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On the Spatial Distribution of Interplanetary Dust near 1 AU

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Summary. Zodiacal light observations obtained with the space probes Helios 1 and Helios 2 between 0.98 and 0.85 AU were analyzed for angular distribution and radial gradient of brightness. The radial brightness gradient can best be explained by a spatial distribution of the dust particles in the size range 10–100 µm of $n(r) \sim r^{-1.3 \pm 0.2}$. No change in the angular brightness distribution was found, which supports the inherent assumption that the scattering properties of interplanetary dust depend little on heliocentric distance. A comparison is made with spatial distributions derived from space observations of individual particles and from radio meteors.

Key words: interplanetary dust — zodiacal light

1. Introduction

Several deep space probes have now measured the distribution of interplanetary dust away from the earth-moon-system. These measurements have so far given an inconsistent picture. Rhee et al. (1974) reported a constant spatial density of micrometeoroids $\geqq 10^{-13}$ g between 0.75 and 1.09 AU from Pioneer 8 and 9 data. Humes et al. (1974) derived a decreasing dust concentration from 1–1.7 AU, followed by constant, or possibly increasing dust concentration beyond 2 AU, based on hits recorded by the Pioneer 10 and 11 penetration detector (particles $\geqq 2\,10^{-9}$ g for $\varrho = 0.5$ g/cm^3). The imaging photopolarimeter on Pioneer 10 and 11 measured decreasing zodiacal light brightness from 1 to 3 AU, which Hanner et al. (1976) interpret as decreasing dust concentration, $n(r) \sim r^{-\nu}$, $\nu \approx 1.5$ from 1 to 3 AU. Beyond ≈ 3 AU the zodiacal light was too faint to be detected. The zodiacal light experiment on Helios 1 and 2 measured the gradient in zodiacal light brightness between 1 and 0.3 AU. Link et al. (1976) concluded that in the average the scattering per unit volume varies as $r^{-\nu}$, with $\nu \approx 1.3$. The micrometeoroid detectors on Helios 1 and 2 recorded on order-of-magnitude increase in dust impact rate between 1.0 and 0.3 AU (Grün et al., 1976) in qualitative agreement with a distribution $\sim r^{-1.3}$.

In contrast Southworth and Sekanina (1973) derived a distribution of radio meteors (particles $\geqq 10^{-5}$ g) which increases with increasing heliocentric distance from 0.7 to 2 AU.

In this paper, we examine in more detail the radial gradient between 1.0 and 0.85 AU observed with the Helios zodiacal light photometers. We also examine whether this gradient can best be explained by a variation in the spatial concentration of the dust or a change in the dust albedo.

2. Instrument and Data Reduction

The Helios zodiacal light experiment has been described by Leinert et al. (1975). It consists of 3 independent telescope-photometer systems, mounted at fixed angles of 16, 31 and 90° to the spacecraft equatorial plane (nominally the ecliptic plane), with respectively 1°, 2°, 3° fields-of-view. Each photometer records brightness and polarization sequentially in U, B, V spectral bands. The one-second spacecraft spin is divided into 32 sectors of 5.°6, 11.°2 or 22.°5 in length. Data from 513 spins are accumulated and averaged before telemetry. The experiment operates continuously, with one complete cycle through all filter-photometer combinations requiring ≈ 5 h. On Helios 1 the telescopes point South of the ecliptic; on Helios 2 they point North of the ecliptic.

The instrument was carefully calibrated in the laboratory before flight, including a determination of the temperature dependence of sensitivity. Absolute calibration from bright star crossings agrees with the laboratory calibration better than ±10%. The instrument sensitivity was constant to within a few percent over the 240-day time interval considered here. The scatter in the raw data is less than 1%.

To derive the zodiacal light brightness, we must take into account calibration, dark current and temperature

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Table 1. Time intervals near aphelion

	First aphelion	Second aphelion
Helios 1 Day	352/1974—18/1975	153/1975—210/1975
Helios 2 Day	22/1976—55/1976	162/1976—240/1976

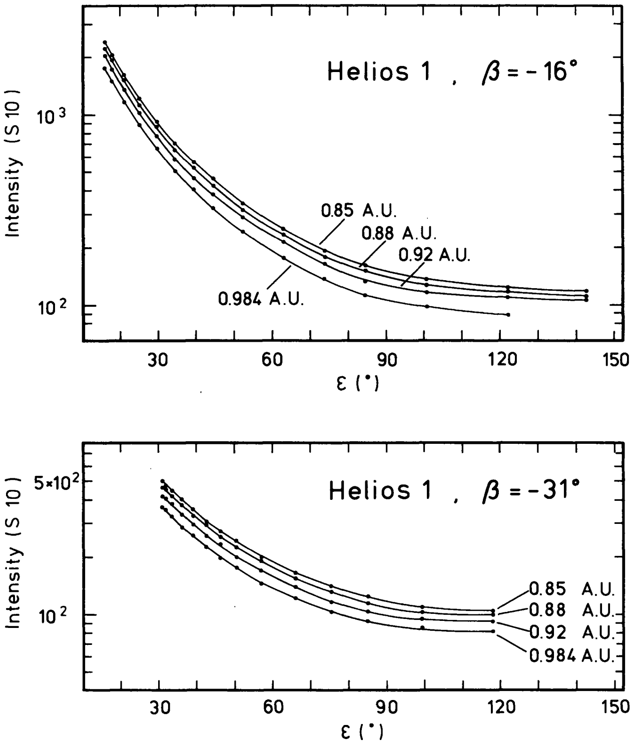

Fig. 1. Brightness profiles measured with Helios 1 at ecliptic latitudes, $\beta = -16°$ and $\beta = -31°$ after second aphelion. The heliocentric distances of Helios 1 are indicated

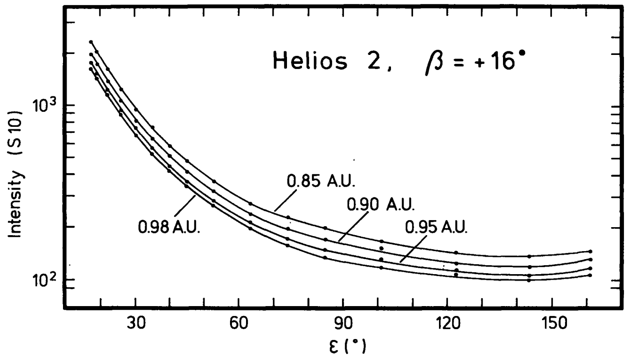

Fig. 2. Brightness profiles measured with Helios 2 at ecliptic latitude $\beta = +16°$ after first aphelion. The heliocentric distances of Helios 2 are indicated

effects and subtract the contributions from individual bright stars, background starlight (integrated starlight plus diffuse galactic light) and electron scattering. Of these, background starlight is the most difficult to evaluate. Recently, a photometric survey of the background starlight in the B spectral band has become available (Classen, 1976). The absolute brightnesses are consistent with the Helios data to within approximately 10%, even in the brightest parts of the Milky Way (Hanner et al., 1977). Therefore, we shall base our discussion here on the Helios Blue data. The same overall brightness gradient is observed in the 3 Helios spectral bands.

Bright stars were individually subtracted to limiting blue magnitude 7.1, the approximate cutoff for the survey of Classen. The correction for electron scattering was computed from a spherically symmetric model for the electron density, with 6 electrons per cm^3 at 1 AU and a radial dependence $n_e(r) \sim r^{-2.1}$. The maximum contribution to the observed intensity amounted to 3% at an elongation (line of sight-sun-angle) of $\varepsilon = 17°$, Data from two successive aphelia, six months apart, were analyzed for each spacecraft. The time intervals are listed in Table 1.

3. Measurements and Interpretation

Figures 1 and 2 show the zodiacal light brightness as a function of elongation, obtained after subtraction of the other brightness components. The measurements left and right of the sun have been averaged. One sees that the brightness increases uniformly with decreasing sun-spacecraft distance. There is no detectable change with time or with heliocentric distance in the shape of the angular brightness distribution. The brightnesses at 0.98 AU are in general agreement with earth-based observations of Dumont and Sanchez (1976) and Frey et al. (1974), when the V/B color measured by Helios is taken into account. The zodiacal light brightnesses at constant elongation are plotted versus heliocentric distance on a logarithmic scale in Figure 3. It can be seen that the brightness increase starts right at aphelion and has approximately the same slope at all elongation. The gradient can be reasonably approximated by a power law.

To derive the radial gradient of interplanetary dust or, more precisely, of the scattering cross section per unit volume, we start from the well known equation relating zodiacal light intensity $I(\varepsilon, \beta)$ observed at heliocentric distance R with the spatial distribution $n(r, z)$ and average scattering cross section $\sigma(\Theta)$ [cm^2 sterad^{-1}] of interplanetary dust:

$$I(\varepsilon, \beta) = \frac{F_0 R_0^2}{R \sin\varepsilon} \int_{\varepsilon}^{\pi} n(r, z)\sigma(\Theta) d\Theta . \tag{1}$$

F_0 is the solar flux per cm^2 at $R_0 = 1$ AU. If $n(r, z)$ is of the form $n_0 r^{-\nu} f(r/z)$ as suggested by previous interpretations of zodiacal light measurements, (e.g. Leinert et al., 1976), the brightness integral takes the form

$$I(\varepsilon, \beta) = \frac{F_0 R_0^{\nu+2} n_0}{(R \sin\varepsilon)^{\nu+1}} \int_{\varepsilon}^{\pi} f(z/r) \sin^{\nu}\Theta d\Theta . \tag{2}$$

If now $\sigma(\Theta)$ is independent of r and z, the observed brightness at a fixed viewing angle will vary as $I \sim R^{-(\nu+1)}$. As we have seen in Figure 3 this is indeed the type of variation recorded by the Helios photometers. However, before transforming the slope of Figure 3 into a radial gradient of the spatial distribution, two effects must be taken into account. First, the orientation of the spin axis was occasionally changed by maneuvers, causing a variation in the ecliptic latitude of the scan. This effect is most conspicuous at small elongations ($\varepsilon = 17°$) where it caused the intensities to be higher during the second aphelion. Additionally, the symmetry plane of dust is inclined with respect to the ecliptic. As the spacecraft move along their orbits in the ecliptic, their distance from the symmetry plane will vary. Since both spacecraft are diving southward through the plane of symmetry near aphelion, Helios 1 with its photometers looking South observes systematically higher intensities before aphelion (open circles versus points).

Accordingly, we computed the expected brightness variation for the specific spacecraft orientations and viewing directions of the observations, based on different radial gradients and symmetry plane orientations (Ω, i) of the dust distribution. The exact orientation chosen for the symmetry plane and the dust distribution perpendicular to the plane had little effect on the fit to the radial gradient for the limited range in heliocentric longitude covered by the spacecraft near aphelion. Finally we used $n(r,z) \sim r^{-\nu} \exp - (2.1 z/r)$ which reasonably reproduces the brightness ratio between $\beta = -16°$ and $\beta = -31°$ observed with Helios 1, and a symmetry plane with $\Omega = 86°$, $i = 2.7°$, halfway between the invariable plane of the solar system and the plane proposed for the inner zodiacal light in an earlier paper (Leinert et al., 1976).

We obtained a best fit with $\nu = 1.3 \pm 0.2$ as shown in Figure 4, where calculations for $\nu = 1.3$ are compared to a sample of measurements from Helios 1 and Helios 2. The absolute value of the computed intensities has been adjusted to the different data groups. The change from first to second aphelion was -2.3% for $\beta = -16°$, $+1.4\%$ for $\beta = -31°$ and $+4.7\%$ for $\beta = +16°$. Although variations of this size in the zodiacal light cannot be excluded, we ascribe these changes mainly to changes in instrument sensitivity of the different photometers.

In view of the small effects discussed a word seems necessary on the accuracy of the data points. Of course each individual point bears an absolute error due to uncertainties in the reduction procedure and especially the calibration of the order of $\pm 5\%$ to $\pm 10\%$. However, for a *relative* comparison these uncertainties tend to cancel and the apparent scatter of $\approx 1\%$ is not unreasonable over such limited portions of the orbit. A systematic error of the relative comparison could most easily come from an error in the correction for temperature effects. With less than 5° temperature range and temperature effects of less than 0.4% per °C we exclude this as an important error source.

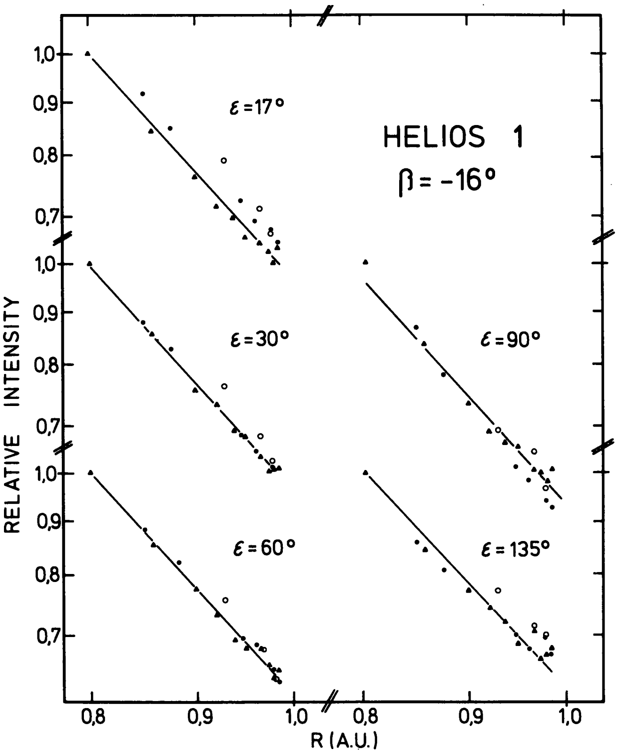

Fig. 3. Gradient of brightness versus heliocentric distance observed with Helios 1 for different elongations. Intensities are normalized to 1 at 0.8 AU. The symbols indicate, whether the measurements were taken after first aphelion (after launch), before (○) or after (●) second aphelion. To aid the eye a line with the same slope has been drawn through each group of data. An observed relation $I(R) \sim R^{-\nu}$ would result in a straight line

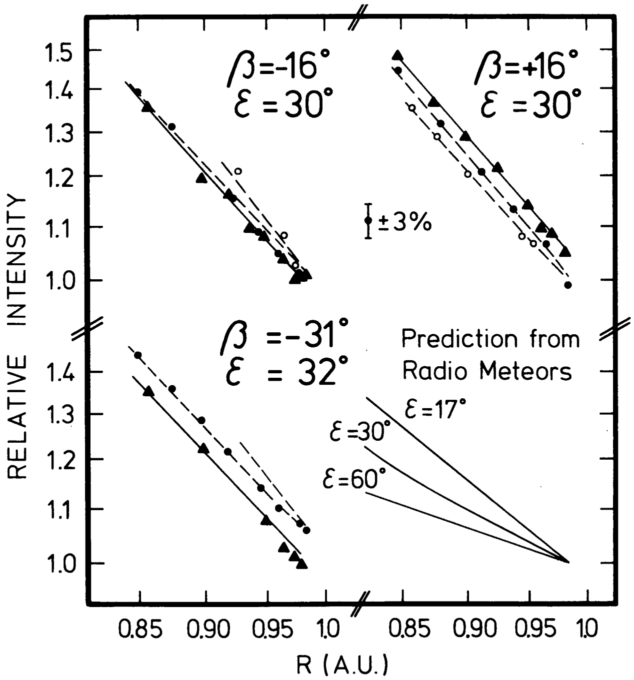

Fig. 4. Comparison of model calculations with $\nu = 1.3$ for first (—) and second aphelion (– –) with data from Helios 1 and 2. Symbols for data are the same as in Figure 3. A change in ν by ± 0.2 would change the predicted brightness increase from 0.98 to 0.85 AU by $\pm 3\%$. In addition brightness gradients are given that would result if the spatial distribution of particles causing the zodiacal light was the same as for radio meteors

4. Discussion

The Helios brightness measurements directly indicate only that the product of spatial density times average scattering function or the volume scattering, varies as $r^{-1.3}$. We must use other evidence to decide whether the spatial concentration or the scattering function is responsible for the variation.

The average scattering properties of the dust could, in principle, vary with heliocentric distance because of changing mean particle size or changing optical properties. A variation in either size or optical properties generally leads to a change in the angular scattering characteristics of small particles. As illustrated in Figures 1 and 2, no change in the relative brightness distribution is observed. Indeed, we have observed no change in the shape of the brightness distribution inward to spacecraft perihelion at 0.3 AU (Leinert et al., 1977). Furthermore, no wavelength-dependent changes were observed; Helios measured a constant color between aphelion and perihelion. The telescope line of sight at perihelion passes to 0.09 AU. Therefore, the albedo would have to increase by a factor of 20 from 1 to 0.1 AU to explain the observed brightness increase. It seems difficult to imagine a uniform, 20-fold increase in particle scattering efficiency, independent of both scattering angle and wavelength. From the optical evidence, then, we conclude that the variation with heliocentric distance very probably is a variation in the spatial density of the dust. Since the relative brightness distribution at $\varepsilon = 90$–$160°$, where the line-of sight contribution comes from distances >1 AU, also did not change with sun-spacecraft distance, it is likely that $n(r) \sim r^{-1.3}$ extends beyond 1 AU. This is consistent with the zodiacal light observations from Pioneer 10 (Hanner et al., 1976), where $\nu \approx 1.5$ fits data from 1 to 3 AU.

We now ask what other evidence exists, concerning the spatial distribution of the dust. The Helios 1 and 2 spacecraft also carried a meteoroid impact ionization detector (Grün et al., 1976). As mentioned above the overall increase in impact rate between aphelion and perihelion, measured for particles $\geqq 10^{-12}$ g, is consistent with $n(r) \sim r^{-1.3}$. Since the instrument sensitivity changes with relative spacecraft-particle velocity, the final, corrected dust density variation has not yet been evaluated.

The impact ionization detector on Pioneer 9 surveyed the region between 0.75 and 0.99 AU, recording 256 events in 928 days of operation. Rhee et al. (1974) concluded from these data and an identical experiment on Pioneer 8 (0.97–1.09 AU) that the spatial density of particles $\geqq 10^{-13}$ g is independent of heliocentric distance between 0.75 and 1.09 AU. Zook (1975) pointed out that these data can be fit at least equal well by a spatial distribution having a minimum near 1 AU. The Pioneer 9 data would be consistent with a spatial density $n(r) \sim r^{-1.3}$, the Pioneer 8 data not, because they show an increase by about a factor of two between 0.95 and 1.09 AU. Although the submicron particles detected by Pioneer 8 and 9 probably give negligible contribution to the zodiacal light (Giese and Grün, 1976), their spatial distribution is related to the distribution of larger meteoroids on the assumption that they are mainly produced by collisions of the latter. Zook (1978) concludes there should be an enhancement of the parent meteoroids of roughly a factor of two between 1.0 and 1.1 AU. Schmidt (1967) also found, from trajectory calculations, that micronsized particles could accumulate just outside the orbit of the Earth. Such a distortion in the spatial distribution would show in the Helios data.

Specifically we calculated the effect of a dust ring, superimposed on a $n(r) \sim r^{-1.3}$ spatial distribution between 0.94 and 1.20 AU, with the density in the ring linearly increasing to a maximum at 1.09 AU, which was taken twice the value at 0.94 AU. Then the observed brightness increase from 0.98 to 0.85 AU should be less by 20% at $\varepsilon = 90°$ when compared to the increase at $\varepsilon = 17°$ or 30°. We feel that we would see a difference of 5% in our data and therefore we place an upper limit to such an additional dust concentration which is one fourth of the above model.

The model proposed by Rhee (1976), for the radial distribution of zodiacal dust, with an extended flat shelf near 1 AU is not compatible with our observations.

From the dust flux measured with the Pioneer 10 and 11 micrometeoroid penetration detector outward from 1 AU Humes et al. (1974) derived either a very gradually or a quite strongly decreasing spatial density from 1 to 1.7 AU, depending on the assumed particle orbits and therefore impact velocities. The steeper decrease obtained for nearly circular particle orbits agrees approximately with the spatial distribution found from the zodiacal light experiment on Pioneer 10. However, there seems to be a real discrepancy between these two experiments beyond 2 AU, where the zodiacal light rapidly decreases below detectability, while the penetration experiment predicts a constant or increasing particle concentration.

Southworth and Sekanina (1973) derived the spatial distribution of meteoroids from an analysis of 12600 radio meteor orbits. They predicted a minimum in the spatial concentration near 0.7 AU and a maximum beyond 2.0 AU. The spatial concentration near 1 AU is therefore increasing outward. The mass range of their sample was approximately 10^{-2} to 10^{-5} g, concentrated in the 10^{-3} to 10^{-4} g range. We must consider, then, what fraction these particles contribute to the observed zodiacal light. The best information on the size distribution of the dust over range 10^{-1} to 10^{-12} g comes from microcrater counts on Lunar rock samples (Fechtig et al., 1974). Giese and Grün (1976) have shown that the size distribution derived from this Lunar flux curve is compatible with the observed zodiacal light brightness and that the main contribution comes from particles of radius approximately 30–100 μm, near the knee where the differential size distribution changes from a slope of -4.33 to -2.0. Meteoroids larger than 10^{-5} g contribute less than 10% of the total scattered light.

If the meteoroids in the range 30–100 μm followed the spatial distribution given by Southward and Sekanina (1973) the observed brightness gradient would be very different for different elongations. This is illustrated in Figure 4, where the plot refers to the distribution of radio meteors with $\sin i < 0.1$. The result for meteors with $i = 10$–$15°$ is nearly the same.

If radio meteors contribute only 10% to the total scattering cross section at 1 AU as estimated above, while 90% arises from particles distributed $\sim r^{-1.3}$, we still would expect that the intensity increase between 0.98 and 0.80 AU would be smaller by 7% for an elongation $\geqq 90°$ than for $\varepsilon = 17°$. This effect cannot be seen in the data of Figure 3. It also would lead to a zodiacal light brightness at 1.9 AU and $\varepsilon = 135°$ which is still 30% of the value at 1 AU. This is higher than the 20% found by Pioneer 10 (Hanner et al., 1976). Therefore, radio meteors with a spatial distribution according to Southworth and Sekanina probably contribute less than 10% to the zodiacal light.

5. Conclusion

We conclude that the brightness gradient observed with the zodiacal light experiment on Helios 1 and 2 between 0.85 and 0.98 AU can best be explained by a spatial distribution of the dust particles in the 10–100 μm range of $n(r) \sim r^{-1.3 \pm 0.2}$.

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