper belt objects. The goals for the understanding of the "background" components of the outer solar system would certainly benefit from observations performed from spacecraft in an interplanetary cruising orbit. Already Giese (1979) has shown that measurements from spacecraft on out of ecliptic orbits could detect the flux of interstellar dust in the solar system. However, as Hanner (personal communication, 1997) has mentioned with respect to the analysis of the Pioneer 10 photometer data (see Hanner *et al.*, 1976), the fluctuation of the star background light may yield a limit of the dust cloud detection.

8. Summary

As far as the analysis of Zodiacal observations is concerned, it becomes obvious that the application of a homogeneous Zodiacal dust cloud cannot explain the optical properties derived for the dust in the inner solar system. Dynamical reasons will also cause a different view of the inner solar system as well as the outer solar system dust cloud. This means that the Zodiacal cloud models that are derived from brightness observations and that describe especially the dust close to the Earth orbit, only partly tell us the truth about the solar system dust cloud. Further knowledge will be provided by infrared observations from space, but also ground based observations will still yield further progress. Doppler shift measurements of dust near the Earth's orbit may yield a better understanding of the orbital distribution and hence the dynamics evolution in the dust cloud. Further observations of polarization and colour may draw limits about the size distribution of dust and its possible variation within the dust cloud, which indicates the collisional evolution. Finally, observations of the outer solar system dust cloud may enable better comparisons with the dust clouds around other stars.

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