ZODIACAL LIGHT AND INTERPLANETARY DUST

J. L. Weinberg
Space Astronomy Laboratory, University of Florida
1810 NW 6th Street
Gainesville, Florida 32609
USA

ABSTRACT. Recent results on zodiacal light are used to show that optics, dynamics, and infrared must be considered *together* to properly and fully characterize the interplanetary dust complex.

Zodiacal light observations have been widely used to infer the large scale properties of the interplanetary dust - with mixed results. Zodiacal light is certainly more stable (and better understood) than the published literature would suggest over the 25 years that it has been studied by this writer. The interested reader can trace this history in the Proceedings of this Colloquium's predecessor meetings (Honolulu 1967, Heidelberg 1975, Ottawa 1979), in triennial Reports on Astronomy of IAU Commission 21, and in various reviews (e.g.: Leinert 1975; Weinberg and Sparrow 1978; Fechtig, Leinert, and Grün 1981).

There have been intensive ground and space observations over the past two decades together with laboratory and theoretical studies, and, as we entered the 1980's, there was general agreement that:

- zodiacal light has solar color from the near UV to the near IR, except for a slight reddening in sky regions observed near the sun
- zodiacal light brightness is relatively smooth and remarkably stable over times as long as a solar cycle (Burnett 1976; Dumont and Levasseur-Regourd 1978; Leinert, et al. 1982a)
- zodiacal light brightness decreases monotonically with heliocentric distance R and is negligible beyond the asteroid belt (Hanner, et al.; 1974, 1976)
- zodiacal light is partially plane polarized with its electric vector perpendicular to the scattering plane, except for regions at large elongations where there is polarization reversal (electric vector parallel to scattering plane).

Recent results present a somewhat different, more complex picture of the interplanetary dust. Representative of this changing "view" are the recent, exciting observations by IRAS. Figure 1 shows IRAS 4-color data on total thermal emission for representative ecliptic pole-to-pole scans. The zodiacal emission peaks near the ecliptic, is the dominant source at 12, 25, and 60μm, and appears to be the brightest diffuse

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 1–6.

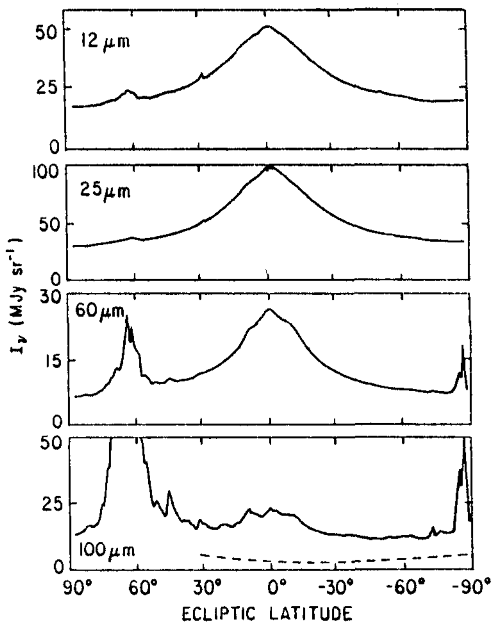

Figure 1. Ecliptic pole-to-pole profiles of total sky brightness at each of the IRAS wavelengths - 12, 25, 60, 100μm - at elongation 91.1° (Hauser, et al. 1984). The enhancement near ecliptic latitude 60° corresponds to the large Magellanic Cloud. Structure near the ecliptic and at 10° on either side corresponds to the zodiacal dust emission bands.

source away from the Milky Way even at 100μm. The sensitive, high resolution IRAS telescope (Neugebauer, et al. 1984a) found the zodiacal emission to be up to a factor of 4 brighter than previously published measurements at 11μm and 20μm (Price, et al.; 1980, 1982). In addition, IRAS found widespread structure in the IR sky background in all four wavelength bands, including an IR "cirrus" in the 100μm data (Low, et al. 1984). Particularly striking was the discovery of relatively narrow dust emission bands in and near the ecliptic for all ecliptic longitudes (Neugebauer, et al. 1984b; Low, et al. 1984). Gautier, et al. (1984) and Hauser, et al. (this volume) find this dust to be at approximately 2.5AU and suggest an asteroidal origin (see, also, Dermott, et al. 1984), compared to the prevailing wisdom that comets are the principal source of the main body of zodiacal dust. At almost the same time, Hong, et al. (this volume) found small scale structure in the elongation dependence of visible wavelength Gegenschein observations from Pioneer 10 and from the ground. In an analysis of additional Pioneer 10 observations, Toller and Weinberg (this volume) found similar "structures" at the same elongations above and below the ecliptic and which reproduced at different heliocentric distances.

Pioneer 10/11 and Helios 1/2 were the first space probes to carry photometric experiments designed to measure zodiacal light from different locations in the solar system: Pioneer for R beyond 1AU and Helios from 1AU to 0.31AU from the sun. Outward-looking measurements from Pioneer found zodiacal light brightnesses for R>2.8AU to be negligible compared to the background starlight (Schuerman, et al. 1977). The R-dependence of dust number density was found from Helios data to vary as $R^{-1.3}$ (Link, et al. 1976; Leinert, et al. 1981), whereas the Pioneer data suggest a steeper decrease for R>1AU (Weinberg and Sparrow 1978; Schuerman 1980a; Toller and Weinberg, this volume). Hong (A&A, in press) suggests that the spatial distribution may be closer to R^{-1} for regions closer than 0.3AU to the sun and (personal communication) that dynamical considerations and the R-dependence of zodiacal light brightness may argue against a single power-law exponent.

Zodiacal light polarization is sensibly zero at the antisun. At other sky positions the orientation of the plane of zodiacal light polarization is either perpendicular or parallel to the scattering plane (i.e., to the direction to the sun/antisun). [By definition this is referred to as positive or negative polarization, respectively.] This is illustrated in Figure 2 for two of ten visible wavelengths observed from Skylab (Weinberg, et al. 1976). The polarization directions are symmetric about the antisun except for distortion caused by Milky Way polarization which, in general, has a different polarization direction. The change from positive to negative polarization or polarization reversal is evident in both colors at large elongations. No evidence was found for time changes in direction or amount of polarization (see, also, Leinert and Planck 1982). Although not readily apparent in the data shown here, the Skylab data are consistent with the result of Weinberg and Mann (1968) that the position of zero polarization or neutral point moves closer to the sun with increasing wavelength. At IR wavelengths there may be more than one such polarization reversal at large elongations and even a reversal in near-sun regions if there are interstellar grain size particles there (Hong, personal communication). As shown by Beard (1984), IR polarization measurements near the sun also "very effectively determine the size of interplanetary dust or place significant limits on the size." [This writer is not aware of the existence of suitable IR polarization measurements.] Sparrow, et al. (1976) and Weinberg and Hahn (1980) found the polarized brightness of zodiacal light to have solar color at five moderate elongation positions, suggesting that the degree of polarization in this region is independent of wavelength between 4000Å and 8200Å. In contrast, Helios results show significant color differences in both brightness and polarization (Leinert, et al; 1981, 1982b). Zodiacal light brightness was found to be redder than the sun, with the reddening decreasing with increasing elongation, and independent of R. The former supports earlier results that the particles primarily responsible for zodiacal light are tens to hundreds of microns in diameter. Polarization degree was found to increase systematically with decreasing wavelength (i.e., from V to B to U) and to be significantly higher at Helios aphelion (1AU) than at perihelion (0.3AU). No explanation was found for the latter.

Zodiacal light brightness Z is a function of both the density n and nature (scattering cross section σ) of the dust. The traditional method of analysis (separation) involves the following two assumptions:

1. dust density is a power of heliocentric distance: $n \propto R^{-\nu}$
2. the nature of the dust is independent of location; i.e., the same type of particle is arbitrarily distributed throughout the solar system.

With these assumptions, observations at different R make it possible to solve for n and σ (Hanner and Leinert 1972). With the second assumption, the brightness Z can be written as $Z(\varepsilon,R) = R^{\alpha}f(\varepsilon,R)$, where ε is elongation and α is an index independent of ε. To test this assumption, Schuerman (1980a) fit a power law of the form $Z \propto R^{\alpha}$, $\alpha = -1-\nu$, to Pioneer data on brightness Z versus ε for 12 different heliocentric distances R. If the aforementioned assumptions are correct, a *single* value of α should apply at all ε. Figure 3 shows the combined result of the 12 (ε) log Z versus log R data sets and of other independent Pioneer data: a systematic

https://doi.org/10.1017/S0252921100084220 Published online by Cambridge University Press

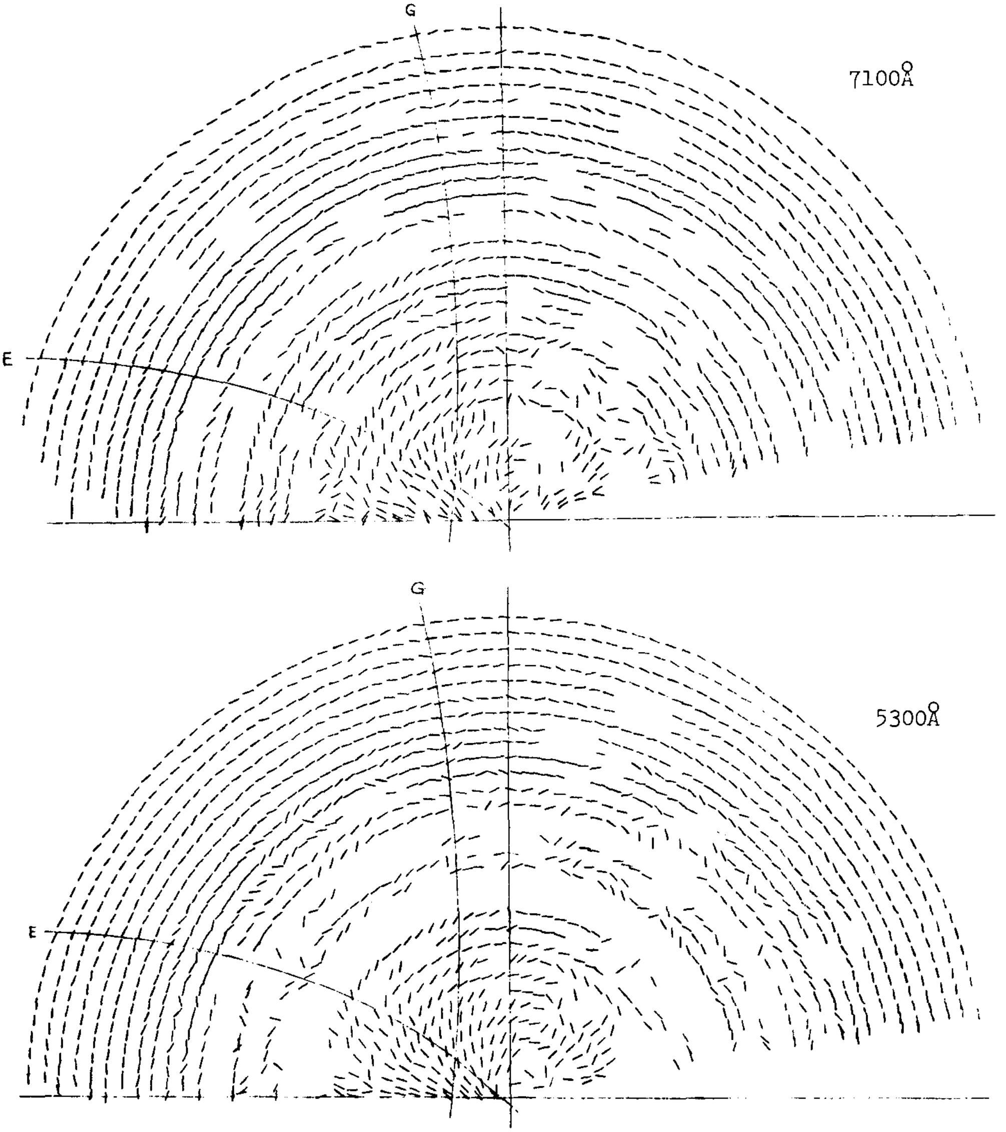

Figure 2. Measured orientations of the plane of polarization (electric vector) taken from Skylab in June 1973. The antisun is at the intersection of the straight lines, and E and G correspond to the positions of the ecliptic and galactic equators, respectively. The outermost data are approximately 70° from the sun. Gaps are primarily due to telemetry data dropouts or noisiness due to bright stars.

decrease in α towards ε=100°. Schuerman's tentative conclusion was that one or both assumptions are incorrect; i.e., *the particles cannot be the same throughout the solar system.* It then follows that the plot of α

https://doi.org/10.1017/S0252921100084220 Published online by Cambridge University Press

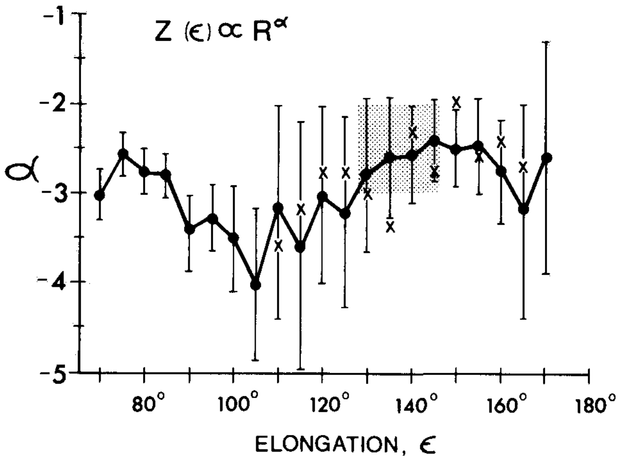

Figure 3. Angular dependence of the index α in brightness $Z \propto R^{\alpha}$, $\alpha = -1-\nu$ (Schuerman 1980a). Data points marked by x's refer to in-ecliptic Pioneer data presented earlier (Schuerman 1979a). The shaded rectangle approximates the earlier and independent Pioneer results of Hanner, et al. (1976). If the scattering properties of the dust are independent of R, α should be constant.

versus ε must contain information concerning the distribution of different types of particles, with the maximum information only able to be obtained from inversion techniques (Dumont 1972, 1973; Schuerman 1979b; others). [D. W. Schuerman's untimely death in May 1982 prevented his completing analysis of the same data with inversion methods.] Changes in polarization with R observed from Helios (see earlier) and from Pioneer 10 (Clarke and Weinberg, unpublished) may be a result of an inhomogeneous dust distribution.

From analysis of the positions of maximum zodiacal light brightness, Misconi and Weinberg (1978) and Misconi (1980) suggest that there may not be a single plane of dust concentration but a "multiplicity" of planes associated with the orbital planes of the planets. Can long-term gravitational perturbations by the planets "shepherd" particles in this way? ... In a search for mechanisms which might produce azimuthal asymmetries in the zodiacal cloud, Schuerman (1980b) found that there may be large scale dust arcs associated with the sun, planets, and the classical L_4 and L_5 Lagrangian points. Special observing geometries, techniques, and timing are needed to search for such arcs from the ground (Giovane, et al., this volume). The demonstrated existence of the arcs and their relatively small particles would add a new dimension to interplanetary dust dynamics. Could such particles contribute to the aforementioned dependence of α on ε? ... IRAS data at different wavelengths refer to particles at different temperatures and therefore at different R. Does the Pioneer data contain information on the same particles? ... As noted earlier, zodiacal scattering is remarkably constant. Are the recently discovered zodiacal emission bands similarly constant? ... Misconi (1977) showed that the F-corona and

https://doi.org/10.1017/S0252921100084220 Published online by Cambridge University Press

inner zodiacal light arise primarily from particles physically close to the sun. Brightness, polarization, color, thermal emission, and spectroscopy (doppler shifts and line/band material "signatures") of the F-corona/inner zodiacal light from several solar radii out to approximately 20° contains *unique* information on the optical and physical nature of the particles, the physics/dynamics/chemistry of particles near the sun, the transition from solar corona (dust and electrons) to zodiacal light, and gas-dust interactions during solar storms. The sensible limit for ground observations of zodiacal light is 30° from the sun, with the result that *ground observations never see the effects of dust closer than 0.5AU to the sun*; i.e., this region can only be observed from space. ... The results and the questions in these few pages are just part of the unfolding picture connecting optics, dynamics, and infrared.

REFERENCES

Beard, D.B.: 1984, Astron. Astrophys. 132, 317-320.
Burnett, G.G.: 1976, Lecture Notes in Physics 48, 53-57.
Dermott, S.F., et al.: 1984, Nature 312, 505-509.
Dumont, R.: 1972, Compt. Rend. Acad. Sci. Paris 275, 765-768.
Dumont, R.: 1973, Planetary Space Sci. 21, 2149-2155.
Dumont, R., Levasseur-Regourd, A.C.: 1978, Astron. Astrophys. 64, 9-16.
Fechtig, H., et al.: 1981, Landolt-Börnstein 2, sub-vol. 3, 228-243.
Gautier, T.N., et al.: 1984, Bull. Amer. Astron. Soc. 16, 442.
Hanner, M., Leinert, C.: 1972, Space Research XII, 445-455.
Hanner, M., et al.: 1974, J. Geophys. Res. 79, 3671-3675.
Hanner, M., et al.: 1976, Lecture Notes in Physics 48, 29-35.
Hauser, M.G., et al.: 1984, Astrophys. J. 278, L15-L18.
Leinert, C.: 1975, Space Sci. Rev. 18, 281-339.
Leinert, C., et al.: 1981, Astron. Astrophys. 103, 177-188.
Leinert, C., Planck, B.: 1982, Astron. Astrophys. 105, 364-368.
Leinert, C., et al.: 1982a, Astron. Astrophys. 110, 111-114.
Leinert, C., et al.: 1982b, Astron. Astrophys. 110, 355-357.
Link, H., et al.: 1976, Lecture Notes in Physics 48, 24-28.
Low, F.J., et al.: 1984, Astrophys. J. 278, L19-L22.
Misconi, N.Y.: 1977, Astron. Astrophys. 61, 497-504.
Misconi, N.Y.: 1980, in Proc. IAU Symp. 90, eds. Halliday/McIntosh, 49-53.
Misconi, N.Y., Weinberg, J.L.: 1978, Science 200, 1484-1485.
Neugebauer, G., et al.: 1984a, Astrophys. J. 278, L1-L6.
Neugebauer, G., et al.: 1984b, Science 224, 14-21.
Price, S.D., et al.: 1980, Astron. J. 85, 765-771.
Price, S.D., et al.: 1982, Astron. J. 87, 131-140.
Schuerman, D. W., et al.: 1977, Bull. Amer. Astron. Soc. 9, 313.
Schuerman, D. W.: 1979a, Space Research XIX, 447-450.
Schuerman, D. W.: 1979b, Planetary Space Sci. 27, 551-556.
Schuerman, D. W.: 1980a, in Proc. IAU Symp. 90, 71-74.
Schuerman, D. W.: 1980b, Astrophys. J. 238, 337-342.
Sparrow, J.G., et al.: 1976, Lecture Notes in Physics 48, 45-51.
Weinberg, J.L., Mann, H.M.: 1968, Astrophys. J. 152, 665-666.
Weinberg, J.L., et al.: 1976, Bull. Amer. Astron. Soc. 8, 502.
Weinberg, J.L., Sparrow, J.G.: 1978, in Cosmic Dust, ed. McDonnell, 75-122.
Weinberg, J.L., Hahn, R.C.: 1980, in Proc. IAU Symp. 90, 19-22.

https://doi.org/10.1017/S0252921100084220 Published online by Cambridge University Press