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ZODIACAL LIGHT AND THERMAL EMISSION

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Optical and Thermal Properties of Zodiacal Dust

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Abstract. Recent progress has been reported in the determination of the zodiacal thermal emission, brightness and polarization. These results, of interest to estimate the foreground sources in astrophysical observations, do not provide immediately information on the dust distribution, and on its optical and thermal properties. To infer local information about the bulk density, and the physical properties of the dust particles, it is necessary to compare the observations with realistic models or to invert the line-of-sight data. The latter approach typically suggests that the bulk density is (in the symmetry plane) inversely proportional to the solar distance, that the particles are not spheroidal, but rather irregular in shape, that their physical properties change with their distance to the Sun and their orbital inclination, and finally that they do not emit like a blackbody. The heterogeneity noticed in the cloud is due to various sources of dust particles. the size, shape or albedo of which evolve as a function of time, under collision and/or evaporation processes.

1. Introduction

The existence of the interplanetary dust cloud has been suspected since the XVIIIth century through zodiacal light observations. Its increasing brightness towards the Sun and towards the near ecliptic symmetry plane has been a clue to the dynamics of dust particles, which mostly spiral towards the Sun under Poynting-Robertson drag, and precess along the orbital plane of massive planets. The interplanetary dust not only scatters solar light, as indicated by the solar light spectrum of the zodiacal light; it also produces thermal emission which prevails in the infrared and is the most prominent feature of the light of the night sky, at least far away from the galactic plane, in the 5-50 μm wavelength domain.

The previous meetings of this series may be associated with new starts in our understanding of the optical and thermal properties of the zodiacal dust: photometric observations (1967), observations from space (1975), local properties deduced from observations (1979), observations of the thermal emission (1984), or evidence for various sources in the dust cloud (1990). This paper emphasizes some recent progress obtained in these various fields of research, and tentatively provides a link between the optical and thermal properties of the interplanetary dust, and those of its sources.

2. Zodiacal light and zodiacal emission

Brightness observations of scattered light have been performed by various groups from Earth based and space based observatories. Although, in the first case, the airglow contamination is difficult to cope with (see e.g. Dumont and Sanchez, 1975) and, in the second case, the completeness of the data sets is impossible because of space constraints, the results have finally been found to be in good agreement (Fechtig et al., 1981). After correction for the oscillations originating in the slight inclination of the symmetry surface of the cloud upon the ecliptic plane (in the 1.5° to 3° range) and in the eccentricity of the Earth's orbit, no major spatial or temporal variation is found in the zodiacal light brightness, as observed from 1 AU heliocentric distance in the ecliptic plane (Dumont and Levasseur-Regourd, 1978; Leinert et al., 1980); it is mainly a function of the ecliptic latitude β and helioecliptic longitude $\lambda-\lambda_0$. A table providing the brightness Z as a function of these coordinates has been provided by Levasseur-Regourd and Dumont (1980). The smoothing has been recently improved by Dumont (personal communication); the corresponding values are presented in Table 1 in SI units (10^{-8} W m^{-2} sr^{-1} μm^{-1}) near 0.55 μm, instead of the previous $S_{10}(V)$ units (equivalent number of 10th visual magnitude stars of solar type per square degree).

Measurements of the polarization of the scattered light have also been performed by various authors and finally found to be quite comparable (Fechtig et al., 1981). The polarization degree, defined as $P = (Z_\perp - Z_{//}) / (Z_\perp + Z_{//})$, where $Z_\perp$ is the polarized component in the plane perpendicular to the scattering plane (Sun - dust particle - observer), and where $Z_{//}$ is the polarized component in that plane, is by definition obtained with greater uncertainty than the brightness. It is usually positive, since the direction of polarization is mostly perpendicular to the scattering plane; however, it is slightly negative in the antisolar Gegenschein region, possibly due to a coherent backscattering mechanism (Muinonen and Lumme, 1991). Smoothed values of the polarization degree, as recently proposed by Dumont (personal communication), are also provided in Table 1.

Measurements of the thermal emission in the infrared domain have been performed both from rockets (Price et al., 1982; Murdock and Price, 1985) and from spacecraft (Hauser et al., 1984; Bogges et al., 1992). The first ones allow a wide coverage in solar elongation ε, while the second ones, mainly retrieved at 90° from the Sun, have unfortunately never been performed below 64° or above 124°. An empirical function providing an analytical value of the thermal emission I at $(90 \pm 5)°$, as a function of the ecliptic latitude and of the day in the year has been obtained at 12, 25 and 60 μm (Vrtilek and Hauser, 1995). It permits the study of the time variation in the geometry of the cloud as probed from the Earth orbit (symmetry surface, trailing/leading asymmetry).

Finally, the observations performed at small solar elongations are poorly documented, since there is an angular gap between the zodiacal light and thermal emission observations, and the F-corona observations performed during eclipses. Visual and infrared brightness data, together with polarization data in the F-corona have been discussed by Mann (1992) and compared with model calculations to provide some clues to the properties of circumsolar dust.

Table 1. Zodiacal light averaged along the line of sight, as seen from 1 AU in the ecliptic plane. The brightness Z (first line, in 10^{-8} W m^{-2} sr^{-1} µm^{-1}, near λ=0.55 µm) and the degree of linear polarization P (second line, in per cent) are given as a function of the ecliptic latitude and of the helioecliptic longitude, after correction for the inclination of the symmetry plane. It is about 7 10^{-7} W m^{-2} sr^{-1} µm^{-1} at the poles of the ecliptic plane near λ=0.55 µm

Z P β $\lambda-\lambda_0$	0°	5°	0°	15°	20°	25°	30°	45°	60°	75°
0°				3090	1590	970	630	271	147	98
				8	10	11	12	16	19	20
5°				2900	1510	930	615	267	147	98
				9	10	11	12	16	19	20
10°			4660	2430	1450	850	580	260	146	98
			11	11	12	13	14	17	19	20
15°		6680	3390	1830	1100	745	515	247	144	98
	13	13	13	13	13	14	15	17	19	20
20°	6300	4410	2370	1390	895	625	447	233	139	97
	14	14	14	15	15	15	15	17	19	20
25°	3780	2780	1700	1080	735	535	403	219	134	96
	15	15	16	16	16	16	16	18	19	20
30°	2440	1840	1200	830	605	460	359	204	129	93
	16	16	16	16	16	17	17	18	19	20
35°	1630	1250	895	670	505	391	315	190	123	92
	17	17	17	17	17	17	17	18	19	20
40°	1170	930	685	525	409	333	277	176	118	91
	17	17	17	17	18	18	18	19	20	20
45°	895	720	550	435	350	287	246	164	115	88
	18	18	18	18	18	18	18	19	20	20
60°	500	435	346	287	239	205	180	132	102	84
	19	19	19	19	19	20	20	20	20	20
75°	333	312	265	223	193	169	149	115	92	81
	18	18	18	18	18	19	19	19	19	19
90°	255	241	222	190	164	145	130	102	84	78
	16	16	16	16	16	16	17	18	18	19
105°	209	207	194	168	147	131	117	94	81	76
	12	12	12	12	13	13	14	15	17	19
120°	185	183	174	151	136	123	111	88	76	73
	8	8	9	9	9	10	11	13	15	18
135°	176	175	164	145	132	120	108	88	76	72
	5	5	5	6	6	7	8	11	14	17
150°	176	175	163	146	135	125	115	94	78	71
	2	2	2	3	3	4	5	8	12	16
165°	193	189	176	163	149	139	129	102	81	71
	-2	-2	1	-1	0	2	3	7	11	16
180°	227	209	192	175	160	146	132	103	82	71
	0	-2	-3	2	-1	0	2	6	11	11

Table 2. Evolution of the local properties (90° phase angle for scattering properties) of the dust in the symmetry plane, as a function of solar distance R (power laws)

	Value at 1 AU	Gradient (power law)	Domain (in AU)
Brightness (near 0.55 µm)	23 10^{-7} (W m^{-2} sr^{-1} µm^{1}/rad)	-1.25±0.02	0.5 to 1.4
Polarization	30 per cent	+0.5±0.1	0.5 to 1.4
Temperature	250 K	-0.36±0.03	1.1 to 1.4
Albedo	0.08 (IRAS data)	-0.32±0.05	1.1 to 1.4
Density		-0.93±0.07	1.1 to 1.4

3. Inversion of the data

From the previous results, which are of interest to estimate the zodiacal foreground, it is indeed impossible to immediately retrieve information about the local properties of the interplanetary dust; the values of Z, $Z_\perp$, $Z_{//}$, P and I are integrated along a line-of-sight which extends from the observer to the outer fringe of the solar system. The first step towards an approach of the local properties is to disregard any inhomogeneity in nature or size within a unit volume of scattering light or emitting dust, and to define a volume scattering function which depends upon the location of the scattering unit. This function, which is isotropic for the emitted light, is also a function of the scattering angle (or of the supplementary phase angle) for the scattered light. Assuming i) the volume scattering function to be only a function $\sigma(\theta)$ of the scattering angle, i.e. the dust to have the same scattering properties everywhere, ii) the local density to be only a function of the solar distance R in the symmetry plane, iii) this function to be a power law $R^{-\nu}$, then it can be found that (Dumont, 1973),

$$\text{with } Z = K \int R^{-\nu+2}\, \sigma(\theta)\, dl,$$

$$\sigma(\theta{=}\varepsilon) = (dZ/d\varepsilon)^{-1}{}_{90°}\, [(1+\nu) \cos \varepsilon\, Z(\varepsilon) + \sin \varepsilon\, (dZ/d\varepsilon)]$$

From such an approach, the density had been inferred to vary approximately as $R^{-1.25\pm0.05}$ (e.g. Dumont, 1973; Leinert et al., 1977). Besides, elaborate model fittings, with careful classification of the hypothesis have allowed to retrieve the volume scattering function and the polarization function (e.g. Lamy and Perrin, 1986; 1991).

A rigorous inversion had been shown by Dumont (1973) to be only feasible for a line-of-sight tangent to the direction of motion of the Earth (or of a moving probe), and for the section of the line-of-sight where the observer is located. To attempt an inversion in regions that are not located on the orbit of the Earth, and to avoid the hypothesis of a cloud with constant scattering properties, the nodes of lesser uncertainty method has been proposed (Dumont and Levasseur-Regourd, 1985). This method only assumes an axial symmetry, a steady state of the cloud, and a rather monotonous variation along the line-of-sight of the local brightness or local thermal emission.

In the symmetry plane, the local contributions are found to be retrieved with less uncertainty than elsewhere at the so-called radial and martian nodes. The first one provides, at 90° phase angle, the evolution with solar distance of the local bulk optical and thermal properties, while the second one provides, at 1.5 AU solar distance, the variation with phase angle of these properties. The mains results have been presented in Dumont and Levasseur-Regourd (1988), Levasseur-Regourd et al. (1991) and Renard et al. (1995).

Table 2 summarizes the results obtained for the evolution of local brightness, polarization, temperature, albedo and density with the solar distance R, assuming power law distributions. Although the uncertainties in the power law exponents (due to the observational errors and to the method of inversion) are not negligible, the following conclusions can be reached:

i) The evolution in local polarization and in local albedo, in agreement with Mann et al. (1995) results in the inner zodiacal cloud, demonstrates that the properties of the grains are not the same everywhere, and suggest that drastic changes may take place below 0.3 AU (in the 500-700 K range); the decrease in polarization and increase in albedo, with decreasing solar distance, indicates a change in the

size distribution and porosity of the particles, with possibly the evaporation of dark organic compounds.
ii) The evolution in local temperature (12 μm/25 μm ratio), in agreement with Reach (1991) results, suggests that the particles do not emit like a blackbody.
iii) The evolution in local density, derived from that of brightness and albedo, is in agreement with a 1/R law, as expected for dust particles under from Poynting-Robertson drag in the region of production (Hanner, 1980).

The phase dependence of the local brightness (Figure 1a) and of the local polarization (Figure 1b) at 1.5 AU from the Sun in the symmetry plane is similar to that of most airless bodies in the solar system. As expected from in-situ studies, it is typical of scattering by irregular and rough dust particles. If one assumes the solar distance dependence in the polarization pointed out at 90° to be also valid for smaller phase angles, then the polarimetric phase curve may be extrapolated down to 0.3 AU (Figure 1c). A comparison between the polarimetric phase curves of interplanetary dust and those of asteroids (Goidet-Devel et al., 1995) and comets (Levasseur-Regourd et al., 1990, 1995) shows that the slopes at inversion are similar for interplanetary dust, C-type asteroids and cometary dust, and that the maximum in polarization is similar for interplanetary dust and Halley type cometary dust. The first result, taking into account the inverse correlation between slope at inversion and albedo, points out similarities in the albedos; the second one may be interpreted in term of similarities in the size distribution and/or the structure of the dust particles.

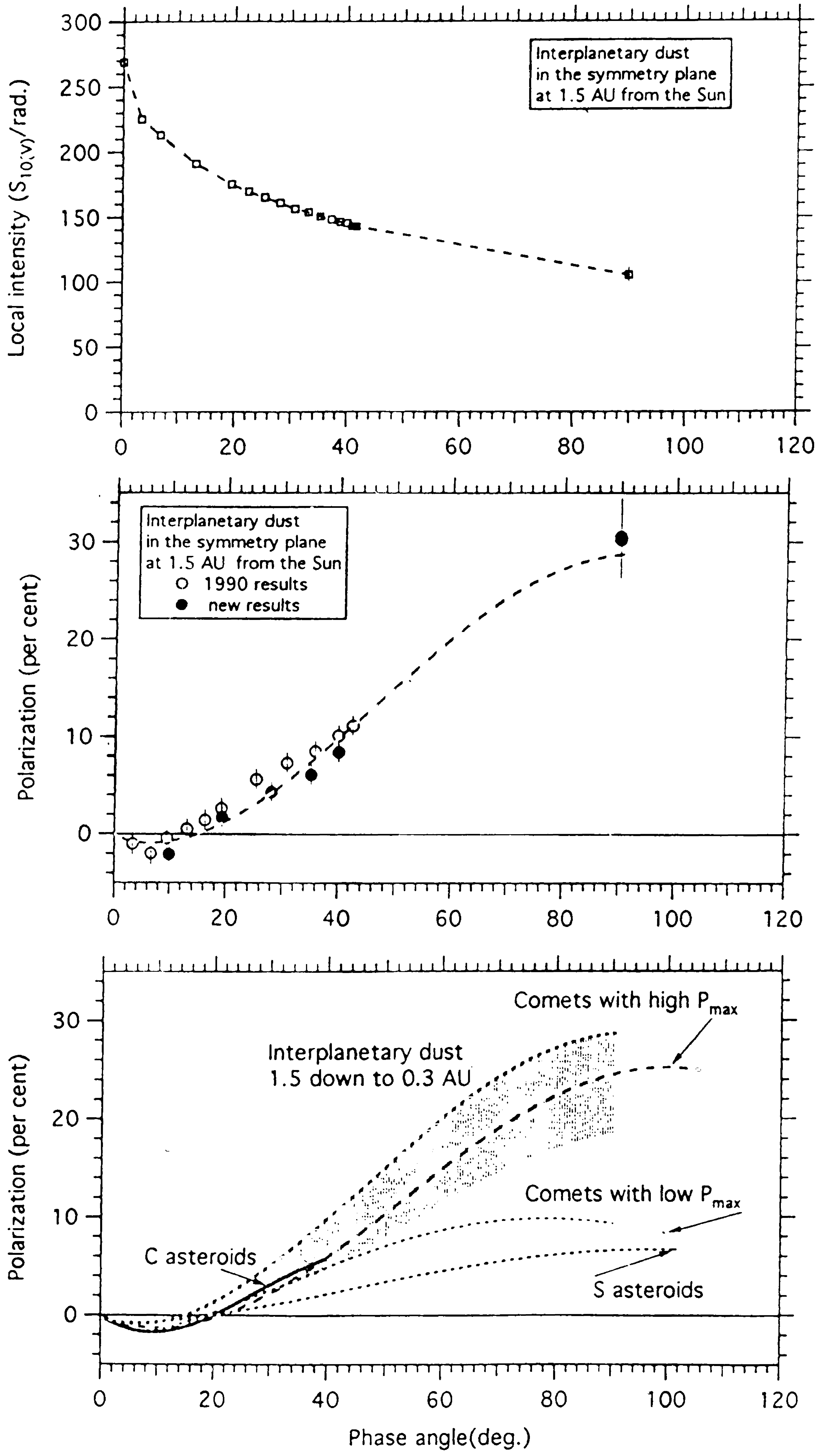
To summarize, some local properties of interplanetary dust particles, deduced from zodiacal light and thermal emission observations, strongly suggest that the physical properties of the particles change as their solar distance, and thus their temperature, vary. Also, the interplanetary dust particles have scattering properties quite similar to those of comets such as Halley, Bradfield or Levy, which have also been found (Hanner et al., 1994) to exhibit strong silicate emission features. The comets are most likely, as confirmed by Dermott et al. (1994) from a dynamical approach, the main source (possibly about 2/3) of dust in the zodiacal cloud. However, it needs to be kept in mind that the zodiacal cloud is messy and complex both in its origin and its structure.

4. Various sources for zodiacal light and emission

Some of the most fascinating observations made by IRAS are those of dust trails along the trajectory of short period comets, and of dust bands near ±10° ecliptic latitude. These bands have been attributed to dust from collisions of asteroids belonging to the Themis, Koronis, and possibly Eos families (see e.g. Dermott et al., 1984; Sykes et al., 1986; Sykes, 1990). Such a result indicates that the asteroids are also a significant source (possibly around 1/3) of dust in the zodiacal cloud.

The discovery of the asteroidal dust bands has confirmed the existence of local heterogeneities in the cloud. Also, the observation of the above-mentioned leading-trailing asymmetry in IRAS data has been a clue to the existence of a ring of dust particles of asteroidal origin corotating with the Earth (Dermott et al., 1994). The existence of this ring has been recently confirmed from COBE infrared data (Reach et al., 1995), and recovered in previous zodiacal light observations (Renard et al., 1996).

Figure 1. Phase curves typical of the local brightness (1a) and the local polarization (1b) of the zodiacal light at 1.5 AU in the symmetry plane, and comparison (1c) with the polarimetric phase curves of small bodies in the solar system.



Finally, the inversion of zodiacal light and emission data, carried on in the plane tangent to the Earth's orbit at 1 AU, strongly suggests that the local polarization decreases, while the local albedo slightly increases, as the inclination of the particles orbits increases (Renard et al., 1991; 1995). Therefore, the bulk properties of the dust particles do not only vary with the solar distance, but also with the inclination of their orbits, possibly due to a change in the relative contribution of long period comets.

Galileo and Ulysses spacecraft have recently (Baguhl and Grün, 1996) provided the first detection of dust impacts from jovian and from interstellar origin in the interplanetary dust cloud. Also, from modelling, Divine (1993) has found five populations of dust particles, which are dynamically, if not genetically, different. It is therefore not surprising that significant differences in the optical and thermal properties of the dust particles are pointed out, at least in the regions where an inversion of the data is possible.

5. Conclusions

The zodiacal cloud, as demonstrated from zodiacal light and emission observations (together with in-situ probing) is definitively less homogeneous that could be assumed a couple of decades ago. Distinct populations, whose mixing ratio changes with the location in the cloud, are pointed out; besides, it is likely that the dust particles suffer, due to collision and/or evaporation processes, significant temporal changes in their physical properties.

The local information on optical properties that is retrieved in various areas of the dust cloud should, through comparison between numerical simulations of scattering by irregular particles and laboratory scattering measurements, provides some clues to the physical properties (e.g. size distribution, porosity, roughness) of the zodiacal dust particles.

Finally, some new and fascinating results are to be expected in a near future from the ISO spacecraft, which will not only provide a remarkable spatial resolution (unfortunately again in a restricted range of heliocentric longitudes), but also allow spectrometric observations.

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References

Baguhl and Grün, 1996, This volume.

Bogges N.W., Mather J.C., Weiss R. et al., 1992, Astrophys. J. 397, 420.

Dermott S.F., Durda D.D., Gustafson B.A.S., et al., 1994, In Asteroids, Comets, Meteor 93, eds. A. Milani, M. Di Martino, A. Cellino, Kluwer, 127.

Dermott S.F., Nicholson P.D., Burns J.A., Houck J.R., 1984, Nature 312, 509.

Divine N., J., 1993, Geophys. Res. 98, 17029.
Dumont R., 1973, Planet. Space Sci. 21, 2149.
Dumont R., Sanchez F., 1975, Astron. Astrophys. 38, 405.
Dumont R., Levasseur-Regourd A.C., 1978, Astron. Astrophys. 64, 9.
Dumont R., Levasseur-Regourd, 1985, Planet. Space Sci. 33, 1.
Dumont R., Levasseur-Regourd A.C., 1987, In Interplanetary matter, eds. Z. Ceplecha, P. Pecina, Czechoslovak Acad. Sci. 281.
Dumont R., Levasseur-Regourd A.C., 1988, Astron. Astrophys. 191, 154.
Fechtig H., Leinert C., Grün E., 1981, In Interplanetary dust and zodiacal light, eds. K. Schaifers, H. Voigt, Landolt-Börnstein, Springer-Verlag, 228.
Goidet-Devel B., Renard J.B., Levasseur-Regourd A.C., 1995, Planet. Space Sci. 43, 779.
Hanner M.S., 1980, Icarus 43, 373.
Hanner M.S., Lynch D.K., Russel R.W., 1994, Astrophys. J. 425, 274.
Hauser M.G., Gillett F.C., Low F.L., et al., 1984, Astrophys. J. 278, L15.
Lamy P.L., Perrin J.M., 1986, Astron. Astrophys. 163, 269.
Lamy P.L., Perrin J.M., 1991, In Origin and evolution of interplanetary dust, eds. A.C. Levasseur-Regourd, H. Hasegawa, Kluwer, 163.
Leinert C., Pitz E., Hanner M., Link H, 1977, J. Geophys. 42, 669.
Leinert C., Hanner M., Richter I., Pitz E., 1980, Astron. Astrophys. 82, 328.
Levasseur-Regourd A.C., Dumont R., 1980, Astron. Astrophys. 84, 277.
Levasseur-Regourd A.C., Dumont R., Renard J.B., 1990, Icarus 86, 264.
Levasseur-Regourd, A.C., Renard J.B., Dumont R., 1991, In Origin and evolution of interplanetary dust, eds. A.C. Levasseur-Regourd, H. Hasegawa, Kluwer, 131.
Levasseur-Regourd AC., Hadamcik E., Renard J.B., 1995, Astron. Astrophys. in press.
Mann I., 1992, Astron. Astrophys. 261, 329.
Mann I., Mukai T., Okamoto H., 1995, Adv. Space Res. 16, (2)37.
Muinonen, K., Lumme, 1991, In Origin and evolution of interplanetary dust, eds. A.C. Levasseur-Regourd, H. Hasegawa, Kluwer, 159.
Murdock T.L., Price S.D., 1985, Astron. J. 90, 375.
Price S.D., Murdock T.L., Marotte L.P., 1982, Astron. J 87, 131.
Reach W.T., 1991, Astrophys. J. 369, 529.
Reach W.T., Franz B.A., Weiland J.L., et al., 1995, Nature, 374, 521.
Renard J.B., Levasseur-Regourd A.C., Dumont R., 1991, In Origin and evolution of interplanetary dust, eds. A.C. Levasseur-Regourd, H. Hasegawa, Kluwer, 199.
Renard J.B., Levasseur-Regourd A.C., Dumont R., 1995, Astron. Astrophys. 304, 602.
Renard J.B., Dumont R., Levasseur-Regourd A.C., Hadamcik E., 1996, This volume.
Sykes M.V., 1990, Icarus 85, 267.
Sykes M.V., Lebofsky L.A., Hunten D.M., Low F.J., 1986, Science 232, 1115.
Vrtilek J.M., Hauser M.G., 1995, Astrophys. J. 455, 677.