ZODIACAL LIGHT – A MEASURE OF THE INTERPLANETARY ENVIRONMENT

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(Received 13 March, 1975)

Abstract. This paper reviews research related to zodiacal light and tries to give the status for the end of 1974.

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Space Science Reviews **18** (1975) 281–339.

1. Introduction

The zodiacal light, which is sunlight scattered by the cloud of interplanetary particles, was one of the earliest sources of information on the interplanetary medium, systematic observations dating back to the seventeenth century (Cassini, 1683). Giving average optical properties of the interplanetary dust on a large scale, zodiacal light observations are a valuable complement to methods based on *in situ* observations of individual particles, like the analysis of meteors or micrometeoroid impacts. From zodiacal light observations it is, in principle, possible to derive the spatial distribution, size and composition of the scattering particles, as a basis for the discussion of more general questions such as the origin and dynamics of interplanetary dust. This goal has been approached slowly, both because of the difficulties of the measurement and the difficulties of interpretation. During the last years space observations have entered the field and provided stimulating results. The improved accuracy of ground observations and the possibility of comparison with the results of micrometeoroid experiments also add to the expectation of active progress in the field of interplanetary dust.

The origin of the zodiacal cloud is not a fundamental question in the history of the solar system, especially since a typical life time for interplanetary dust particles is of the order of 10^4 yr and therefore much too short to relate to the origin of the solar

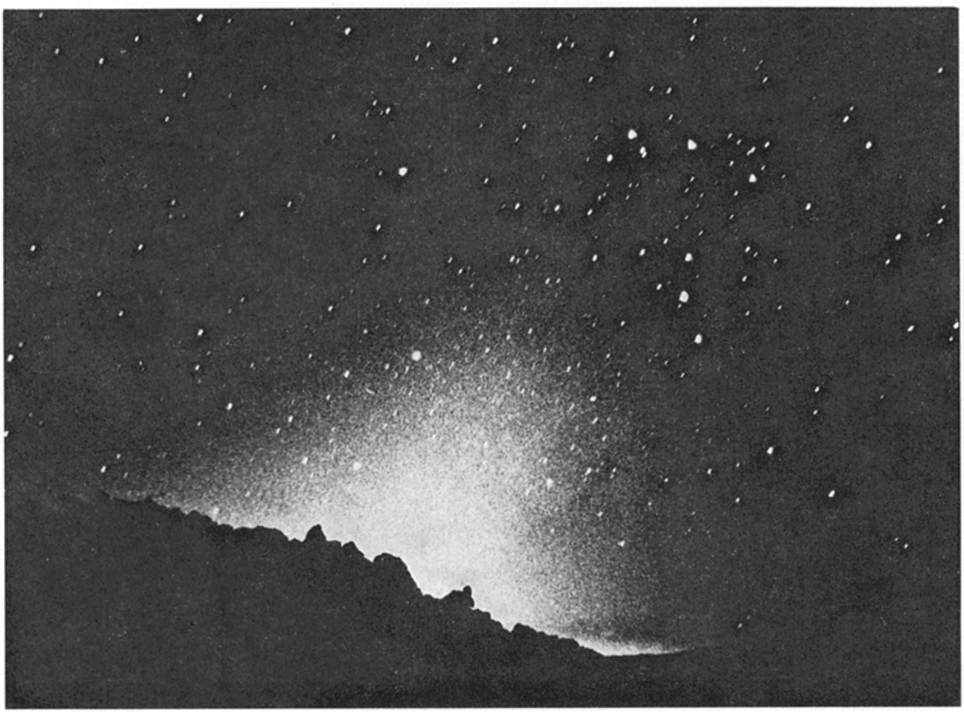


Fig. 1. Zodiacal light, seen from Mount Haleakala, Hawaii, Photograph by P. Hutchinson, January 1, 1967, 5^h45 HST.

system. However, the importance of cosmic dust in astrophysical processes like star formation or the synthesis of molecules makes it worthwile to understand in some detail the physics of the surrounding dust cloud.

From favorable sites the zodiacal light can be seen after sunset or before sunrise as a light cone extending with diminishing brightness from the horizon along the ecliptic (Figure 1). In the antisolar region a broad excess brightness is observed, called the Gegenschein. At angular distances from the Sun smaller than 20°, where the zodiacal light is unobservable in the bright twilight sky, it continues with increasing brightness and has been discovered as the F component (F showing the Fraunhofer lines) of the solar corona by Grotrian (1934). Outside the Earth's atmosphere the extension of the zodiacal light into the corona can readily be seen, as in Figure 2 which shows the inner zodiacal light above the lunar horizon. Pictures like this strongly suggest that the zodiacal light is an interplanetary phenomenon with limited, if any, contribution from the near Earth environment.

A comprehensive review of the zodiacal light and the solar corona has been given

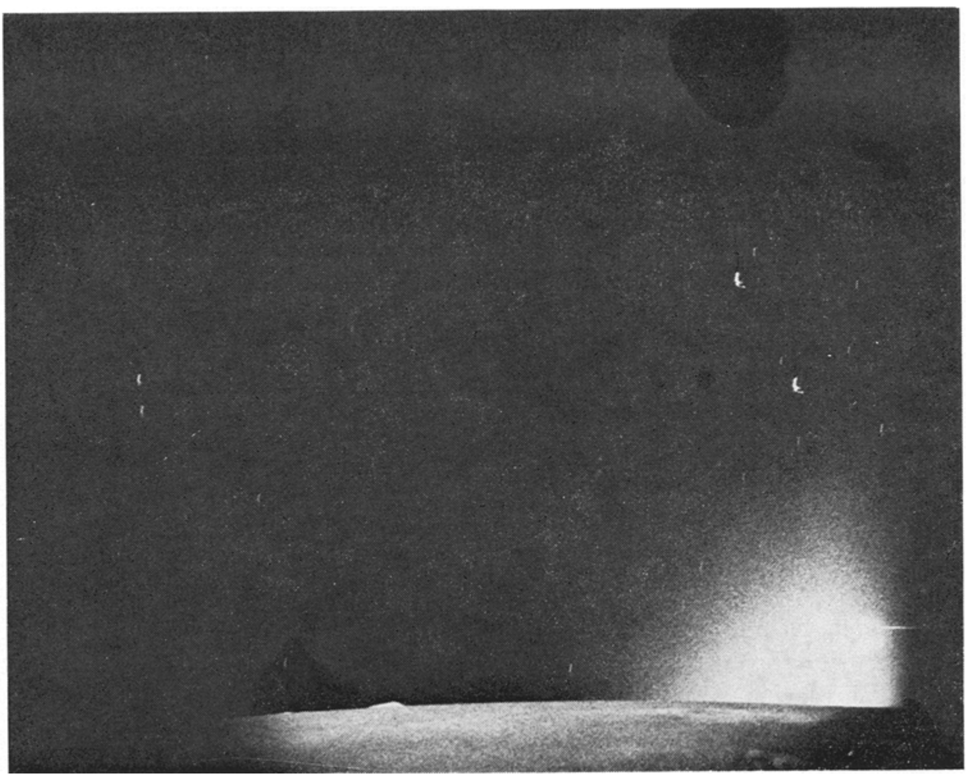


Fig. 2. Inner zodiacal light over the lunar horizon. The ecliptic is approximately vertical passing near Regulus and Mercury, the two bright objects in the upper part of the picture. The zodiacal light is seen from 5° to 20° elongation with a distortion of the symmetry by a coronal streamer extending 14° from the Sun, a rare event. NASA photograph AS 15-98-13 311 by Worden during the Apollo 15 flight.

by Blackwell *et al.* (1967b). Among the earlier reviews are Elsässer's (1963) clear account and Divari's (1965b) refreshing presentation of unorthodox views. Dohnanyi (1972) has critically discussed the different methods used in the study of interplanetary dust and meteors, including zodiacal light observations. The present paper puts the emphasis on the more recent zodiacal light measurements, including space observations (Section 3), and on methods (Section 4) and results of interpretation (Section 5). Part of the discussion is contained in the presentation of the observations (Section 3). The typical difficulties of zodiacal light observations are discussed in Section 2. It is not intended to present experimental techniques.

The zodiacal cloud may loosely be defined as the ensemble of those interplanetary particles which 'significantly' contribute to the zodiacal light. For practical purposes these are particles smaller than about 100 μm in diameter. The meteoritic complex (Whipple, 1967), in contrast, includes the larger particles up to the size of meteorites.

2. Zodiacal Light Photometry

2.1. Ground observations

In the visual spectral range the observed intensity of the light of the night sky is composed of about equal parts of starlight, zodiacal light and airglow and is altered by extinction and scattering in the lower atmospheric layers:

$$I_{\text{obs}} = (I_{ST} + I_{ZL} + I_{AG}) \cdot e^{-\tau} + I_{SCA}. \tag{1}$$

The symmetry of each component with respect to its plane of reference and the daily and annual motions of the respective coordinate systems, galactic, helioecliptic and horizontal, give some aid in disentangling this intricate mixture of different brightness components. The separation of these components constitutes the main difficulty of zodiacal light observations and may have been responsible for the large discrepancies reported in the past. In this section current techniques of separation are described.

2.2. Calibration and physical units

Besides calibration in physical units a number of historical measures of intensity are in use in low light level photometry: 1 Rayleigh/Å (R/Å)$=10^6/4\pi$ photon cm^{-2} s^{-1} ster^{-1} Å^{-1}; 1 S10$=$1 star of magnitude $m_v=10.00$ per square degree, usually using 'solar type' or 'A_0' stars; $B/\overline{B_\odot}$=intensity in units of the mean intensity of the solar disk. Among these pictorial units those relating the intensity of the zodiacal light to the illuminating solar radiation are most justifiable. Only this kind of normalization allows a direct comparison between narrowband and broad-band-measurements and between measurements taken at different wavelengths. In this paper zodiacal light intensities will be given in S10 units where 1 S10 is defined as 1.94×10^{-15} of the solar irradiance per square degree or 6.37×10^{-12} of the solar irradiance per ster. The transformation into other units for three common wavelengths is given in Table I which is based on the solar irradiance $H(\lambda)$ given by Labs and Neckel (1970) and a solar visual magnitude of -26.78 (Allen, 1963). Using different measurements of

TABLE I

Conversion factors for photometric units

λ, $\Delta\lambda$ (nm)	erg cm^{-2} s^{-1} ster^{-1} Å^{-1}	$B/\overline{B_{\odot}}$	R/Å
505±5	1.21×10^{-9}	4.33×10^{-16}	3.87×10^{-3}
530±10	1.20×10^{-9}	4.33×10^{-16}	4.04×10^{-3}
555±5	1.17×10^{-9}	4.33×10^{-16}	4.12×10^{-3}

The equivalent of 1 S10 is given in the table.

solar irradiance and visual magnitude 1 S10 'at' $\lambda=530$ nm was determined to be equivalent to 1.30 or 1.36×10^{-9} erg cm^{-2} s^{-1} ster^{-1} Å^{-1}, respectively (Weinberg, 1964; Robley, 1965). This variety of definitions has to be taken into account in the comparison of results. Of course it would be convenient if one single definition would be generally accepted. To reduce confusion S10 units other than those based on 'solar type' stars should not be used as a unit for zodiacal light intensities.

A typical accuracy for laboratory calibrations of low brightness sources in the visual range is ±5% to ±10%. Calibration by stars, according to Dumont and Sanchez-Martinez (1973), gives an accuracy of ±4%. Disadvantages of this method to be kept in mind are the slight deviations between the solar and a 'solar type' star spectrum and the additional error connected with transformation from the system of stellar magnitudes into physical units. The method of calibration by star crossings may be seriously in error if the response of an instrument depends on the position of the star in the field of view. A combination of laboratory calibration and star crossings should give the most reliable results, especially for space experiments which often are not recovered and not available for recalibration.

2.3. Integrated Starlight

Based on the Groningen star counts (van Rhijn, 1925) in Kapteyns Selected Areas, Roach and Megill (1961) have given tables of the integrated starlight which still are in general use. The quoted intensities are said to be correct to ±20% or about ±10 S10 for galactic latitudes $b>30°$.

The spectral distribution of the integrated starlight carefully computed by Sternberg and Ingham (1972) can be used to extrapolate from the original photographic system to the wavelength of a given observation. At lower galactic latitudes the diffuse galactic light, starlight scattered by the interstellar dust clouds, becomes important. In the average it adds about 30% to the direct starlight (Roach, 1967; Witt, 1968; Lillie, 1968; Peters, 1970), values of up to 120 S10 being reported in dense regions of the milky way (Witt, 1968; Roach *et al.*, 1972; Mattila, 1970a).

The correction for background starlight is still one of the main sources of error in the photometry of zodiacal light, although observations usually are confined to galactic latitudes $b>30°$. Considerable improvement can be obtained by using a narrow field of view which excludes stars brighter than a limiting magnitude. For $m_{\text{lim}}=12.5$ the star background is reduced by roughly a factor 3, with a corresponding accuracy of ± 3 S10 at $\lambda = 500$ nm (Dumont and Sanchez-Martinez, 1973). The use of this technique which requires a larger light collecting surface to compensate for the reduced field of view is not feasible if weight and size of the instrument are strongly limited as is typical for space experiments. There remains a need for better data of star background which give good accuracy also for moderately large field of views of some square degrees. Existing photometric maps (Elsässer and Haug, 1960; Smith *et al.*, 1970; Pfleiderer and Mayer, 1971) are only of limited advantage for the purposes of a zodiacal light photometry. They concentrate on the Milky Way region with only sparse and less reliable results outside. The first measurements of the star background in the absence of zodiacal light are now available from the Pioneer 10 and 11 space probes (Weinberg *et al.*, 1974) which went out past Jupiter where the intensity of zodiacal light is negligible (Hanner *et al.*, 1974).

A few attempts have been made to improve the star counting technique. Applying corrections to the catalogues used in the Groningen star counts, Sharov and Lipaeva (1973) found the integrated starlight reduced by a factor 1.5 compared to Roach and Megill. From the Palomar Sky Survey Tanabe and Mori (1971) found in two fields that the integrated starlight should be decreased by 10% while Sternberg and Ingham (1972) from more recent photographic photometries found an increase by 10%. The subject is still controversial. To illustrate its importance we note that Sparrow and Ney's (1972) experiment on satellite OSO-5 did not yield zodiacal light intensities at the ecliptic pole in the red wavelength band, because the integrated starlight was not known with sufficient accuracy.

2.4. Airglow

Most of the airglow radiation between 0.2 μm and 1.0 μm is emitted in a layer between 90 and 110 km (Greer and Best, 1967; Harrison, 1970). From spectra of the night sky (e.g. Broadfoot and Kendall, 1968) spectral regions avoiding the bright line and band emissions can be selected. Sternberg and Ingham (1972) give the spectrum of the remaining continuum or unresolved structure. The sometimes strong temporal and spatial variability of the airglow makes a correction difficult. Observations with bandpasses including the strong airglow emissions therefore are suspected to be unreliable. Often the approximation is made that the airglow intensity is independent of azimuth and distributed with zenith distance according to the van Rhijn function for a thin homogeneous emitting layer (see Chamberlain, 1961). Dumont (1963) gives an example that this assumption may lead to incorrect results especially if the airglow is varying with time.

A positive correlation between the airglow continuum at 500 nm and the intensity of the O I line emission at 557.7 nm was discovered by Barbier and Glaume (1960) and, although not yet confirmed by all observers, seems to be real. It is qualitatively supported by a recent discussion of photochemical reactions (Sternberg, 1972). On the basis of this correlation, shown in Figure 3, Dumont (1965) developed, independently of similar suggestions by Chuvayev (1961), the method of multiple heights which allows

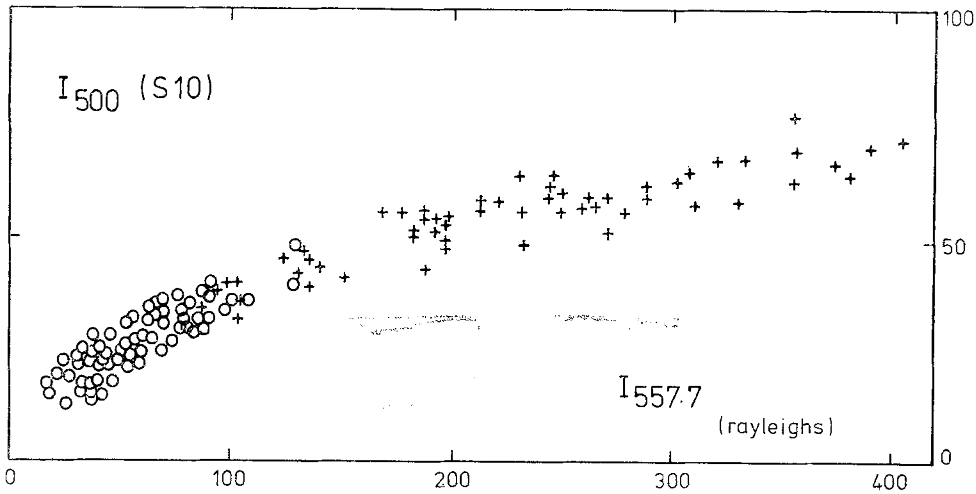


Fig. 3. Correlation between the O I airglow line at 557.7 nm and the airglow continuum at 500 nm as observed by Dumont (1965). Both intensities have been corrected to zenith and for scattering in the lower atmosphere.

subtraction of the airglow continuum individually for every viewing direction. The method as proposed by Dumont assumes the extraterrestrial light (zodiacal light plus starlight) to be constant over one night and requires two groups of measurements:

(1) Repeated recordings of continuum and line emission at the celestial pole. This will establish the trend of the correlation leaving the absolute level unknown.

(2) Recordings of continuum and line emission, following a fixed point on the celestial sphere over as much a range in zenith distance as possible. Combining these measurements with the first group both the intensity of the extraterrestrial light and the correlation between line and continuum emission can be determined.

Usually the correlation is linear and only measurements of the second group for several points on the celestial sphere are required (Sanchez, 1969).

The physical limitation to the accuracy of a single measurement is given by the scatter of the correlation which is about ± 5 S10 in the zenith intensity of the airglow continuum.

2.5. Scattering in the Atmosphere

An exact solution of Rayleigh scattering in a plane parallel atmosphere has been given by Chandrasekhar (1950). The tables of Ashburn (1954) present the numerical results for the special case when the atmosphere is illuminated by a homogeneous layer at a given altitude. Because of this assumption they describe the scattered airglow radiation with good accuracy but give only approximate values for strongly inhomogeneous light sources like the zodiacal light and the Milky Way. Additional shortcomings are the neglect of polarization, the neglect of the spherical symmetry of the atmosphere and the neglect of scattering by the aerosols. Typically the corrections for scattered light increase from ≈ 20 S10 in the zenith to ≈ 110 S10 at $z = 80$ (Weinberg, 1964). From these numbers the necessity of accurate knowledge of the scattered light for the photometry of zodiacal light is obvious. Numerical calculations have been performed under the assumption of single scattering. For the typically small optical thickness $\tau_{zenith} \leqslant 0.2$ correction factors to include the effect of multiple scattering are available. Compared to the calculations of Fesenkov (1963) or Wolstencroft and van Breda (1967) the work of Staude (1975) has the advantage of including the scattering by atmospheric aerosols using Mie theory and known size distributions and of presenting a large sample of constellations for Milky Way and zodiacal light, which should allow a safe interpolation for a given date and place of observation. He estimates that the total uncertainty of the scattered light correction is less than $\pm 10\%$. The high degree of polarization predicted by Divari (1968b) in similar calculations has generally been confirmed. A detail worth being noted is the scattering function of the aerosols which despite of the strong forward scattering distributes most of the scattered light over a comparatively broad cone of 30° half-angle.

The effect of twilight was considered by Divari (1966) and found to be important for solar depression angles less than 20°, affecting mostly observations at small elongations.

2.6. Observations of the F corona

The historical name F corona for the innermost part of the zodiacal light reminds us of the required different observational technique. From ground the F corona can be observed only during solar eclipses. The remaining sky brightness limits the observations to a few degrees from the Sun where the corrections for star background and airglow are negligible. More recent experiments were carried out from aircraft or balloon where the darker sky allowed observations out to 13° elongation (Blackwell, 1955; Gillett *et al.*, 1964). Intensity and polarization of the eclipse sky are determined at large distance from the Sun. The uncertainty of this correction determines the error in the outer F corona. Within 2° from the Sun the light scattered by the electrons of the solar corona is of comparable or greater intensity. The coronal temperatures of about 2×10^6 K cause very strong Doppler shifts making it effectively a continuum

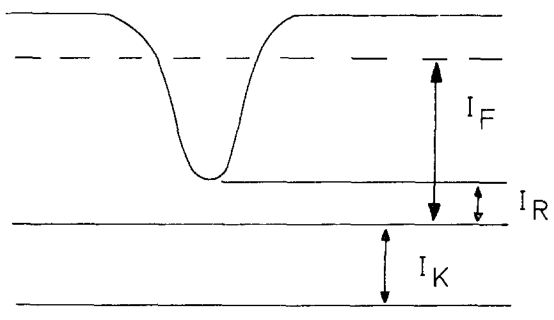


Fig. 4. Effect of an added continuum intensity I_K on the line depth $d_F = (I_F - I_R)/I_F$ of the F corona. I_F is the average intensity of the F corona in the spectral interval containing the line, I_R the residual intensity in the center of the line.

radiation. The intensity of this added continuum I_K can be determined by measuring relative line depths d in the coronal spectrum (see Figure 4) and comparison with the solar values d_F which are expected to hold for the F corona:

$$d/d_F = \frac{I_F - I_R}{I_K + I_F} \bigg/ \frac{I_F - I_R}{I_F} = \frac{I_F}{I_K + I_F}. \tag{2}$$

This method has been used by Blackwell and Petford (1966a, b) to derive intensity and polarization of the F corona. Other authors have assumed the polarization of the F corona to be zero, which is a good approximation in the inner corona, and calculated I_K from models of the solar corona which were fitted to the observed values of $I_K + I_F$ (e.g. Ney *et al.*, 1961).

Usually coronal observations require careful stray light suppression, the source of unwanted light being either the Sun or – during eclipses – the bright inner part of the corona.

2.7. Space Observations

The possibility to avoid extinction and scattering in the atmosphere (with balloon flights) and even the airglow radiation (with rockets and satellites) makes space observations attractive also for observations of the visible zodiacal light. However some difficulties of the reduction process remain or are enhanced and new problems may occur. The uncertainties of the actual attitude of the instrument which are typical for space experiments may be a disadvantage in the measurement of intensity gradients, in polarization measurements or the subtraction of starlight. The calibration and performance of the instrument are more difficult to check. On many of the satellites and on all space probes the measurements have to be performed in the presence of the Sun. Since the ratio of zodiacal light to solar intensity is typically 10^{-14}, stray light is one of the most annoying problems for zodiacal light photometry in space (Wolff, 1966; Rouy *et al.*, 1971; Sandford *et al.*, 1973), and requires much care to be handled satisfactorily (Leinert *et al.*, 1974). A detailed discussion of stray light suppresion has been given in a previous paper (Leinert and Klüppelberg, 1974). The enhanced corpuscular radiation, especially in the south atlantic anomaly, increases the noise in photometric experiments. Nevertheless space observations should finally give an accuracy superior to ground observations.

3. Results

The coordinates used in the description of the results are elongation ε and inclination i, alternatively also helioecliptical longitude $\lambda - \lambda_\odot$ and ecliptical latitude β (see Figure 5).

3.1. Brightness

Starting with the thorough observations of Weinberg (1964) and Dumont (1965) there has been a growing consistency between the results of different observers. At the same

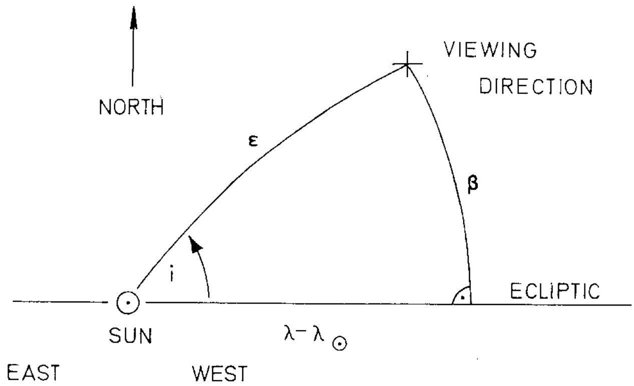


Fig. 5. Coordinates used in zodiacal light photometry.

time more effort is spent in determining the errors inherent in the measurements (especially Dumont and Sanchez-Martinez, 1973). The intensity of the zodiacal light along the ecliptic according to photometric measurements including space experiments performed after 1960, is shown in Figure 6. The figure has been broken into a classical zodiacal light and an inner zodiacal light or coronal part because of the wide variation in intensity. It shows the well known increase of the intensity at small elongations which is proportional to $\varepsilon^{-2.2\pm0.2}$ between $\varepsilon=1°$ and $\varepsilon=45°$. At larger elongations there is a minimum near $\varepsilon=130°$ and the characteristic excess brightness of the Gegenschein which will have to be discussed later. The agreement between different observers is reasonable, especially in the shape of the brightness curve. The values of Weinberg (1964) and Smith *et al.*, (1965) have been increased by 8% to conform with Table I, and they belong to a group of ground observations which are higher than the others, the difference being larger than the quoted error bars. A few photometries were not included in Figure 6, the reason being possible airglow contamination (Tanabe and Huruhata, 1967), stray light contamination (Sandford *et al.*, 1973), an unusual transformation from S10 to physical units (Robley, 1962) or high values at large elongations (Wolstencroft and Rose, 1967). The inclusion of earlier investigation seemed to be of no advantage, because the observational techniques and reduction procedures generally were not so well developed then. For special questions they still contain valuable information. Judged from Figure 6b the zodiacal light is a rather stable phenomenon. Therefore it seems worthwile to understand and possibly reduce the remaining inconsistency between the results of Weinberg and Dumont, who both gathered a large amount of data over a long time period. A sample of joint parallel observations might be a practical way to do it.

Perhaps as a consequence of the most interesting variety of processes in the true solar corona little attention has been paid to the innermost zodiacal light during the last years. No new separation of coronal intensities into K- and F corona has come to my attention. Therefore I have nothing to add to the discussion and the model of Blackwell *et al.* (1967b) which is based on measurements by different observers during

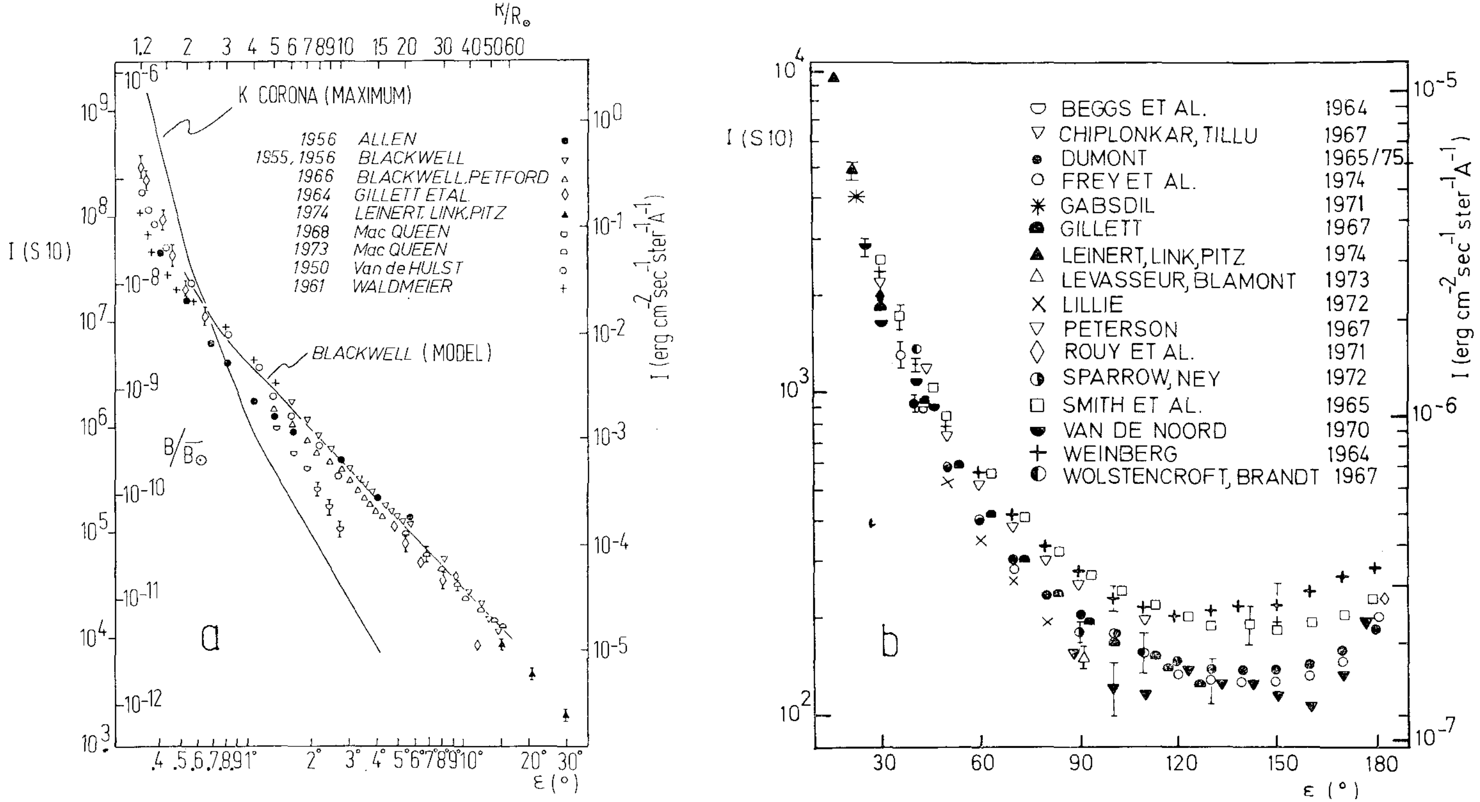


Fig. 6. *Intensity of the zodiacal light in the ecliptic. For* $\varepsilon > 5°$ *the contribution from the K corona is small and has not been separated from the total intensity. Where indicated by the authors and compatible with the readability of the diagram error bars have been included. Results given in S10 (B) units have been converted to the S10 scale by multiplication with 1.77, corresponding to a solar colour index* $B-V=0.62$*, except for Sparrow and Ney (1972), who use a factor of 1.54 for their instrument. The energy scale is valid for* $\lambda=530$ *nm. More information about the experiments (effective wavelength, time and location) is given in Appendix A.*

eclipses between 1954 and 1963. Considering the difficulty of separation from the K corona the agreement between different observers in Figure 6a is satisfactory and again an argument for the stability of the zodiacal light phenomenon. The transition to the classical zodiacal light is smooth within the given limits of accuracy. The steep increase in intensity for $\varepsilon<0.7°$ has been explained by Van de Hulst (1947) as an effect of the finite size of the solar disc.

Out of ecliptic observations are most detailed on the circles $\varepsilon=15°, 21°, 30°$ and 90°. The latter is well observed because it includes the ecliptic pole. For this point most of the results obtained by recent experiments (Table II) group around a value

TABLE II

Zodiacal light at the north ecliptic pole

Author	I(S10)	I_p(S10)	P (%)	λ_{eff}(nm) or system	Location
Smith, Roach and Owen (1965)	110	–	–	530	Ground
Dumont and Sanchez-Martinez (1966)	65±17	9.8±2.6	15±3	460, 502	Ground
Wolstencroft and Rose (1967) [a]	123	22.8	18.5±1	703	Rocket
Gillett (1967) [c]	50±12	10.5±3	23±5	V(?)	Satellite
	–	10.2±1	–	B	Balloon
Chiplonkar and Tillu (1967) [b]	79	–	–	530	Ground
Ingham and Jameson (1968)	–	10.7	–	510	Aircraft
Sparrow and Ney (1968)	50±20	10.5±1	21±8	V	Satellite
Lillie (1968) [c]	53	–	–	410 broadband	Rocket
Jameson (1970)	–	12±3	–	510	Ground
Lillie (1972) [c]	53	–	–	425	Satellite
Roach (1972) [d]	79	–	–	530	Ground
Sparrow and Ney (1972) [e]	54±10	10.9±1	20±4	$\approx B$	Satellite
Levasseur and Blamont (1973)	57±5	–	–	653	Satellite
Frey *et al.* (1974)	60±16	–	–	350, 500, 710, 820	Balloon

[a] Conversion to S10 by authors, observed also in B.
[b] Observed also at 440 nm, 600 nm.
[c] Multiplied by factor 1.77 to convert to S10.
[d] Extrapolation from measurements by Roach and Rees (1956).
[e] Authors multiply by 1.54 to convert to S10 although $\lambda_{eff}=418$ nm.

of 60 S10. Definitely there is a considerable amount of zodiacal light at the ecliptic pole. As many data originally were presented in units of S10 (blue) the factors for conversion to S10 units have to be known accurately in order to avoid confusion or errors. The results are sensitive to the correction for starlight which is about 40% of the total signal in this viewing direction. The additional correction for the diffuse galactic light as applied by Lillie (1972) is of the order of 10 S10. The results of Smith *et al.*, (1965) and especially those of Wolstencroft and Rose (1967) are difficult to reconcile with the others and probably not correct.

The concentration of zodiacal light brightness to the ecliptic is almost the same for $\varepsilon = 15°$ to $\varepsilon = 90°$ (see Figure 7), $I(\varepsilon, 0)/I(\varepsilon, 90°) \approx 3.2$, and gradually decreases to 1 at

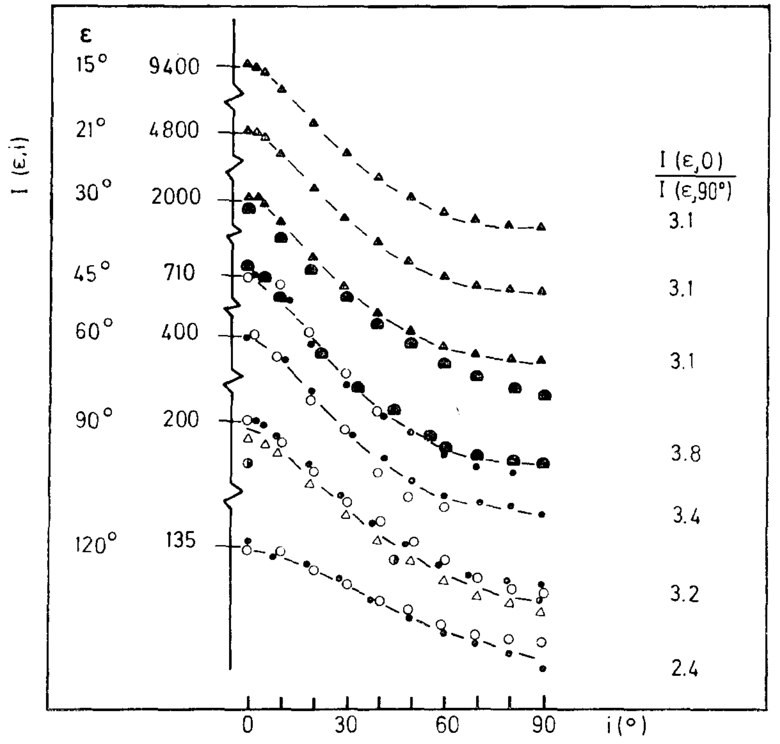


Fig. 7. Zodiacal light intensity outside the ecliptic on circles of constant elongation. Left of the intensity scale, which has been broken to allow equidistant plotting, the intensity $I(\varepsilon, 0)$ in the ecliptic in S10 is given. For $i = 45°$, 60° and 120° most of the values have been determined from isophote maps. Explanation of symbols: ● Dumont (1965), Dumont-Sanchez-Martinez (1973), ○ Frey *et al.* (1974), ◓ Gillett (1967), ▲ Leinert *et al.* (1974), ◑ Levasseur and Blamont (1973), △ Sparrow and Ney (1972).

larger and smaller elongations. This ratio and the shape of the brightness decrease are important for studies of the distribution of interplanetary dust perpendicular to the ecliptic. The ratio is also shown in Table III which summarizes intensity and polarization of the zodiacal light measured in the ecliptic and perpendicular to it. The minimum of zodiacal light intensity is found 20° from the pole of the ecliptic towards the Gegenschein.

Almost full coverage of the zodiacal light has been achieved by Dumont (1965), Frey *et al.* (1974) and Smith *et al.*, (1965). The results are presented in isophote maps. The latter authors also give a tabulation of absolute zodiacal light intensity with 5°

TABLE III

Intensity and polarization of the zodiacal light [a]

ε(°)	$I(\varepsilon, 0)$ [b]	$I_p(\varepsilon, 0)$	$p(\varepsilon, 0)$	$I(\varepsilon, 90°)$	$I_p(\varepsilon, 90°)$ [c]	$p(\varepsilon, 90°)$ [c]	$\frac{I(\varepsilon, 0)}{I(\varepsilon, 90°)}$
1	4.1×10^6		0.000	2.9×10^6		0.000	1.4
2	9.0×10^5	630	0.001	4.5×10^5	300	0.001	2.0
5	1.3×10^5	1560	0.012	5.2×10^4	500	0.01	2.5
10	2.5×10^4	1750	0.070	8900	500	0.06	2.8
15	9600	1310	0.137	3100	245	0.08	3.1
20	4990	760	0.152	1610	150	0.09	3.1
30	1940	320	0.165	630	70	0.11	3.1
40	920	166	0.180	290	43	0.15	3.2
50	570	108	0.190	160	30	0.19	3.6
60	394	77.6	0.197	115	23	0.20	3.4
70	296	58.3	0.197	93	19	0.20	3.2
80	239	44.5	0.186	76	15	0.20	3.1
90	202	33.3	0.165	65	12	0.19	3.1
100	174	25.1	0.144	58	10	0.17	3.0
110	154	18.5	0.120	55	8	0.15	2.8
120	142	13.5	0.095	58	7	0.12	2.4
130	137	10.5	0.077	70	6	0.09	2.0
140	136	7.9	0.058	80	5	0.06	1.5
150	137	3.7	0.027	110	3	0.03	1.2
160	142	0.0	0.000	133	0	0.00	1.1
170	158	−3.2	−0.020	154	−3	−0.02	1.0
180	180	0.0	0.000	180	0	0.00	1.0

[a] Summarized from Figures 6, 7, 10, 11.

[b] $I(\varepsilon, i)$ and $I_p(\varepsilon, i)$ in S10 units.

[c] Based on Dumont and Sanchez-Martinez (1966), Jameson (1970), Leinert *et al.* (1974), reduced accuracy.

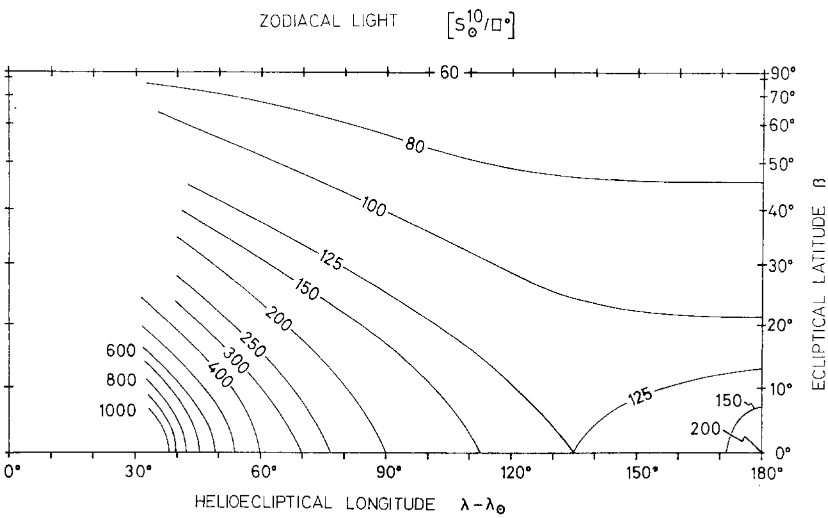


Fig. 8. Isophote map of the zodiacal light according to Frey *et al.* (1974) Intensities are given in S10.

steps in $\lambda - \lambda_{\odot}$ and β, which has been widely used. The first revision of this model (Roach, 1972) reduces the differences with the other isophote maps and makes it more similar to Table III. Still his minimum is at the pole of the ecliptic and comparatively high and the ratio $I(\varepsilon, 0)/I(\varepsilon, 90°)$ is less than 2 for $\varepsilon < 20°$, which makes his value I (15°, 90°) twice as large as the value given in Table III. With results of long term space observations (Pioneer 10 and 11, Helios A and B) and extended ground observations (Weinberg) to be expected during the next years a model giving more detail than Table III seemed not justified at present. Instead in Figure 8 an isophote map of the zodiacal light is shown (Frey *et al.*, 1974)

3.2. Gegenschein

This excess brightness of about 40 S10 centered on or near the antisolar point, has been explained by many theories, including a gas tail or dust tail of the Earth, cometary debris in the libration points of the Earth-Moon system and scattering by the cloud of interplanetary particles. Of these only the interplanetary hypothesis is compatible with the observations and the Gegenschein is now generally accepted as part of the zodiacal light.

There is no question about its existence and its size of roughly 20° between points of half intensity. Points of discussion are the exact position, shape and the value of the photometrical quantities. A valuable annotated bibliography of the Gegenschein literature has been presented by Roosen (1970b). Many observers including Elsässer and Siedentopf (1957) and Tanabe (1965) reported a deviation of the point of maximum brightness from the antisolar point. Among the recent observations Dumont

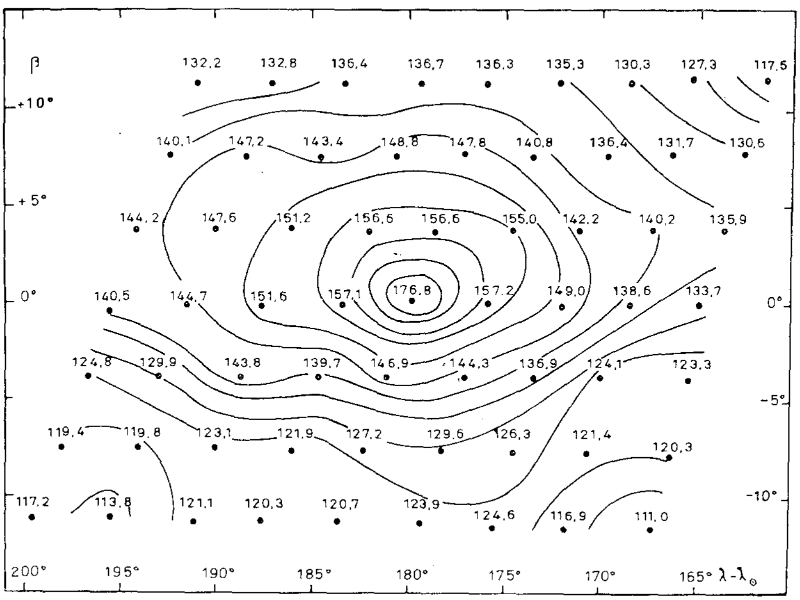


Fig. 9. Isophote map of the Gegenschein at 502 nm on February 9, 1964 according to Dumont (1965).

(1965) and Roosen (1970a) found that these two points coincide, while two rocket experiments (Lillie, 1968; Wolstencroft and Rose, 1967) found a deviation of approximately 3°, and the satellite experiment of Roach *et al.* (1973a) is in favour of a small deviation. If the coincidence with the antisolar point is true it probably is due to the backscatter peak of the scattering function and does not imply that the maximum concentration of interplanetary dust is in the orbital plane of the Earth. Note that for the observation shown in Figure 9 the maximum of brightness was not symmetrical with respect to the outer isophotes, an effect already discussed by Roach and Rees (1956).

The maximum intensity in the Gegenschein is about 200 S10. The individual measurements summarized in Table IV are compatible with the result of Tanabe (1965) that the Gegenschein is a comparatively stable phenomen. Roosen's (1970a) careful observations have shown that in the average there is no effect of the Earth's shadow

TABLE IV

Gegenschein observations

Author	I (S10)	Relative intensity decrease		λ_{eff} (nm) or system	Location
		In ecliptic (percent/deg.)	Out ecliptic (percent/deg.)		
Roach and Rees (1956)	218±40	1.4	1.7	530	Ground
Elsässer and Siedentopf (1957)	207±11	1.4	1.5	$\approx V$	Ground
	196±10 [a]	1.3	1.4	$\approx B$	
Weinberg (1964)	281±30 [b]	1.0	–	530	Ground
Robley (1965)	166	–	–	455	Ground
	190	(1) [c]	(1.5)	528	
	249	–	–	608	
Dumont (1965), Dumont-Sanchez-Martinez (1973)	180±18	1.3	1.8	502	Ground
Tanabe (1965)	156±18	(1) [c]	1.5	523 and 530	Ground
Smith *et al.* (1965)	223±29 [b]	1.0	1.0	530	Ground
Chiplonkar and Tillu (1967)	195	3.3	3.7	530 [d]	Ground
Lillie (1968)	182	0.6	1.6	410	Rocket
Roosen (1970a)	–	1.6	–	B	Ground
Rouy *et al.* (1971)	–	–	2.0 [e]	500	Satellite
Weinberg *et al.* (1973)	–	0.9	–	390–500 and 595–720	Satellite
Roach *et al.* (1973a)	–	–	1.9 [f]	500	Satellite
Frey *et al.* (1974)	165±20			350, 500	Balloon
	200±30	2.8	3.5	710, 820	

[a] Transformation to S10 units by multiplication with 1.69 according to color index given in reference.
[b] Value increased by 8% to conform to Table I.
[c] Values enclosed in parentheses were not well defined on the isophote charts.
[d] Observed also at 440 nm and 600 nm with reduced accuracy.
[e] Inclined ≈70° with respect to ecliptic.
[f] Inclined 48° with respect to ecliptic.

in the Gegenschein larger than 1%. This places the scattering material at a distance greater than 100 Earth radii.

The general shape of the Gegenschein is oval (see Figure 9) but difficult to define photometrically because of the influence of atmospheric and background light. Reports on day to day changes in shape and the occurance of complicated or elongated shapes (Lillie, 1968) may be due at least partly to these difficulties. The relative intensity gradients of $\approx 1\%\ \mathrm{deg}^{-1}$ and $\approx 2\%\ \mathrm{deg}^{-1}$ found in and perpendicular to the ecliptic, respectively, were also found by the experiment on the space probe Pioneer 10 (Weinberg *et al.*, 1973) which gave the final proof in favor of an interplanetary hypothesis by observing the Gegenschein far from the Earth.

3.3. Polarization

The measurements of zodiacal light polarization show a similar trend to consistency as discussed above for the intensity, but more discrepancies remain. The results of photometric measurements performed after 1960 have been plotted in Figures 10 and 11. Both the degree of polarization along the ecliptic and the polarized intensity are shown because both presentations have their justification.

The degree of polarization is defined as

$$p = \frac{I_1 - I_2}{I_1 + I_2}, \tag{3}$$

were I_1 and I_2 denote the component of intensity with the electric vector perpendicular and parallel to the plane of scattering. p is negative if the direction of polarization is

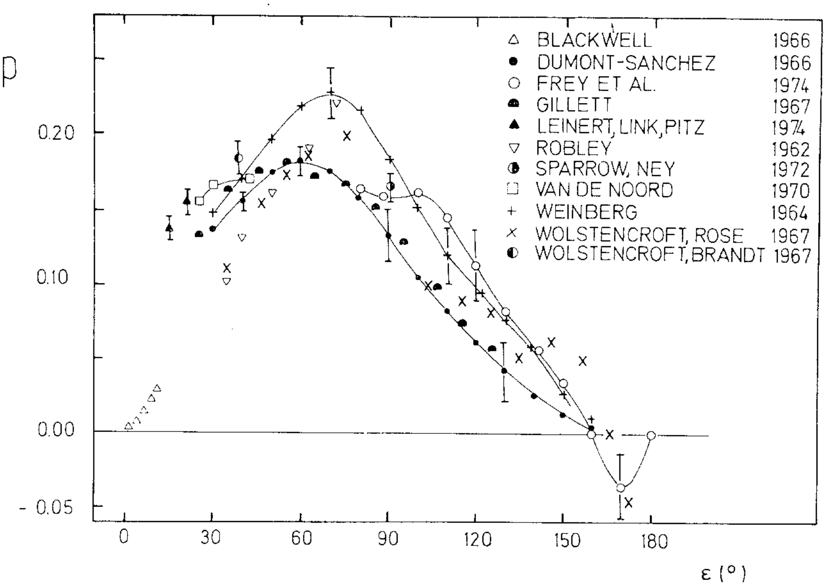


Fig. 10. Degree of polarization of the zodiacal light in the ecliptic. For $\varepsilon < 25°$ the effect of interplanetary plasma has been separated from the measurements. Error bars have been given where the information was available. More information about the experiments is given in Appendix A.

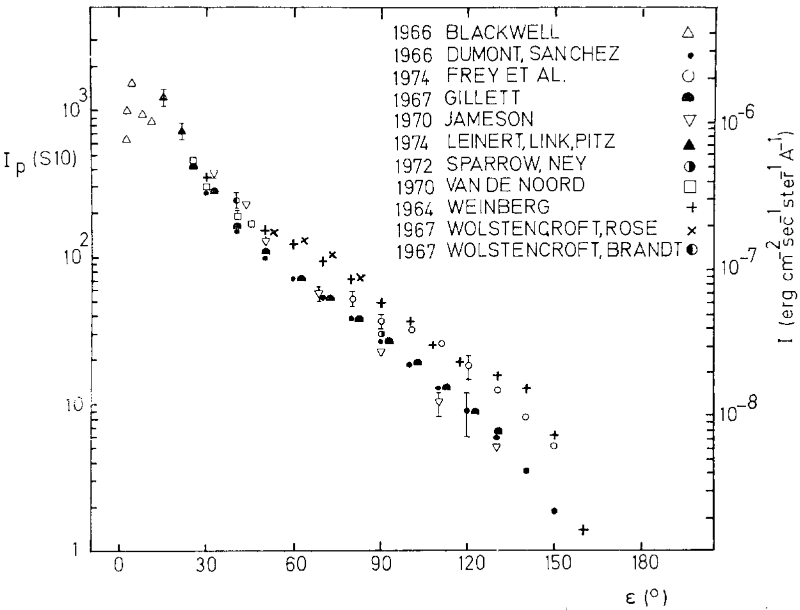


Fig. 11. Polarized intensity in the ecliptic. For $\varepsilon < 25°$ the effect of interplanetary plasma has been separated from the measurements. Error bars have been given where the information was available. Values given in S10 (B) have been converted to the S10 scale by multiplication with a factor 1.77, except for Sparrow and Ney who use a factor of 1.54 for their experiment. The energy scale is valid for $\lambda = 530$ nm. More information on the experiments is given in Appendix A.

in the plane of scattering. It is an easy imaginable quantity, generally independent of calibration errors, to a first approximation independent of the spatial distribution of interplanetary dust, and therefore mainly an indicator of the optical properties of the scattering particles. It has often been noted that p is sensitive to errors in the total intensity $I = I_1 + I_2$ resulting from the difficult corrections for background starlight, airglow or scattered light.

The polarized intensity

$$I_p = I_1 - I_2$$

on the other hand is independent of these corrections to the extent to which these sources of light are indeed unpolarized. A polarization of starlight has to be expected only in regions of the Milky Way with strong interstellar absorption and is typically less than 2% (Staude *et al.*, 1973). A polarization due to scattering in the lower atmosphere has been found in the O I airglow line at 557.7 nm (Weinberg and Mann, 1967) and is one more reason to exclude these lines from the bandpass of the instrument. The polarized intensity is the basic observable quantity and some observers have only given I_p. The expectation that the scatter in I_p is considerably smaller than in p is not fulfilled in the sample of observations shown in Figures 10 and 11. Therefore one should be cautious about interpretation of small changes in I_p. Since I_p is sensitive to calibration errors this could mean that calibration is one of the main sources of error in todays zodiacal light photometry.

The variation of the degree of polarization with elongation along the ecliptic is reasonably established. Except for the observations of Robley (1962) and Wolstencroft and Rose (1967) the scatter of the data points is more or less compatible with the quoted accuracy. There is a flat maximum of about 20% near $\varepsilon = 60°$ with a gradual decrease to smaller and larger elongations. A reversal of direction of polarization giving negative polarization between $\varepsilon = 160°$ and 180° has been reported by Weinberg (1964), Wolstencroft and Rose (1967) and Frey *et al.* (1974). Especially the latter observations give considerable confidence that this effect, which would imply the presence of dielectric interplanetary particles, is real. A shift of the point of zero polarization with increasing wavelength closer to the Sun has been found by Weinberg and Mann (1968) disagreeing with the results obtained at $\lambda = 710$ nm by Wolstencroft and Rose (1967) and has to be confirmed or contradicted by additional observations.

In the innermost zodiacal light (F corona) polarization measurements are difficult to perform and only the results of Blackwell and Petford (1966a) are available. A model extrapolation of these observations given in the same paper fits the zodiacal light observations at 30° but is in conflict with the high degree of polarization found by Leinert *et al.*, (1974) at $\varepsilon = 15°$ and $\varepsilon = 21°$. Pepin (1970) also observed a higher polarization in the outer corona than Blackwell (1955), but this difference could be due to a different plasma density during different eclipses. The contribution of the interplanetary plasma, which is very important in the corona, is negligible in the classical zodiacal light. Measuring the relative depth of Fraunhofer lines, as discussed in Section 2.6, Beggs *et al.* (1964b) have set an upper limit of 16 ± 20 electron cm^{-3} to the average plasma density at 1 AU. From satellite plasma experiments the average plasma density is now known to be about 6 electron cm^{-3}. From this and the radial distribution of the plasma the contribution of electron scattered light to the zodiacal light can be calculated. At $\varepsilon = 30°$ it is 8 S10 or 0.4% in I and 0.25% in p.

The polarized intensity shows a maximum between $\varepsilon = 5°$ and $\varepsilon = 10°$ which, however, has no direct physical significance. There is a considerable spread in the data, which cannot be explained on the basis of a typical accuracy of $\pm 10\%$ for the brighter regions of zodiacal light. Also the discrepancies are not an obvious function of the effective wavelengths of the experiments or the date of observation. The uncertainty of 50 S10 in the polarized intensity at $\varepsilon = 60°$ certainly needs clarification by future experiments.

Outside the ecliptic according to Dumont and Sanchez-Martinez (1966) the degree of polarization is nearly constant on circles of constant elongation. This gives the average picture, a decrease being observed at small elongations (Leinert *et al.*, 1974) and an increase with increasing inclination at $\varepsilon = 90°$ (Sparrow and Ney, 1972). A table of I_p has been given by Jameson (1970). Table III gives values of p and I_p in the ecliptic and on the great circle perpendicular to it ($i = 90°$). Introducing the degree of polarization (Equation 3) and the polarized intensity it was tacitly assumed that the direction of the linear polarization of the zodiacal light is either parallel or perpendicular to the plane of scattering. A significant deviation of the direction of polarization from these angles usually indicates the presence of contaminating light which has not been properly subtracted. This check on the validity of the polarization measurements contained in the angular information should not be missed. A real deviation of the direction of polarization could occur if the scattering particles were elongated and aligned. This interpretation has been given by Roach *et al.* (1974), Wolstencroft and Brandt (1974) and Bandermann and Wolstencroft (1974) to non radial directions of polarization they found in the antisolar hemisphere.

A small day-to-day change in the polarized intensity at large elongations was reported by Wolstencroft and Bandermann (1973). They argue that a large fraction of the interplanetary dust particles are elongated and that changes in alignment would explain the effect. More experimental evidence seems necessary before this far-reaching conclusion can be accepted.

Circular polarization in the zodiacal light also would be a proof for the existence of nonspherical aligned interplanetary particles (van de Hulst, 1957). Wolstencroft and Kemp (1972) found a small circular polarization of about 0.5% at $\varepsilon = 120°$. Staude and Schmidt (1972) interpreted a similar measurement as null result and pointed to the influence of atmospheric scattering on such measurements (Staude, 1975). The high values reported in the rocket experiment of Wolstencroft and Rose (1967) seem not to be upheld.

One of the best ways to determine optically the material of the particles causing the zodiacal light would be to observe the wavelength dependence of polarization. In contrast to this theoretical implication little observational material is available. The data of Figure 10, obtained by different observers, suggest that there is no strong change of polarization with wavelengths. Van de Noord (1970) found the polarization in the blue higher by 1% than in the visual which is within the errors of the measurement. The observations of Wolstencroft and Brandt (1967) also are in favour of a slow variation of polarization with wavelength. Although probably a small effect, the wavelength dependence of polarization should be taken into account in the comparison of different measurements. A recent survey of polarization measurements in the zodiacal light has been given by Weinberg (1974).

3.4. Line Spectrum

The appearence of the solar absorption line spectrum in the zodiacal light proves that it is sunlight scattered by slowly moving particles and has shown the presence of zodiacal light in the solar corona. Spectra with good resolution covering the blue part of the visible spectrum have been given by Grotrian (1934) for the F corona and by Blackwell and Ingham (1961a, b) for the zodiacal light. Analysis of the depths of spectral lines relative to the solar spectrum is the only empirical way to separate the zodiacal light from the continuum contributed by the scattering on the interplanetary electrons (see Sections 2.6 and 3.3). The motion of the scattering dust particles, apart from a slight broadening of the lines, leads to a Doppler shift of about 0.3 Å (see Figure 12), an effect which has been predicted by Ingham (1963) and detected by

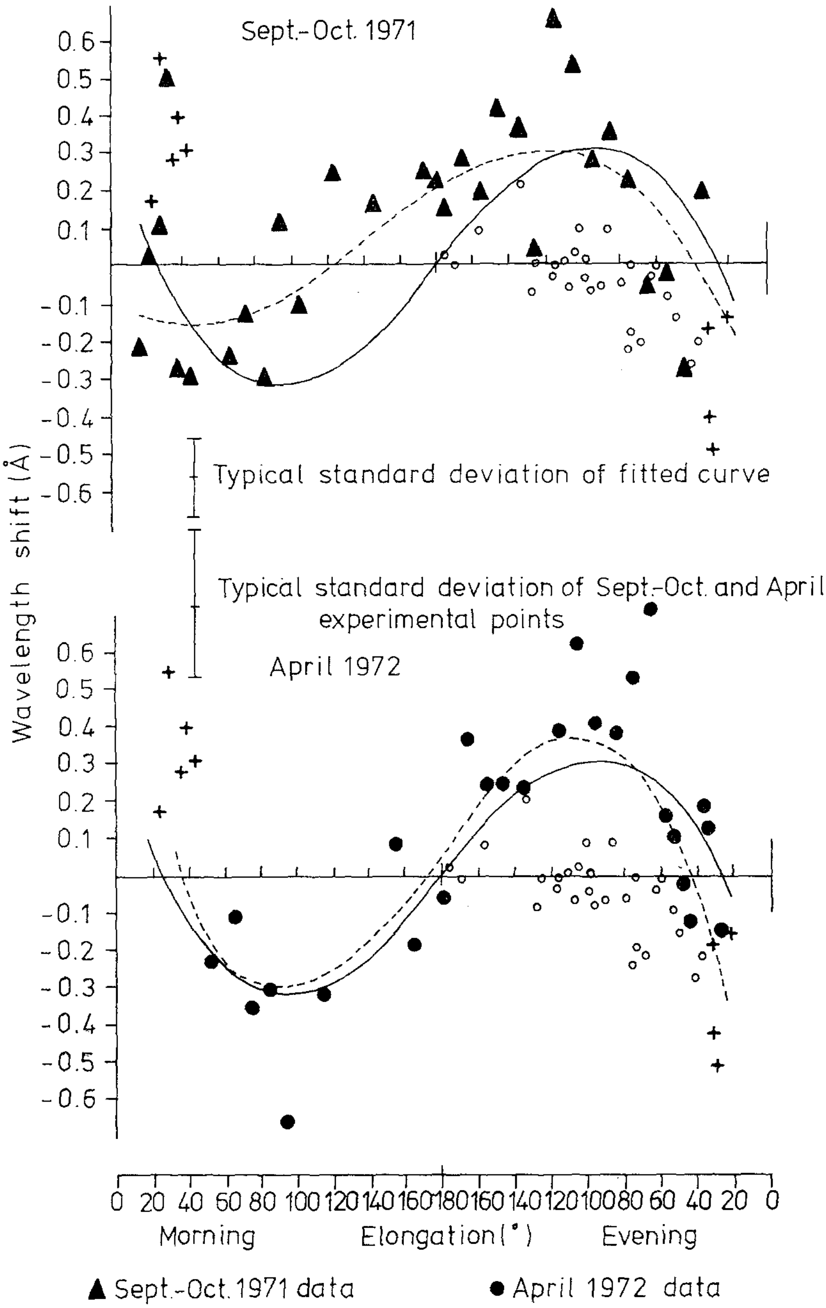


Fig. 12. Doppler shift in the zodiacal light observed by Hicks *et al.* (1974). Included are earlier data by Reay and Ring 1968 (○) and James and Smeethe 1970 (+).

Ring *et al.* (1964) in the Hβ-line using a pressure scanned Fabry Perot interferometer. Subsequently more detailed experimental evidence has been gathered (Reay and Ring, 1968; James and Smeethe, 1970; Hicks *et al.*, 1974). Unfortunately this is a very difficult measurement associated with large errors and the latest data, taken on the 518.3 nm Magnesium line are in agreement with earlier measurements for low elongations but disagree for $\varepsilon > 40°$ and show discrepancies between observations in spring and autumn (Figure 12). However, the conclusion based on the earlier data, that at least 95% of the scattering particles are in prograde orbits (James and Smeethe, 1970) should remain valid, both for circular or elliptic orbits (Bandermann and Wolstencroft, 1969). 'Best fits' to the data with the particle size distribution as parameter have so far given contradicting results and should be treated with caution. The Doppler shift measurements are an important independent test for models of interplanetary dust derived from other evidence. Of course, line profiles if experimentally obtainable in the zodiacal light would contain valuable information on motion and number density of the interplanetary particles along the line of sight.

3.5. Colour

The often repeated statement that the colour of the zodiacal light is 'close' to the solar colour is still valid, at least for the visible spectral region. This conclusion has considerable impact on the possible size distributions of interplanetary particles if the agreement of the colours is sufficiently close. In this paper colour is defined as the ratio of the intensities in two wavelengths bands. A colour ratio relative to the Sun is defined ($\lambda_1 < \lambda_2$)

$$C(\lambda_1, \lambda_2) = \frac{I_{ZL}(\lambda_1)/I_\odot(\lambda_1)}{I_{ZL}(\lambda_2)/I_\odot(\lambda_2)} \tag{4}$$

which is related to the colour indices (CI) by

$$CI_{ZL} - CI_\odot = -2.5 \log C(\lambda_1, \lambda_2).$$

This normalization gives reasonable independence of the choice of the wavelength bands and is suitable for theoretical applications. There is no advantage to discuss the earlier broad-band measurements of colour. Most of them included the 577.7 nm O I line in the visual band and their accuracies are difficult to assess. After 1960 when it became standard to use interference filters to exclude the brightest airglow lines, Robley (1962) found the zodiacal light slightly bluer, Wolstencroft and Brandt (1967) slightly redder than the Sun. Dumont and Sanchez-Martinez (1973) found no wavelength dependence and Peterson's (1967a) 12 colour photometry at elongations $30° < \varepsilon < 110°$ gave the colour of the zodiacal light equal to the solar colour within the probable error, ± 0.02 in $B-V$.

Space experiments have continued to measure the colour of the zodiacal light in the visible spectral region and have extented the range in wavelength and elongation. The results should be less subject to systematic errors than the ground measurements but so far have larger standard deviations. Figure 13 shows the colour ratio of zodiacal

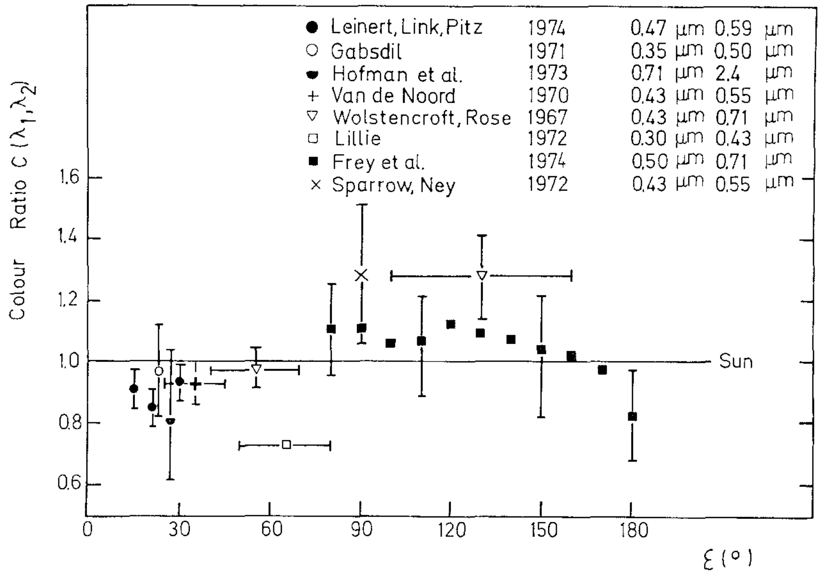


Fig. 13. Colour of the zodiacal light in the ecliptic. The wavelengths λ_1 and λ_2 used in the determination of the colour ratio are given after the name of the author.

light observed by recent space experiments as a function of elongation. Having confidence in the four colour photometry of Frey *et al.* (1974) there is no deviation from solar colour for $\varepsilon > 45°$ within the uncertainty of about $\pm 15\%$ to $\pm 20\%$. At smaller elongations a reddening of the zodiacal light is indicated, mainly by Leinert *et al.* (1974). A tendency to reddening has also been reported for the zodiacal light in the corona. The measurements are presented in Table V in form of the ratio defined by Blackwell (1952),

$$R = \frac{I(\lambda_2, \varepsilon_2)/I(\lambda_1, \varepsilon_2)}{I(\lambda_2, \varepsilon_1)/I(\lambda_1, \varepsilon_1)},$$

where λ_1, λ_2 are the wavelengths and ε_1, ε_2 the angular distances from the center of the solar disc. The definition differs from the colour ratio given above in that the

TABLE V

Reddening of the corona

Author	$\lambda_1 (\mu m)$	$\lambda_2 (\mu m)$	$\varepsilon_1 (R_\odot)$	$\varepsilon_2 (R_\odot)$	R
Blackwell (1952)	0.43	$1.9^{+0.6}_{-0.9}$	1.5	2.5	2.17
Allen (1956)	0.4	0.6	1.5	4.0	1.04
Ney *et al.* (1961)	0.475	0.83	1.2	2.1	1.08 (equator)
					1.13 (pole)
Gillett *et al.* (1964)	0.475	0.83	1.2	2.1	1.0 (equator)
					1.2 (pole)

normalization is not made to the Sun itself but to a point in the inner corona ($\varepsilon_1 \approx \approx 1.5\ R_{\odot}$) where electron scattering is dominant and the solar colour is expected. Blackwell's measurement shows a large deviation from the solar colour which will be discussed in the next Section.

A broadband spectrum of the zodiacal light composed from results of recent space experiments is shown in Figure 14. In the visible and near infrared it follows the

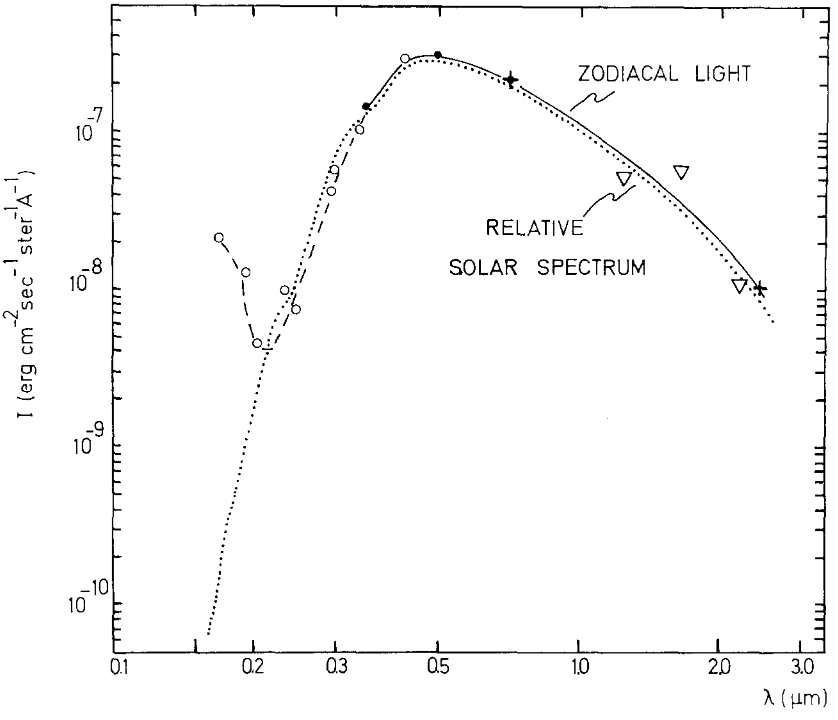


Fig. 14. Spectrum of the zodiacal light. Observations by Frey *et al.* (1974) (●), Hofmann *et al.* (1973) (+), Nishimura (1973) (▽) and Lillie (1972) (○) are shown. The ordinate is valid for $\varepsilon = 80°$ (Frey *et al.*, 1974), the other observations have been fitted to agree in the region of overlap.

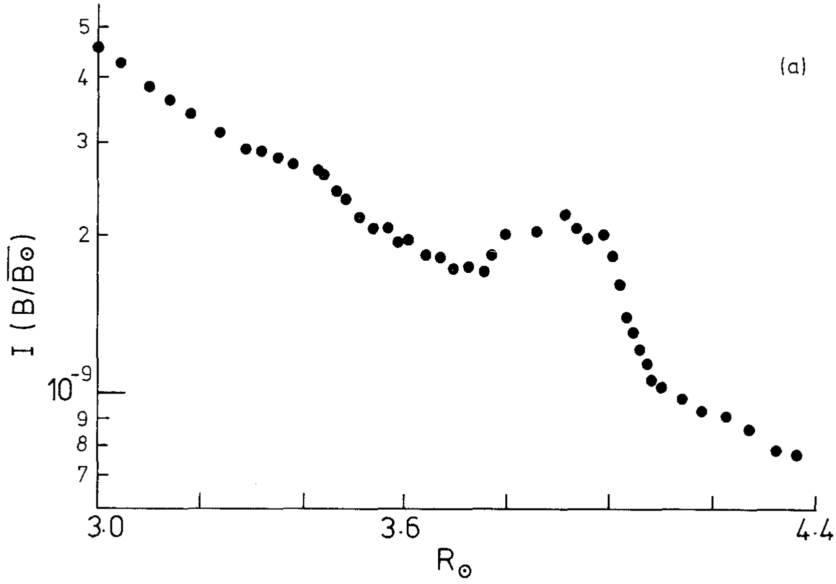
solar spectrum within the limits of accuracy (Frey *et al.*, 1974; Hofmann *et al.*, 1973; Nishimura, 1973). In the ultraviolet there is a sharp upturn below 250 nm according to Lillie (1972), who suggested the presence of a halo of small graphite particles ($\alpha \approx 20$ nm) as a second component of the zodiacal cloud and a relation to the shape of the interstellar extinction curve in explanation of his results. On the other hand Kurt and Sunyaev (1967) gave an upper limit for the zodiacal light intensity at 130 nm of 2×10^{-12} erg cm^{-2} s^{-1} Å^{-1} which is compatible with a solar type spectrum and Lillie (1973) found from the Apollo 17 ultraviolet spectrometer experiment that at 147 nm no considerable excess brightness is present in the zodiacal light. A detailed discussion of the phenomenon should await further experimental evidence.

3.6. Thermal emission

The infrared emission of interplanetary dust is governed mainly by its temperature which again strongly depends on physical properties like chemical composition and size. This and the geometric simplicity of isotropic emission places infrared observations nearer to the physics of interplanetary dust than the measurements in the visible region of the spectrum, a partial compensation for the increased experimental difficulty. Thermal emission in the zodiacal light has first been detected where it was expected because of the necessarily higher dust temperatures, in the F corona. Blackwell's measurement (1952) of a strong reddening of the corona at 1.9 μm probably included the effect of thermal emission. During the eclipse of November 12, 1966 Peterson (1967b) detected peaks in infrared intensity at 3.4 and 4.0 $R_\odot$, for wavelenghts of 2.2 μm and 3.5 μm. At the same eclipse and on a subsequent balloon flight MacQueen (1968) measuring at $\lambda = 2.2$ μm confirmed these peaks and found two others at 8.7 and 9.2 $R_\odot$ (Figure 15).

The occurance of these sharp peaks has to be attributed to thermal emission and cannot be explained by scattering where a large fraction of the total light is due to low angle scattering of particles far from the Sun. The explanation given by the authors is a stepwise decrease of the number density of the interplanetary dust particles due to fractional evaporation. When the line of sight starts crossing these 'dust-free' zones a drop in infrared intensity occurs with the result of apparent peaks in the brightness distribution. This interpretation, which gives indirect evidence for a force driving interplanetary particles towards the Sun as required by the Poynting-Robertson effect, seems generally accepted. Kaiser (1970) proposed that two materials could account for the four peaks, the outer peaks corresponding to sublimation of large ($r \approx 100$ μm) particles and the inner ones to sublimation of particles with radii not far from the radiation pressure limit ($r \approx 1$ μm). He finds that the materials could be slightly absorbing silicates like olivine or pyroxene and predicts that the outer peaks would disappear at longer wavelengths. While his models reproduce the total intensity in the peaks, the separation of the 2.2 μm intensity between the peaks into a scattered light and a thermal emission part remains to be done and would require infrared observations at longer wavelengths. Even assuming only scattered radiation the observed intensity is low when compared to measurements of the F corona in the visible spectral region with a discrepancy of a factor of four at 10 $R_\odot$ (Figure 6). Recently Lena *et al.* (1974) measuring at $\varepsilon = 3$ $R_\odot$, detected emission features near 10 μm, which probably are due to silicates. The spectra were taken from the high flying (17 km) aircraft Concorde during the June 30, 1973 solar eclipse. A previous attempt by ground based measurements (Mankin *et al.*, 1974) was unsuccesful because of sky noise. Both experiments found an intensity exceeding the predictions of Kaiser's (1970) model. Peaks in the 10 μm radiation were found at 4.0 $R_\odot$ and 6.4 $R_\odot$.

The interpretation of the infrared emission in the F corona gave no indication of temperatures higher than in the case of a gray particle, where $T = 280/\sqrt{R}$ K, R being the distance from the Sun in AU. This is in agreement with the rocket experiment by



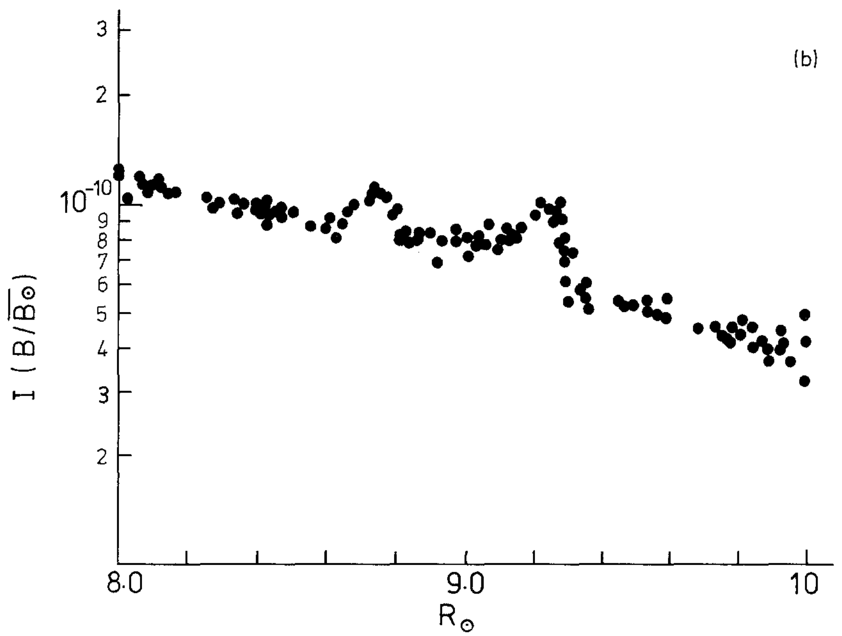


Fig. 15. Thermal emission features in the corona at 2.2 μm according to MacQueen (1968). (a) Eclipse observations November 12, 1966, (b) Balloon observations January 9, 1967.

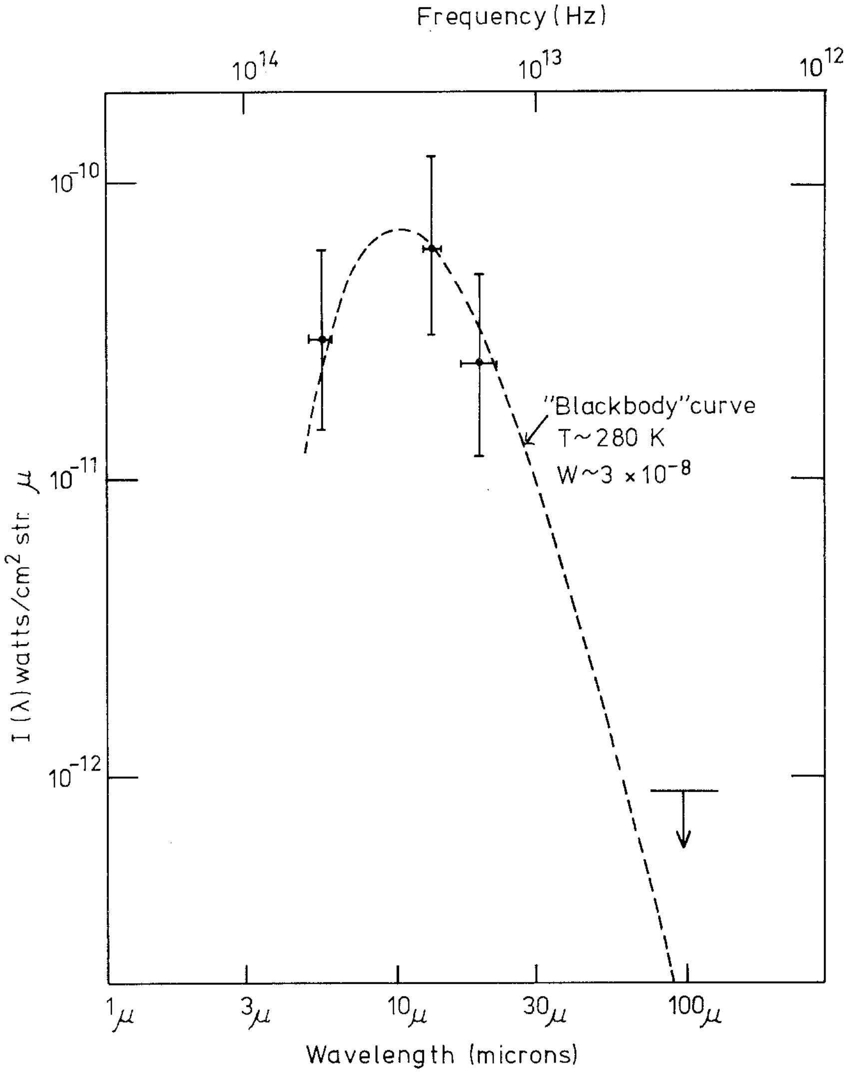


Fig. 16. Thermal emission of zodiacal light at $\varepsilon = 160°$. Spectrum measured by Soifer *et al.* (1971).

Soifer *et al.* (1971) which detected infrared emission in the zodiacal light at $\varepsilon = 160°$ in three spectral bands between 5 μm and 23 μm. Although their experiment was subject to considerable stray light contamination from the surface of the night-time Earth, the colour temperature of about 280 K determined by their measurement (Figure 16) is not very sensitive to errors in the recorded intensities. Assuming neutral scattering in the zodiacal light Hofmann *et al.* (1973) derived an upper limit of 340 K for an interplanetary particle at 1 AU from their measurement at 2.4 μm.

3.7. Symmetries

The plane of symmetry of the zodiacal light which usually coincides with the plane of maximum zodiacal light brightness contains information on the spatial distribution and hence the dynamics of the scattering dust particles. The question of symmetry is as old as zodiacal light research itself.

If a considerable fraction of the zodiacal light were due to a geocentric dust cloud in cislunar space, as argued by Divari (1965a, 1967a) in concordance with Fesenkov (1971) a coupling of the ecliptic latitude of the zodiacal light axis to the instantaneous ecliptic latitude of the Moon seems possible. Such an effect has been announced by Divari and Komarnitskaja (1965) but contradicted by others (Saito and Huruhata, 1967; Dumont and Sanchez-Martinez, 1968; Leinert, *et al.*, 1974). Serious arguments against the importance of a possible geocentric dust cloud come from observations of the zodiacal light at small elongations from the Moon (McQueen *et al.*, 1973a) or at large elongations from Pioneer 10 (Hanner and Weinberg, 1974) which show a close quantitative agreement with the results of earthbound observations. A safe upper limit to the cislunar contribution to zodiacal light has not been given to my knowledge. According to micrometeorid detecting experiments (Hoffmann *et al.*, 1975) a rapid transition to interplanetary number densities occurs outside the Earth's atmosphere, within less than 10 Earth radii. This is compatible with results of OSO-2 (Gillett, 1967), where no effect of the Earth's shadow larger than 1 S10 at $\varepsilon = 90°$ was found.

For the assumed heliocentric distribution of interplanetary dust particles it may be expected that the gravitational influence of Jupiter and Saturn make the dust cloud symmetric to the invariable plane ($i = 1.6°$, $\Omega = 105°$) of the solar system. This symmetry was found by Hoffmeister (1940) on the basis of extended visual observations for the outer zodiacal light ($\varepsilon > 65°$) while he found that the axis of the inner zodiacal light was shifted towards the orbital plane of the inner planets (larger inclination, smaller longitude of node). Table VI summarizes the results of recent experiments. i_{ZL} and Ω_{ZL} are inclination and longitude of ascending node for the plane of symmetry of the zodiacal light. Figure 17 shows the geometry involved if the plane of symmetry is coinciding with or near the invariable plane (IP). For observations

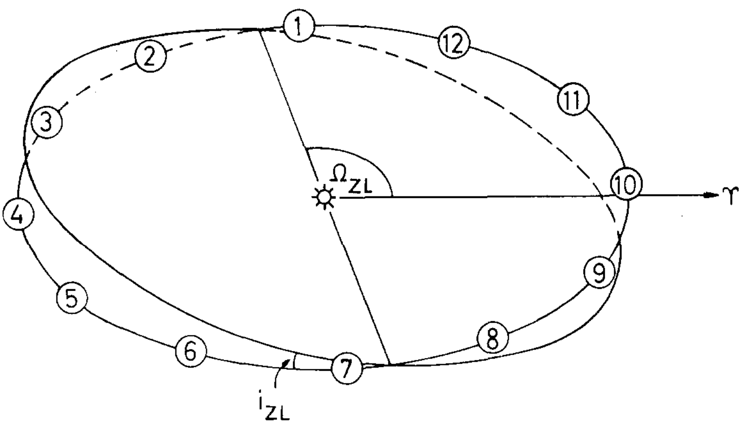


Fig. 17. Geometry for observations of the plane of symmetry of zodiacal light. The numbers indicate the position of the Earth at the beginning of the respective month.

near the nodes (June/July or December/January) the observed effect should be a tilt of the plane of maximum brightness with respect to the ecliptic by $i_{IP}=1.6°$. Three months later the main effect would be a displacement towards north (March) or south (September) of the ecliptic, the amount depending on the viewing angle.

If the results of Table VI are compared with Figure 17, keeping in mind that the

TABLE VI

Observed plane of symmetry of zodiacal light

Author	Date of observation	Elongation [a]	Result
Behr and Siedentopf (1953)	Febr., March 52	35°–90° E	brightness decrease faster towards south
Regener (1955)	Sept. 53–Febr. 54	30°–100° E, W	usually $i_{ZL}<1°$
Blackwell (1956)	May 24, 55	25°–43° E	0.2° N
Blackwell and Ingham (1961)	June, July 57	19°–70° E	$i_{ZL}=1.5°$, $\Omega_{ZL}=115°$
Divari and Asaad (1959)	Oct., Nov. 57	35°–100° W	in ecliptic or 1° N, brightness decrease faster towards south
Tanabe (1965)	Summary of Gegenschein observations	180°	compatible with invariable plane
Robley (1965)	April, Oct. 64	180°	Gegenschein in ecliptic
Lillie (1968)	Sept. 2, 64	130°–180° E, W	Gegenschein 2.5° S, corresponding to $i_{ZL}=5°$, $\Omega_{ZL}=70°$
Wolstencroft and Rose (1967)	Sept. 15, 64	174° W	3° S in *B*, 5° S in *R*
Saito and Huruhata (1967)	Febr., March 64, May 65	30°–100° E 40°–110° W	≈1° N ≈2° S } compatible with solar equatorial plane
Dumont and Sanchez (1968)	June, Dec. 66	90° E, W	1.3° S for $\lambda=0°$ 1.9° N for $\lambda=180°$
MacQueen (1968)	Jan. 9, 67	1°–2° E	$i_{ZL}=1°$–$2°$, compatible with inv. plane
Leinert *et al.* (1974)	July 2. 71	15°–30° E, W	$i_{ZL}=2.0°$–$4.4°$, $\Omega_{ZL}\approx 90°$
MacQueen *et al.* (1973)	April 22/23, 72	1°–13° E	$3\pm1°$ N for $\varepsilon>5°$
Levasseur and Blamont (1975)	Apr. 71 to June 73	90°	Symmetry to invariable plane or Jupiter's orbit

[a] E, W: east or west (smaller longitude) of the Sun.

zodiacal light brightness is given by an integral along the line of sight, only the measurements of Blackwell (1956b), Regener (1955) and Robley (1965) are not in qualitative agreement with Hoffmeisters concept. However, none of the above three shows an opposite effect. The six latest experiments definitely exclude the ecliptic as axis of symmetry, again favoring the invariable plane with a tendency to the orbital planes of the inner planets (or the solar equator) inside the Earth's orbit. A more quantitative discussion has to be based on model calculations.

An east-west symmetry of the zodiacal light, corresponding to a rotational symmetry of the zodiacal cloud usually is assumed to exist. Van de Noord (1970) found the zodiacal light intensity at $\varepsilon=30°$ in the evening 30% higher than in the morning, which cannot be a general feature of the zodiacal light. The measurements of Frey *et al.* (1974) and Dumont (1965) show an east-west-symmetry and, scanning on circles round the Sun, Leinert *et al.* (1974) found no deviation larger than 4% in the ecliptic for $\varepsilon=15°–30°$.

No definite deviation from north-south symmetry was found in the out-of-ecliptic measurements of Sparrow and Ney (1972) or Leinert *et al.* (1974). Effects due to the motion of the Earth with respect to the plane of symmetry of the zodiacal cloud are discussed in the following section.

3.8. Variations in the Zodiacal Light

As Weinberg (1970) pointed out, the difference in intensity and polarization of the zodiacal light obtained by different observers can be due to real changes in the zodiacal cloud or a number of reasons like

– calibration errors;

– differences in airglow, atmospheric transmission and scattering which are a function of time, latitude and altitude of the observing site;

– different techniques to allow for starlight, airglow and atmospheric scattering;

– insufficient experimental coverage in time and over the sky;

– annual motion of the Earth with respect to the plane of symmetry of the zodiacal cloud.

Therefore reports on the variability of the zodiacal light usually are regarded with scepticism although, in principle, they can give valuable information on the dynamics of interplanetary dust.

The differences of up to a factor of two between zodiacal light photometries from 1952 to 1961 were explained by Asaad (1967a, b) as a variation of the zodiacal light with the solar cycle, the brightness decreasing and the polarization increasing with solar activity. Weinberg (1970) criticized these conclusions in that they were based on very inhomogeneous observational material. In addition the satisfactory agreement between recent observations excludes such large variations. A much smaller variation with solar cycle of about 25% peak to peak was found by Weill (1966) from a homogeneous set of observations of zenith and celestial pole 1953–1966. The minimum zodiacal light intensity occured 1956–57, two years before maximum solar activity. Application of his curve to normalize the observational results in Figures 6 and 11 would not reduce the discrepancies which therefore must have a different origin. A different type of long term variation was suggested by Fracassini and Pasinetti (1966) who tried to correlate the zodiacal light intensity with the total number and brightness of yearly appearing comets. In a study of the Gegenschein from three different sites between January 1957 and January 1963 Tanabe (1965) found no significant variation in intensity. From the satellite experiment in OSO-5, Sparrow and Ney (1973) detected no changes in the zodiacal light between January 1969 and January 1973 greater than the experimental accuracy of about $\pm 10\%$. Their measurement covers the period of maximum solar activity. Robley (1973) also found no systematic change of brightness in his observations of the celestial pole from 1964 to 1972. The evidence today is in favour of a remarkably stable zodiacal light with rather small long term variations.

The classical example of a short lived fluctuation is the brightness increase observed by Blackwell and Ingham (1961c) on July 8–9, 1958 following a class 3^+ solar flare. They also found a correlation between zodiacal light intensity and the planetary magnetic *Kp* indices (which are a measure of the solar wind velocity) opposite in sign to Asaads (1967b) correlation. Banos and Koutchmy (1973) photographed from ground an enhancement in the region of the inner zodiacal light which they discussed as an effect of solar activity on the motion of the interplanetary particles. Sanchez (1969) supports strongly the effect of solar activity on zodiacal light intensity, Sparrow and Ney (1968), Van de Noord (1970), Robley (1973) and Sparrow and Ney (1973) found none. It is not possible to explain the increase in intensity found by Blackwell and Ingham by fluorescence of interplanetary particles because of the large volumes involved in the constitution of the observed zodiacal light intensity. The most simple explanation of such events would be an enhanced plasma density in a cloud of the size of the order 1 AU. This would not necessarily change the zodiacal cloud and the effect could most easily be observed in polarized light. But an increase by 19 electron cm^{-3} to four times the average value would be required to change the polarization at $\varepsilon = 90°$ by only 0.5%. This may serve as an example for the difficulties in explaining changes in zodiacal light brightness. I am not aware of observations reporting simultaneous changes in brightness and polarization.

A variability of the zodiacal light with lunar phase was postulated by Divari (1963) but not confirmed by others observers.

A number of arguments for local concentrations of material in interplanetary space have been given. Roosen (1970a) detected a central dip in the profile of Gegenschein intensity obtained on February 21, 1969. He does not exclude the possibility that the effect was due to a dust cloud related to the orbit of Comet Encke, which according to Whipple (1967) probably is a main contributor to the zodiacal cloud. From 15 months of OSO-6 data Roach (1975) deduced that particles trapped near the libration points L4 and L5 of the Earth-Moon-system contribute 20 S10 to the Gegenschein intensity. This is an astonishingly high value, given the negative results of observers searching for this phenomenon from ground (Roosen, 1968; Weinberg, 1970) or space (Burnett *et al.*, 1974). In a parallel paper (Roach *et al.*, 1973b) irregularities in the OSO-6 Gegenschein observations are taken as evidence for both a dust cloud passing the Earth-Moon-system and an increased particle concentration near the libration point L4. More direct arguments for the existence of particle streams or cloud have been given by Levasseur and Blamont (1973, 1975) from observations with the satellite D2A from April 1971 to June 1973. At $\varepsilon = 90°$ they usually observed a rather constant distribution of zodiacal light with inclination. On particular dates a selective enhancement of the zodiacal light intensity in some directions was observed ,up to 100% decaying with a time constant of 2^d–25^d. The authors correlate the viewing directions with orbits like that of comet Biela (Andromedids) or the Lyrids and conclude that the zodiacal cloud is composed of such streams developing under the forces acting on the interplanetary particles. This stream-like structure would also be an explanation of observational discrepancies. Fascinating as these views are they should be subject to careful cross checking of the data with the simultaneous satellite experiment on OSO-5 and ground observations, where some overlap for measurements critical to the interpretation might exist. In a first comment Burnett *et al.* (1974) pointed to the possibility that at least some of the observed peaks may be due to scattered Moon light. The question of short term variations and structure of the zodiacal light is still controversial, but most of the observed types of variation are sufficiently predictable to allow conclusive experimental verification.

The effect of the annual motion of the Earth with respect to the plane of symmetry of the zodiacal cloud amounts to a few percent only. The first measurement, reported by Robley (1973) and Levasseur and Blamont (1975) for $\varepsilon = 90°$, are compatible with a concentration of the zodiacal cloud to the invariable plane. Wolstencroft and Rose's (1967) report on a higher intensity at the south than the north ecliptic pole would be in qualitative agreement with this picture. Because of the importance of the correction for star background in these regions his result should be considered with caution.

3.9. Changes with heliocentric distance

Deep space probes traveling through the zodiacal cloud offer a unique opportunity to zodiacal light research. Measuring at varying heliocentric distances they add a new dimension to the zodiacal light observations, in the mathematical sense of this word. It is immediately plausible that such measurements will greatly improve the knowledge on the spatial distribution of interplanetary dust over that obtainable from Earth or earthbound satellites. A mathematical formulation of the expected gain is given in Section 4.

The first measurements of this type were performed on Pioneer 10 and 11 going out past Jupiter in 1972–1974, followed by measurements on the Helios A and B solar probes, passing within 0.3 AU of the Sun in 1975 and 1976. Figure 18 shows the zodiacal light intensity at $\varepsilon \approx 120°$ as a function of heliocentric distance between 2.4 AU and 3.3 AU as observed from Pioneer 10 (Hanner *et al.*, 1974). These results show that there is only little contribution to the zodiacal light from the asteroid belt and virtually none from beyond 3.3 AU. Consequently there is a strong decrease of particle number density outside the Earth's orbit, preliminary results (Hanner and Weinberg, 1974) supporting a distribution law of $n(r) \sim 1/r$. Special care has been given to the determination of the correction for starlight which is critical at the low light levels encountered in the outer solar system (Weinberg *et al.*, 1974). The Helios observations in the inner solar system will be less subject to these difficulties.

3.10. Forthcoming experiments

This necessarily incomplete list contains mainly space experiments which are easier to be noticed because of the long preparation times involved. The Pioneer (Hanner, Weinberg) and Helios (Leinert, Link, Pitz) interplanetary probes will supply inten-

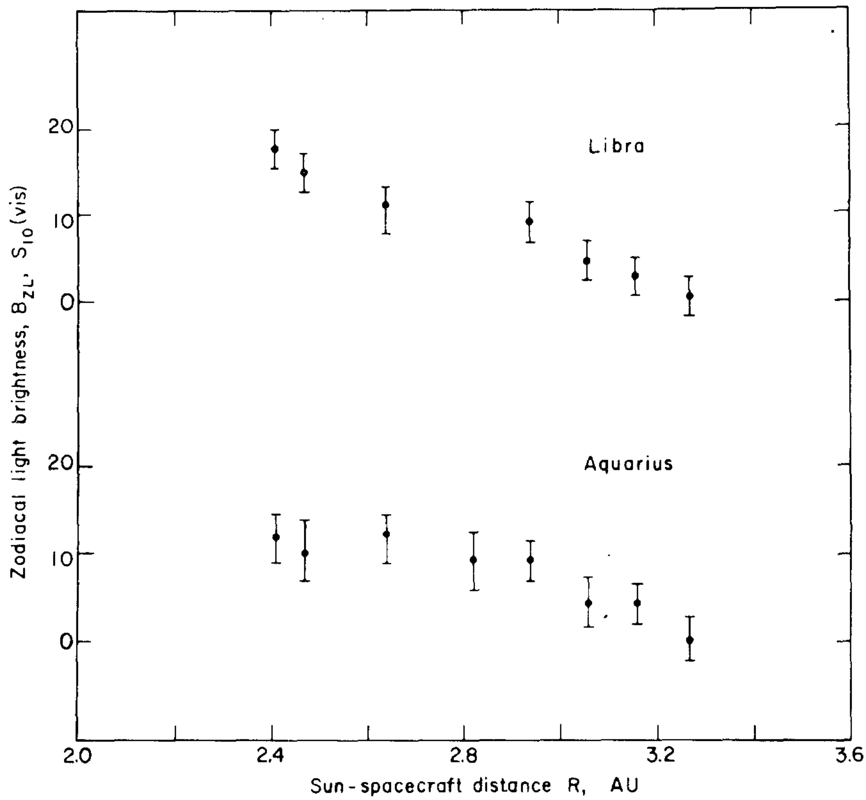


Fig. 18. Zodiacal light intensity as a function of heliocentric distance at $\varepsilon \approx 120°$ (Hanner *et al.*, 1974).

sity, colour and polarization of the zodiacal light as a function of heliocentric distance. Although seriously hampered by the difficulties of the spacecraft, Skylab (Weinberg) may provide valuable data on wavelength dependence of polarization. Further contributions concerning the variability of the zodiacal light are expected from the late satellite experiments on OSO-5 (Sparrow and Ney), OSO-6 (Roach *et al.*), D2A (Levasseut and Blamont). The ultraviolet zodiacal light is being studied from rocket (Lillie, Pitz) and balloon (Frey *et al.*). Work is in progress on zodiacal light measurements taken from Apollo 15, 16, 17, concerning Gegenschein, libration points of the Earth-Moon-system, colour, polarization and F corona (Mercer *et al.*, 1973a, b; Lillie, 1973; MacQueen *et al.*, 1973b).

A considerable amount of OAO-measurements (Lillie) and ground observations from Hawaii (Weinberg) await reduction.

4. Interpretation of the Observations

Apart from special features like an occurence of circular polarization or fluctuations in the zodiacal light which are accessible to direct physical interpretation there are mainly two approaches in the interpretation of zodiacal light observations. One is comparing models with the observations concluding that the best fitting model contains the best information on spatial distribution, material and size distribution of the particles. It is the weakness of this method that incorrect assumptions in one parameter may be balanced by variations of the other parameters, which leads to ambiguities. The second starts from the observations trying by mathematical operations to deduce spatial distribution and scattering properties of the interplanetary particles. The scattering properties admittedly are an intermediate results but at least provide a reasonably defined basis for discussions of size distribution and material. Although the second method scarcely has been used it is promising and will be discussed in Section 4.2.

4.1. The brightness integral

The geometry of scattering with the observer in the plane of symmetry of the zodiacal cloud is shown in Figure 19. The contribution of particles in a unit volume at P to

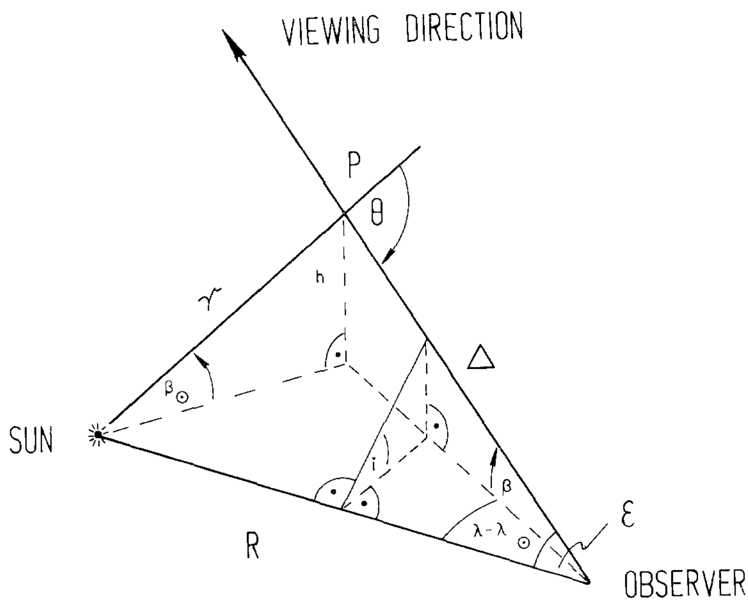


Fig. 19. Geometry of scattering.

the observed intensity is proportional to the solar irradiance $F_0 \cdot (r_0/r)^2$ (erg cm^{-2} s^{-1} Å^{-1}), the particle number density $n\ (r, h)$ cm^{-3} and their average scattering function $\sigma(\theta)$ cm^2 ster^{-1}. The deviation from the $1/r^2$-law due to the finite size of the Sun is less than 1% for $r > 10\ R_\odot$. For a viewing direction in the plane of symmetry integration along the line of sight gives

$$I\,(\varepsilon, R) = F_0 \cdot R_0^2 \cdot \int\limits_{\Delta=0}^{\infty} \frac{\sigma(\theta) \cdot n(r)}{r^2}\, \mathrm{d}\Delta \;[\text{erg cm}^{-2}\ \text{s}^{-1}\ \text{ster}^{-1}\ \text{Å}^{-1}]. \qquad (5)$$

Single scattering may be assumed since a typical value for the optical thickness of the zodiacal cloud is 10^{-6}. R is the heliocentric distance of the observer which for space experiments may be different from $R_0 = 1$ AU. Equation (5) is fairly general since the only assumption made is rotational symmetry. $\sigma(\theta)$ still may be a function of heliocentric distance. The equation is valid for the total and polarized intensities respectively, if the corresponding scattering functions are used. The degree of polarization is obtained according to Equation (3). Changing the integration to θ and with a spatial distribution $n(r) = n_0 \cdot (r/r_0)^{-\nu}$, where $r_0 = 1$ AU, the equation takes the form

$$I(\varepsilon, R) = \frac{F_0 \cdot R_0 \cdot n_0}{(R/R_0)^{1+\nu} \cdot \sin^{1+\nu} \varepsilon} \cdot \int_{\theta=\varepsilon}^{\pi} \sin^{\nu} \theta \cdot \sigma(\theta) \, \mathrm{d}\theta \times \times [\mathrm{erg\,cm^{-2}\,s^{-1}\,ster^{-1}\,Å^{-1}}]. \tag{6}$$

The average scattering function

$$\sigma(\theta) = \frac{\int_{a_1}^{a_2} \sigma(a, m, \theta) \, n(a) \, \mathrm{d}a}{\int_{a_1}^{a_2} n(a) \, \mathrm{d}a} \quad [\mathrm{cm^2\,ster^{-1}}] \tag{7}$$

depends strongly on the particle size distribution $n(a)$ and the particle material, characterized by the complex refractive index m. $\sigma(a, m, \theta)$ is the scattering function of a particle of radius a; a_1 and a_2 are the lower and upper limits of the size distribution which usually is taken in the form of a power law,

$$n(a) \, \mathrm{d}a \sim a^{-k} \, \mathrm{d}a. \tag{8}$$

If Mie theory is used to calculate the scattering function, $\sigma(\theta)$ is obtained in units of $\lambda^2/8\pi^2$ cm^2 ster^{-1}. If in addition θ is expressed in degrees and $I(\varepsilon, R)$ in S10, the 'constant' in front of the integral has the value $1.30 \times 10^{-12}/(R/R_0 \cdot \sin \varepsilon)^{1+\nu}$ for $\lambda = 500$ nm. For out-of-ecliptic observations, with the observer in or outside the plane of symmetry, the two-dimensional spatial distribution function $n(r, h)$, has to be used giving

$$I(\varepsilon, i, R, H) = F_0 \cdot R_0^2 \cdot \int_{\Delta=0}^{\infty} \frac{\sigma(\theta) \cdot n(r, h)}{r^2} \, \mathrm{d}\Delta. \tag{9}$$

H and h stand for the height above the plane of symmetry of the observer and the scattering particles, respectively. For geometrical relationship involved in expressing $n(r, h)$ as function of ε, θ and i or β see Aller (1967) or Giese and Dziembowski (1969), who, however, partly use a different notation.

Thermal emission and wavelength shift are described by slight modifications of the brightness integral which are inserted here because of their importance but not included in the following discussion.

4.1.1. *Wavelength Shift*

According to the relative motions of Earth and interplanetary particles the light scattered from a volume along the line of sight towards the observer experiences a wavelength shift $d\lambda(\Delta)$. The weighted mean of the wavelength shift along the line of sight constitutes the wavelength shift of the 'center of gravity' of the line

$$\Delta\lambda(\varepsilon) = \frac{\int\limits_{\Delta=0}^{\infty} \frac{\sigma(\theta)\cdot n(r)\cdot d\lambda(\Delta)}{r^2}\, d\Delta}{\int\limits_{\Delta=0}^{\infty} \frac{\sigma(\theta)\cdot n(r)}{r^2}\, d\Delta} \tag{10}$$

observable in the zodiacal light spectrum. For particles in circular orbits $d\lambda$ takes the form (Ingham, 1963)

$$d\lambda = \pm \frac{V\cdot\lambda}{c}\left(\sin^{1/2}\varepsilon \mp \mu\, \frac{\sin^{3/2}\theta}{\sin\varepsilon}\right), \tag{11}$$

where V is the Earth's orbital velocity, c the velocity of light and μ^2 the factor by which the gravitational force is reduced due to the solar radiation pressure. The plus sign in front of the brackets is for the eastern (evening), the minus sign for the western (morning) zodiacal light. The signs in the brackets are for prograde $(-)$ and retrograde $(+)$ orbits respectively.

4.1.2. *Thermal Emission*

In analogy to Equation (5) the intensity of the thermal emission at wavelength λ is given by (Peterson, 1963)

$$I_\lambda(\varepsilon) = \int\limits_0^{\infty}\int\limits_{a_1}^{a_2} n(r, a)\, C_\lambda(a)\, B_\lambda[T(r, a)]\, da\, d\Delta, \tag{12}$$

where $C_\lambda(a)$ is the absorption cross section of a particle of radius a at wavelength λ and $B_\lambda(T)$ the Planck function.

The temperature $T(r, a)$ of the interplanetary dust particles is calculated from the equilibrium condition

$$\int\limits_0^{\infty} F_0(\lambda)\cdot\frac{r_0^2}{r^2}\cdot C_\lambda(a)\, d\lambda = \int\limits_0^{\infty} C_\lambda(a)\cdot B_\lambda[T(r, a)]\, d\lambda \tag{13}$$

giving

$$T = 280\cdot(r_0/r)^{1.2}\,\mathrm{K} \tag{14}$$

in the blackbody approximation

More generally the temperatures (14) are reduced with respect to the blackbody temperatures by the factor $(C_A/C_E)^{0.25}$, where C_a and C_E are the mean cross-sections for absorption and emission (Kaiser, 1970).

4.2. Inversion of the Brightness Integral

The expression for the zodiacal light intensity (Equation (5)) contains the product of the unknown spatial distribution $n(r)$ and the unknown scattering properties $\sigma(\theta)$. For an observer in a fixed heliocentric distance, e.g. on the Earth or an earthbound satellite, a solution is only possible if values for one of the two unknown functions are assumed. If the observer changes the heliocentric distance one would expect that it is possible to deduce the two unknown functions $n(r)$ and $\sigma(r, \theta)$ from the two-dimensional set of observations $I(R, \varepsilon)$. This advantage of space probes like Helios or Pioneer is best demonstrated under the additional assumptions that $\sigma(\theta)$ does not depend on r and the spatial distribution is given by a power law $n(r) \sim r^{-\nu}$. In this case observations at one angle are sufficient to determine the spatial distribution:

$$R \cdot I(\varepsilon, R) = \text{const}(\varepsilon) \cdot R^{-\nu} \tag{15}$$

according to Equation (6). The $1/R^2$ decrease in intensity observed by Hanner and Weinberg (1974) therefore would correspond to a $1/r$ dust distribution. If the spatial density does not follow a power law, the left hand side of Equation (15) still is a reasonable approximation of the spatial distribution (Hanner and Leinert, 1972).

The general equations which relate the observed intensity $I(R, \varepsilon)$ and polarization $p(R, \varepsilon)$ of the zodiacal light to the spatial distribution $n(r)$, the scattering function $\sigma(r, \theta)$ and its polarization $p_\sigma(r, \theta)$ are obtained by differentiating Equation (5) with respect to Δ and, on the left hand side, taking into account the geometrical relationship between r, Δ and ε:

$$\begin{aligned} n(R) \cdot \sigma(R, \theta = \varepsilon) &= -\frac{R}{\text{const.}} \frac{\partial I}{\partial \varepsilon} \sin \varepsilon + \frac{R^2}{\text{const.}} \frac{\partial I}{\partial R} \cos \varepsilon \\ p_\sigma(R, \theta = \varepsilon) &= I \cdot \frac{\mathrm{d}p}{\mathrm{d}I} \bigg|_{\substack{\text{along} \\ \text{line of sight}}} + p(R, \varepsilon). \end{aligned} \tag{16}$$

The constant has the value $F_0 R_0^2$. All the quantities on the right hand side can be observed from space probes which therefore are able to provide the full information obtainable by photometry (at least in the plane of symmetry). Differentiation is involved in the inversion of the brightness integral, enhancing the importance of small effects in the observed quantities. This shows in a formal way the need for accuracy in zodiacal light observations.

Dumont (1972, 1973) who introduced this kind of analysis pointed out that for $\varepsilon = 90°$ these equations may be used also for earthbound measurements, since then the second term in the first equation, which involves the radial dependence, vanishes. He finds that the scattering efficiency of 1 km^3 near $R_0 = 1$ AU for $\varepsilon = 90°$ is 7.8×10^{-8} cm^2 ster^{-1} $\pm 20\%$ and $0.27 < p_\sigma(R_0, 90°) < 0.41$ for $\lambda = 0.5$ μm. These are empirical results which have to be met by models of the zodiacal cloud. The scarcity of the results is not an inherent disadvantage of the method but rather indicates how little is known conclusively about interplanetary dust from zodiacal light observations. More empirical constraints are expected as a result of the space probe measurements.

In the interpretation of earthbound observations approximations have to be used. With an arbitrary assumed spatial distribution $n(r)$ and with $\sigma(\theta)$ independent of r Equation (6) reduces to an integral equation of first kind of Volterra type which has a unique solution for $\sigma(\theta)$. A simplified analysis of this kind has been presented by Gillett (1967) and by Southworth (1967b). If in addition $n(r) \sim r^{-\nu}$ is assumed, an explicit solution of Equation (6) is possible (Dumont, 1973),

$$
\begin{aligned}
n(R_0)\cdot\sigma(R_0, \theta=\varepsilon) &= -\frac{R_0}{\text{const.}}\left[(1+\nu)\cdot\cos\varepsilon\cdot I + \sin\varepsilon\,\frac{\partial I}{\partial\varepsilon}\right] \\
p_\sigma(R_0, \theta=\varepsilon) &= \frac{\sin\varepsilon\cdot I\cdot\dfrac{\partial p}{\partial\varepsilon}}{(1+\nu)\cdot\cos\varepsilon\cdot I + \sin\varepsilon\,\dfrac{\partial I}{\partial\varepsilon}} + p(R_0, \varepsilon)
\end{aligned}
\tag{17}
$$

Results for $0.4 < \nu < 2.0$ are given in Figure 20.

For the viewing direction of maximum polarization in the zodiacal light the first term in the second equation of (17) vanishes, giving $p_\sigma(R_0, \theta \approx 65°) = 0.20 \pm 0.02$ independent of the assumed value of ν, which therefore is considered a correct result. The curves of Figure 20 are compatible with this as well as with the constraints given above.

A similar analysis for out-of-ecliptic observations has not yet been given. The geometry is more complicated because the rotational symmetry in the plane of scattering is missing.

4.3. Zodiacal Light Models

Models are built on assumptions concerning the spatial distribution and scattering properties of the particles. A compilation of zodiacal light models has recently been given by Gary and Craven (1973).

4.3.1. *Which Scattering Function to Use?*

Mie Theory. The scattering of smooth homogeneous spheres is correctly described by the Mie Theory, a solution of Maxwell's equations (see Born and Wolf, 1959). It gives the scattering function of a single sphere as an infinite series, where the coefficients only depend on the size parameter $\alpha = 2\pi a/\lambda$ and the complex refractive index m. Since the availability of high-speed computers made the calculation of Mie scattering functions feasible they have been widely used, although no one really expects the interplanetary particles to be smooth homogeneous spheres. Computations were performed by Deirmendjan *et al.* (1961), Giese (1961) and others. Tabulations of scattering functions for size distributions $n(a)\,\mathrm{d}a \sim a^{-2.5}$ and $n(a)\,\mathrm{d}a \sim a^{-4.0}$ have

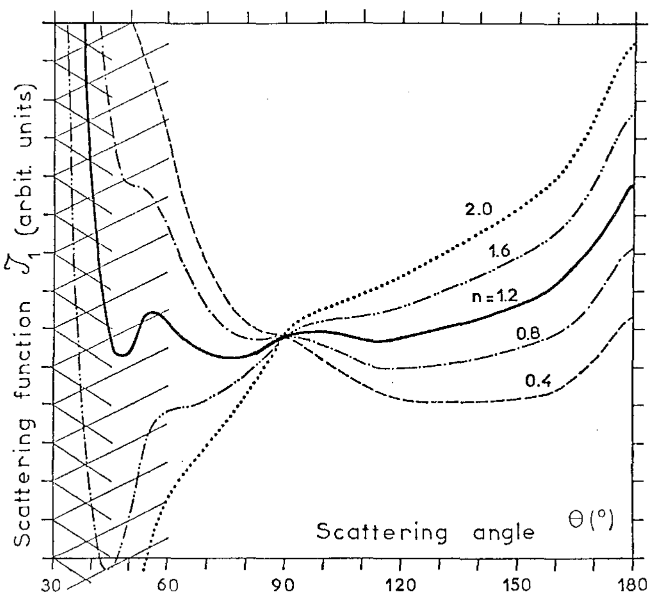


Fig. 20b.

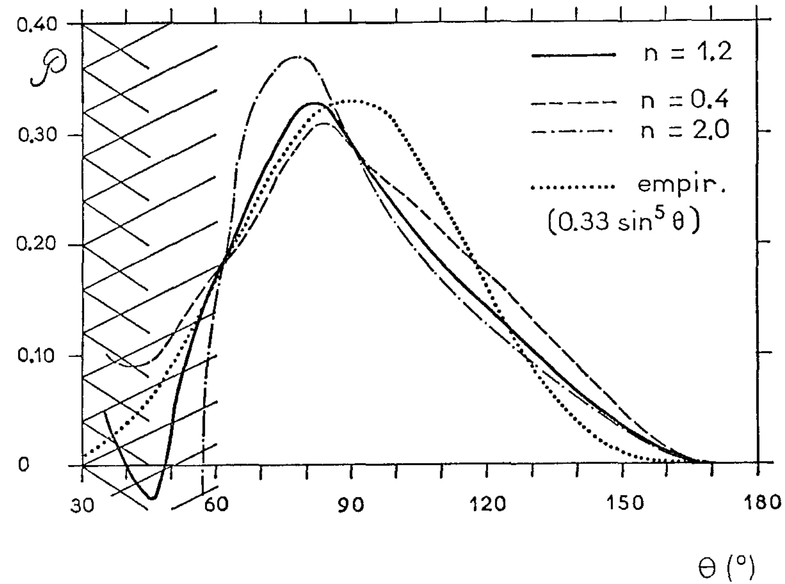


Fig. 20a.

Fig. 20. Scattering function of interplanetary dust as determined for several heliocentric distributions of density $\sim r^{-n}$ (Dumont and Sanchez, 1975). For $\theta < 60°$ the results are not considered reliable. The scattering is nearly isotropic for $60° < \theta < 150°$. The maximum polarization occurs at $\theta < 90°$.

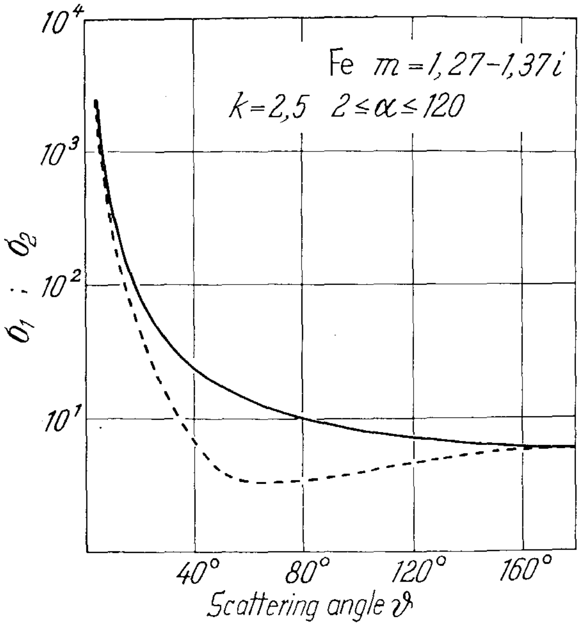


Fig. 21a.

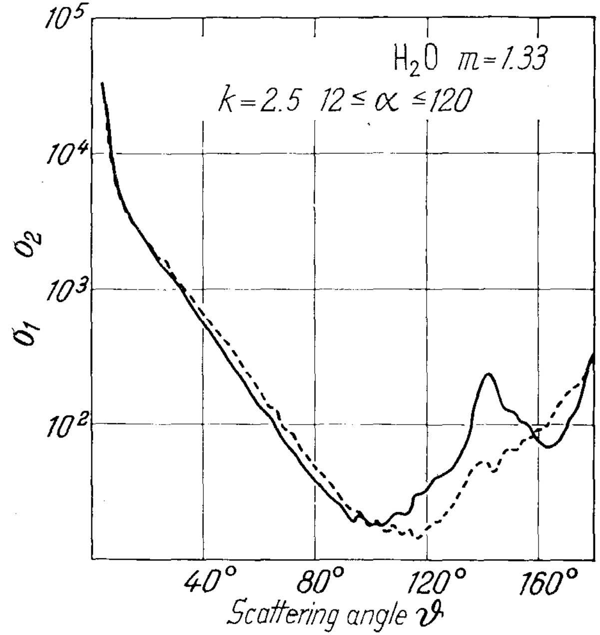


Fig. 21b.

Fig. 21. Typical example for the scattering of a mixture of absorbing (left) or dielectric particles (right). σ_1 is given by the solid, σ_2 by the broken line (Giese, 1963).

been given by Giese (1970, 1971a) together with zodiacal light models based on these scattering functions (Giese, 1973a). Usually dielectric materials, $m=1.33$, $m=1.50$, $m=1.70$, with or without a small ($\leqslant 0.10i$) imaginary component of the refractive index are used, supplemented by metallic (iron) particles. Two typical examples are shown in Figure 21, the scattering function for dielectric particles showing enhanced backscattering and negative polarization at small and large scattering angles, the absorbing particles showing no enhanced backscattering and high polarization at small scattering angles.

Mie theory also predicts colour and polarization. It is cumbersome to extend the calculations beyond $a=10\ \mu$m ($\alpha \approx 120$) and extended tabulations for these larger particles are missing.

Approximations. The classical approximation is the description of the scattering function by superposition of a diffraction peak and isotropic scattering (Van de Hulst, 1947)

$$\sigma(\theta) = a^2 \cdot \frac{J_1^2(2\pi a\theta/\lambda)}{\theta^2} + A \cdot \frac{a^2}{4}, \tag{18}$$

where $J_1(x)$ is the first Bessel function and A the Bond albedo of the particle. In order to explain the Gegenschein, reflection laws with enhanced backscattering have to be used, e.g. Lambertian reflection or an exponential increase for large scattering angles as observed on asteroids (Briggs, 1962; Roosen, 1970a; Singer and Bandermann, 1967). The assumption of Fresnel reflection on smooth spheres yields intensity and polarization and is a good approximation for absorbing particles with size parameters $\alpha > 20$. Ingham (1961) took the polarization of the scattered light in the form

$$p_\sigma(\theta) = \frac{\sin^2\theta}{q - \sin^2\theta} \tag{19}$$

which is representative for the experimental results of Börngen and Richter (1962) for micronsized particles. q is an adjustable parameter giving the maximum polarization of the scattered light. These approximate scattering functions are not well suited to discuss a wavelength dependence of zodiacal light although the parameters could be wavelength dependent and the Fraunhofer diffraction in fact is.

Blackwell *et al.* (1967a) have argued in favour of the scattering functions (18) and (19) because they are simple, unrestricted in size range and physically not unrealistic. In addition the vast discrepancies in the older observations did not justify a detailed analysis. Giese (1973b), however, pointed out that Hodkinson's (1962) measurements on irregular quartz particles were better represented by Mie theory than by the above approximations. Generally the approximative scattering functions do not increase as fast for $\theta < 90°$ as Mie theory predicts. To explain the increase of zodiacal light intensity at small elongations they require an increase in the spatial density of the dust towards the Sun which is larger by about a factor $1/r$ than for models based on the Mie theory.

Empirical scattering functions. Nothing definite is known about the shape of the interplanetary particles. Earlier collections were subject to contamination in the laboratory and the atmosphere. Among the physical processes in interplanetary space break-up during collisions, probably the most important for the zodiacal cloud (Dohnanyi, 1972) would lead to irregular but large-volume shapes while sputtering by the solar wind and melting near the Sun would produce spheres. The search for experimental scattering functions therefore may be limited to particles not differing too much from spherical shape.

The aerosol scattering in the low atmospheres was taken as an empirical approximation to the scattering of interplanetary particles (Pyakovskaya-Fesenkova, 1959).

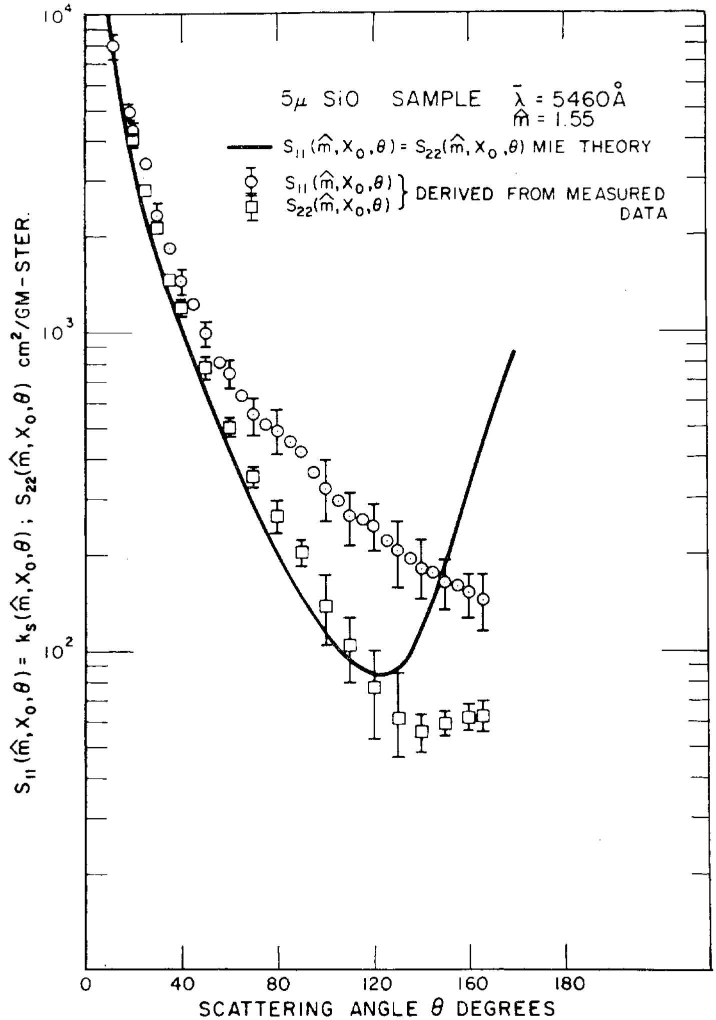


Fig. 22. Scattering of irregular quartz particles according to Holland and Gagne (1970). S_{11}, S_{22} are elements of the Mueller Matrix. For practical purposes S_{11} corresponds to σ_{tot}, while S_{22} does not appear in our notation. There is an increasing deviation from Mie theorie for $\theta > 40°$.

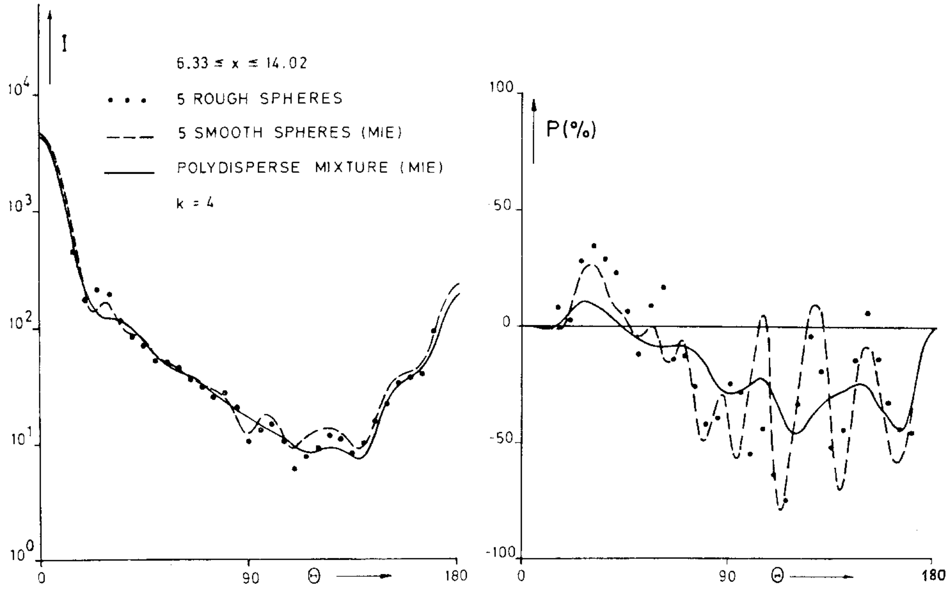


Fig. a.

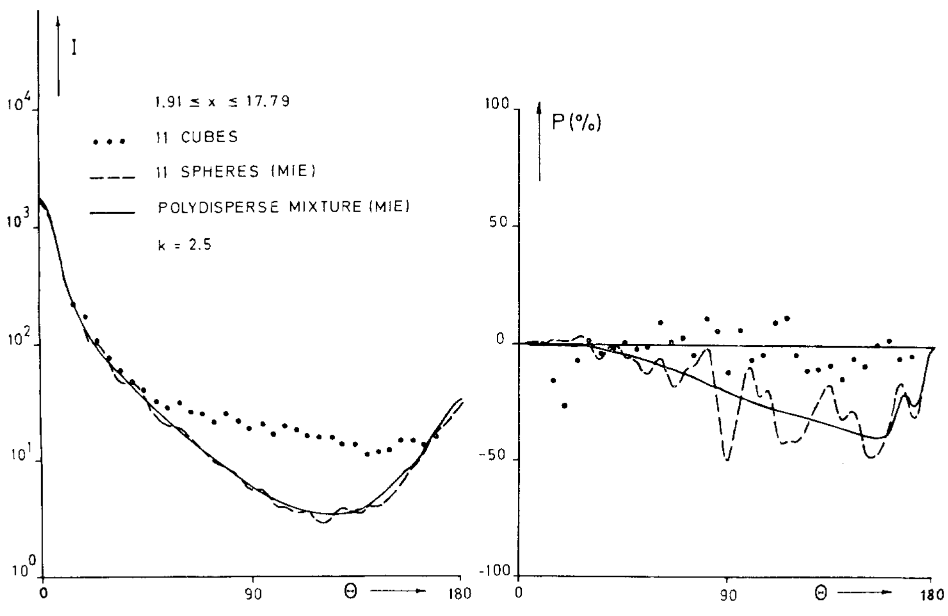


Fig. b.

Fig. 23. Scattering of rough spheres and cubes according to microwave measurements by Zerrull (1974). Note the close agreement between measurement and Mie theorie for rough spheres and the absence of backscatter and negative polarization for the cubes. The refractive index of the scattering material is m=1.57−0.006 i.

Experimental scattering functions for ensembles of randomly distributes micronsized particles were determined by Börngen and Richter (1962), Hodkinson (1962), Napper and Ottewill (1963), Powell *et al.* (1967), Holland and Gagne (1970). An example is shown in Figure 22. A different approach is to measure the scattering characteristics of individual nonspherical particles. These will show little similarity to the scattering of a single sphere, but for a broad size distribution and random orientations the individual resonances will average out. A large number of particles have to be measured before the scattering function of a size distribution can be given. However, once the results for single particles are available, the scattering function of various size distribution can be constructed by appropriate weighting. Most measurements on individual particles were performed by microwave scattering ($\lambda \approx 1$ cm) with the particles scaled to the applicable size parameter. Greenberg (1974) made measurements on a 'rough sphere' constructed from seven symmetrically composed cylinders. Zerrull (1974) used spheres with a surface roughness of only 0.1–0.2 λ, octahedra and cubes (Figure 23).

The existing empirical scattering functions do not cover a sufficient range in particle size and material to replace Mie calculations. Additional measurements are desirable in order to put the zodiacal light interpretations on a less questionable basis. The present results show that Mie theory is not an acceptable approximation for randomly oriented particles which deviate much from the spherical shape, like fourlings (Powell *et al.*, 1967) very rough 'spheres' (Greenberg, 1974), probably also needles and platelets. On the other hand a small surface roughness has virtually no influence on the scattering. Both optical and microwave measurements on dielectric nonspherical particles (see Figures 22 and 23) show that Mie theory predictions are comparatively reliable for $\sigma < 60°$ where the scattering function shows a strong increase. The enhanced backscattering and the negative polarization, seem to be typical characteristics of the spherical particles only. For absorbing material damping inside the particle tends to reduce shape dependent interferences. Therefore a better fit to Mie theory is expected, and for convex particles predicted (van de Hulst, 1957) but the experiments still have to be performed. According to Powell *et al.* (1967) the wavelength dependence of the scattering by micronsized cubes is predicted with sufficient accuracy by Mie theory. Hapke (1965) found a strong influence of radiation damage on the scattering from micronsized powders. The main effect of irradiation seems to be the formation of an amorphous coating on the individual grains (Maurette and Price, 1975). This effect deserves attention when discussing the scattering function of interplanetary particles.

The present limitations of empirical scattering functions encourage calculations for nonspherical particles. The scattering of infinite cylinders can be calculated and approximations for orbitary shapes are, in principle, possible by the so-called point matching method (Kerker, 1969). A practical answer to the question of this chapter seems to be the use of Mie theory being aware of the uncertainties resulting from nonspherical shape. Later sufficient experimental scattering functions may be available. The increasing amount of more reliable observational data is not in favour of the simplified scattering functions discussed above.

4.3.2. *Spatial Distribution Functions*

The common assumption of a power law for the radial dependence of the number density in the plane of ecliptic $n(r) \sim r^{-\nu}$, is mathematically simple and physically not unrealistic. The Poynting Robertson effect acting on particles in circular orbits injected at some heliocentric distance would produce a distribution $n(r) \sim r^{-\nu}$ inside this distance (Southworth, 1967a). Typical adopted values for ν range from 0.1 (Giese and Dziembowski, 1969) to 1.5 (Singer and Bandermann, 1967). For a detailed analysis the interplanetary space has been divided into zones and a broken power law been used, with the exponent changing from zone to zone and $n(r)$ continuous on the boundaries (Blackwell *et al.*, 1967a). This method allows to approximate any spatial distribution.

The three dimensional spatial distribution now usually is separated into the radial dependence given above and an decrease with distance from the ecliptic which is a function of heliocentric ecliptic latitude only,

$$n(r, h) \sim r^{-\nu} f(\beta_\odot). \tag{20}$$

For circular orbits $f(\beta_\odot)$ is related to the distribution function $g(i)$ of orbit inclinations by (Fessenkov, 1947; see Divari, 1968a)

$$f(\beta_\odot) = \int\limits_{\varphi}^{\pi-\varphi} \frac{g(i)\,\mathrm{d}i}{\sqrt{\sin^2 i - \sin^2 \beta_\odot}}. \tag{21}$$

For $\nu = 0$ the lines of equal number density according to Equation (20) give a fan-like structure of the zodiacal cloud. For $\nu \neq 0$ a more complicated pattern appears. The function $f(\beta_\odot)$ has been taken by different authors as

$$\begin{array}{ll} \text{(a)} & \exp(-\tan\beta_\odot)/\cos^\nu\beta_\odot \\ \text{(b)} & \exp(-k\sin\beta_\odot) \\ \text{(c)} & \exp(-k_1\sin^{k^2}\beta_\odot) \\ \text{(d)} & 1 - k\sin\beta \end{array} \tag{22}$$

((a) Ingham and Jameson, 1968; (b) Divari, 1967b; (c) Zook and Kessler, 1968; (d) Giese, 1971b; a linearization of (b), zero for $\beta_\odot > \sin^{-1}(1/k)$). Except the possibility of obtaining a fit to zodiacal observations the only physical argument for the function (22) was given by Divari (1967b) who found (22b) close to the latitude distribution function of meteors.

A spatial distribution resting on particles dynamics was given by Briggs (1962). Taking the orbital distribution of photographic meteors for the injection of the particles of the zodiacal cloud he calculated the equilibrium spatial density with the Poynting-Robertson-effect as the only force acting on the particles. Since the force is coplanar his distribution is of type (22) and, according to Ingham and Jameson (1968) may be approximated by (22a) with $\nu = 1$.

An intermediate approach was followed by Divari (1967b, 1968a) and Singer and Bandermann (1967) who started from orbital distributions for meteors, comets, asteroids or a parametrized orbital distribution function respectively and compared calculated to observed zodiacal light intensities in order to determine the best orbital distribution. Southworth (1967b) used a form of the radial distribution function

$$\log n(r) = C_1 \log r + C_2 (\log r)^2 \tag{23}$$

resulting from a study of the action of the Poynting-Robertson-effect on cometary particles. He determined the latitude distribution $f(\beta_\odot)$ by a least squares fit of calculated intensities to the observation.

5. Results of Zodiacal Light Analysis and Comparison to Other Investigations

Following Singer and Bandermann (1967) we have to understand the present state of zodiacal dust and the effects that modify this state before the origin of the interplanetary dust particles can be discussed.

5.1. Relative spatial distribution

It is a minimum consensus between different models of the zodiacal light that the particle number density in the ecliptic plane does not decrease with decreasing solar distance between 0.5 and 1.5 AU. This could already be a significant conclusion, indicating a deviation from the distribution of meteors which according to Southworth and Sekanina (1973) show a minimum in their spatial distribution at 0.7 AU. A difference in the distribution of micrometeoroids and larger interplanetary particles is also indicated for the region of the asteroid belt. The three experiments on Pioneer 10, which measured dust particles of different sizes, found the micrometeoroids deficient compared to the larger particles.

A detailed knowledge of the spatial distribution is necessary to discuss the dynamics of the zodiacal cloud. Only those models seem acceptable which explain intensity *and* polarization of the zodiacal light. Blackwell *et al.* (1967a), on the basis of the approximative scattering functions (18, 19) derived a distribution $n(r) \sim 1/r$ between 0.5 and 1.0 AU, the spatial density being constant outside, and decreasing towards the Sun at smaller distances. Instead of a decrease in particle number they also discuss a decrease in particle albedo. Using Mie theory Giese (1973b) finds $n(r) \sim r^{-0.1}$ to $r^{-0.5}$. His analysis, however, does not include the inner zodiacal light. Although these models could be refined including colour effects etc. convincing information on the spatial distribution probably only will come from space probe observations. These results to be expected within the next few years will provide interesting checks on earlier model assumptions. E.g., the decrease of number density outside 1 AU indicated in the preliminary results of Pioneer 10 would not be compatible with the fact, that the Earth's shadow was missing in the Gegenschein, unless the material responsible for the excess brightness was located at larger distance, in the asteroid belt (Roosen, 1970a). This assumption, however, is in poor agreement with the mentioned deficiency of micrometeoroids in this region and with the low zodiacal light brightness measured at a heliocentric distance $R \geqslant 2.4$ AU (Hanner *et al.*, 1974).

Out of ecliptic observations of the zodiacal light were discussed by Giese and Dziembowski (1969) who assumed the lines of equal density to be of ellipsoidal shape. This gives too steep a decrease of zodiacal light brightness outside the ecliptic plane. Models where f is a function of the height above the ecliptic plane only, fail to reproduce the brightness concentration to the ecliptic at small elongations. Relating the spatial density $n(r, h)$ to the density $n \sim (r \cdot \cos\beta_\odot)^{-\nu}$ of the projection into the ecliptic plane, Aller *et al.* (1967) even predicted an increase of zodiacal light brightness outside the ecliptic plane at small elongations. The observations seem to require a 'fan-like' spatial distribution like given in Equation (22). Fesenkov (1959) used an approximation to the spatial distribution of periodic comets but the results of Figure 7 are better represented by the broader spatial distribution $f(\beta_\odot) \sim \exp(-2.0 \sin\beta_\odot)$ (Southworth, 1967b), or an orbit distribution $g(i) \sim \sin i \cdot e^{-3i}$ which corresponds to an average inclination $\bar{i} \approx 30°$ (Bandermann, 1967). This is markedly different from that for asteroids ($\bar{i} \approx 9°$), short period comets ($\bar{i} \approx 11°$), photographic meteors ($\bar{i} \approx 16°$) radio meteors ($\bar{i} \approx 17°$) and long period comets (random distribution). Accepting an average inclination of $\bar{i} \approx 30°$ for the particles of the zodiacal cloud, a process leading to a dispersion of orbital inclinations is necessary, if it is to be replenished by one of the above sources. Divari (1967b, 1968a) on the contrary found the distribution of meteors suitable to account for the out-of-ecliptic observations of the zodiacal light.

Zodiacal light observations which give an integral over the light scattering of all interplanetary particles may be used to establish upper bounds for the spatial density of interplanetary particles of any size. The Gegenschein observations, where the geometry is simple and only one scattering angle involved, have been transformed by Kessler (1968) into upper bounds for the spatial density of meteoritic matter which are significant in the discussion of particle concentrations in the asteroid belt (Sobermann *et al.*, 1974; Auer, 1974).

5.2. Size distribution and spatial density

From the increase of intensity in the F corona, attributed to the diffraction of spherical interplanetary particles, Van de Hulst (1947) derived a size distribution $n(a) \sim a^{-2.6}$, and Elsässer (1955), taking into account the center-to-limb variation on the solar disc, found $n(a) \sim a^{-2.0}$. Ingham (1961) and Blackwell *et al.* (1967a) were able to explain intensity and polarization of F corona and zodiacal light with a steeper size distribution, $n(a) \sim a^{-4}$. Generally the zodiacal light intensity only implicitely depends on the size distribution. The size dependent scattering function determines the weight with which the sections along the line of sight contribute to the observed quantity. Therefore even the Doppler shift of the Fraunhofer lines in the zodiacal light can be used to deduce a size distribution (Reay, 1969). Analysis of size distributions based on only one observable quantity are questionable, since effects of spatial distribution or particle material could be misinterpreted as size effects.

A more direct access to the size distribution is given by the colour of the zodiacal light. The absence of a definite blue enhancement and the closeness to the solar spectrum out to 2.4 μm seems to rule out 'steep' size distributions for the range

0.1 μm$<a<$10 μm which is most important for the zodiacal light (Giese *et al.*, 1973) and requires that only a small function of the zodiacal light is due to scattering by particles with radii much less than 2.4 μm (Nishimura, 1973). No explanation has been given for the large ultraviolet excess found by Lillie (1972) except the speculation that graphite submicron particles could be involved. Singer and Bandermann (1967) concluded from the Al^{26} content in deep sea sediments, which is thought due to the deposit of micrometeroids, that the zodiacal cloud consists mainly of large (micron-sized) particles. Direct measurements of micrometeoroids lead to the same conclusion. Figure 24 shows the size distribution according to Fechtig *et al.* (1974). Interesting

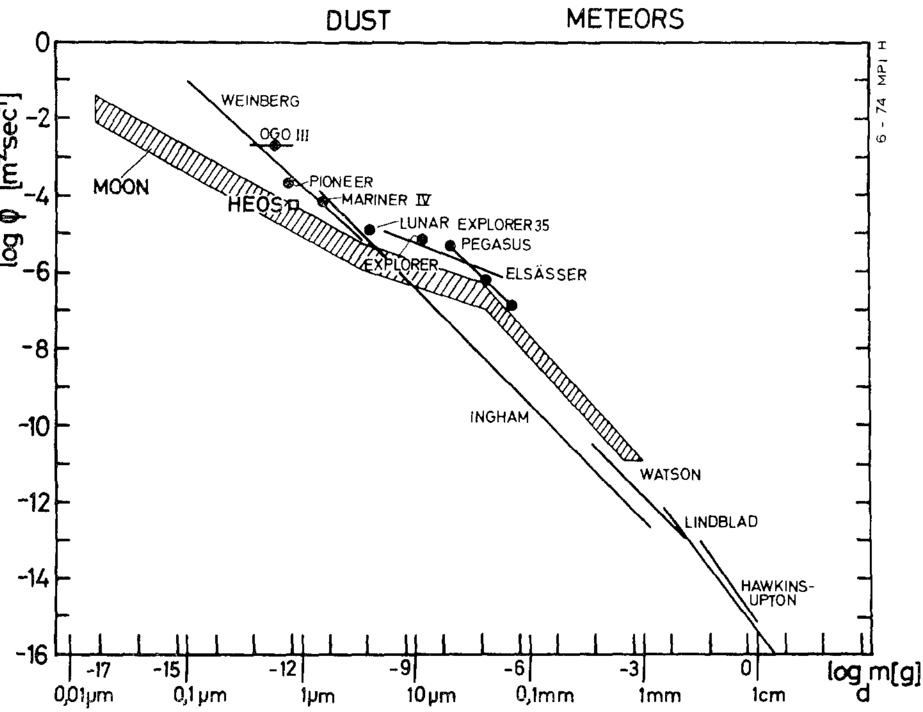


Fig. 24. Cumulated flux of interplanetary dust particles as a function of mass. Most weight is given to the evaluation of microcraters on lunar surfaces (Moon) and the HEOS experiment. The lines labelled 'Elsässer', 'Ingham' and 'Weinberg' are interpretations of earlier zodiacal light measurement. 'Watson', 'Lindblad' and 'Hawkins-Upton' refer to meteor observations.

features are the knees at about $a\approx 1$ μm and $a\approx 30$ μm. Particles larger than 50 μm are rare and therefore no important contributors to the zodiacal light. The particles smaller than 0.5 μm don't contribute much because they are inefficient scatterers. They seem to come from the direction of the Sun at velocities of $\geqslant 50$ km s^{-1} (Berg and Grün, 1973). Are these remnants of melting particles driven outwards by the solar radiation pressure? The intermediate part of the size distribution can be represented by a power law $n(a)\sim a^{-2.2}$, in general accordance with the zodiacal light observations. Finally, the detailed size distribution in the zodiacal cloud could be determined by the micrometeoroid experiments, with the zodiacal light observations providing a check on the overall shape.

For years the particle number densities derived from micrometeoroid detecting experiments were higher by three to four orders of magnitude than the densities required to account for the zodiacal light. This discrepancy has been resolved by now, since the discovery of a 'knee' in the size spectrum near $a=30$ μm leads to a much smaller number of micronsized meteoroids than estimated earlier and facilitates the comparison with zodiacal light models (Leinert, 1971). The absolute scale of Figure 24 is in agreement with the observed zodiacal light intensity (see Giese, 1972) within the limits of accuracy which for this comparison are not much less than a factor of ten (Elsässer, 1970). According to the Heos and lunar microcrater experiments shown in Figure 24 the density of the zodiacal cloud is 4×10^{-23} g cm^{-3}.

5.3. Material and Shape

Most arguments are in favour of a stony material for the interplanetary particles. The Al^{26} content of deep sea sediments can only be explained by silicate-type interplanetary particles (Singer and Bandermann, 1967). The presence of the Gegenschein, which probably is a phase effect, requires the scattering particles to be predominantly dielectric. The same is true for the 'negative' polarization observed at large elongations in the zodiacal light. The existence of interplanetary dust as near as 3.4 $R_\odot$ from the Sun (Peterson, 1967b) again cannot be explained with metallic (iron) particles and the emission features near 10 μm observed by Lena *et al.* (1974) are a strong case for the presence of silicate material. Micrometeoroid experiments measuring the chemical composition of the particles by a time of flight analysis of the ions produced during impact will be performed during the next years (Dietzel *et al.*, 1973).

The recent hypothesis of an elongated shape for the interplanetary particles rests on pecularities of the polarization of the zodiacal light, the observations being unconvincing so far. It is contradicted by well documented effects like the Gegenschein and negative polarization. The experimentally determined scattering functions show that only particles close to the spherical shape, e.g., rough spheres do show the required backscattering and proper polarization. From this, a large fraction of the zodiacal cloud would have to be of nearly spherical shape, a somewhat puzzling conclusion. Hörz *et al.* (1975) analyzed the symmetry of microcraters on lunar rocks and came to the conclusion that the micrometeoroids are of large-volume shapes. Recorded particle break-ups (Berg and Gerloff, 1971; Hoffmann *et al.*, 1975) indicate the presence of low density and perhaps fluffy objects. The question seems open. A very large deviation from spherical shape would be a serious difficulty for zodiacal light interpretations.

5.4. Dynamics and Origin

The solar radiation pressure is comparable to the gravitational attraction for particles with a $(\mu m)\cdot\varrho(g\ cm^{-3})\approx1$. The radiation pressure limit, i.e., the radius for which radiation pressure equals gravity has been calculated for spheres by Shapiro *et al.* (1966), Aller *et al.* (1967), Gindilis *et al.* (1969). For iron and nickel it is found between $a = 0.15$ μm and 0.20 μm, for hypothetical dielectric ($m = 1.33 - 0.05i$, $\varrho = 1.0$) a $= 0.50$ μm, while for a pure dielectric material (e.g., quartz with $m = 1.55$) or very small non-metallic particles (Schmidt and Elsässer, 1967) the radiation pressure force F_r is always smaller than gravity. The motion of the particles enhances the effect of radiation pressure. The reduction of gravity necessary to put particles released during the perihelion passage of a comet into hyperbolic orbits is 7% for comet Encke and 2% for comet Halley (Harwit, 1963). The solar radiation pressure is important both as a loss mechanism for small particles and an obstacle for the injection of new particles up to about 10 μm–100 μm. Dohnanyi (1972) argues that the decrease in the slope of the particle size distribution (Figure 24) near 10^{-7} g is due to this effect.

A particle orbiting the Sun with a tangential component of velocity $V_{\tan}$ experiences a breaking force

$$F_{pr} = F_r \frac{V_{\tan}}{c} \tag{24}$$

which is due to the aberration of the solar radiation (for an observer on the particle) resp. the relativistic forward emission of radiation (for an observer on the Sun) and called the *Poynting-Robertson-effect* (Robertson, 1937). Its main effect is a reduction of the semimajor axis of the particle orbit with a simultaneous decrease in eccentricity. Dobrovolskii *et al.* (1974), however, pointed out that under the combined influence of Poynting-Robertson-effect, vaporization and sputtering there will be no substantial decrease in eccentricity. The time for a particle in circular orbit to spiral into the Sun is approximately (Wyatt and Whipple, 1950)

$$t_{PR} = 10^3 \cdot a(\mu\text{m}) \cdot \varrho(g\ \text{cm}^{-3}) \cdot r^2(\text{AU})\ \text{yr} \tag{25}$$

which gives about 10^4 yr for a typical particle of the zodiacal cloud ($a = 1$ μm, $\varrho = 3$ g cm^{-3}, $r = 2$ AU). Near the Sun the particles may evaporate completely or down to a size where they are blown out of the solar system by radiation pressure (Belton, 1966). A special effect, suggested by Hemenway *et al.* (1973), would be the formation of submicron particles in the cooler parts of the solar atmosphere, which again would be driven into interplanetary space by radiation pressure. The evaporation of particles has been discussed in detail by Huebner (1970). The lifetime of the particles of the zodiacal cloud thus is determined by the Poynting-Robertson-effect. This is in contrast to the larger meteoric particles which predominantly are destroyed by collisions (Dohnanyi, 1972). If the zodiacal cloud is stable over the Poynting-Robertson lifetime (25) for its particles the required mass input to maintain equilibrium is proportional to the total brightness of the zodiacal light, since both effects depend on the particle cross section, and was determined to be $\approx 1 \times 10^6$ g s^{-1} (Whipple, 1955). Including the effect of collisions between the larger particles the total mass input necessary to maintain the meteoritic complex was found to be 10–20 $\times 10^6$ g s^{-1} (Whipple, 1967) resp. $\approx 25 \times 10^6$ g s^{-1} (Dohnanyi, 1972). Dohnanyi also shows that sporadic meteors – the class of interplanetary objects most similar to the zodiacal cloud in size and spatial distribution – probably are replenished from the meteor streams by collisions. No explicit statement is made where the mass disappears. Possibly the catastrophic collisions produce a large amount of very fine dust grains which then are expelled by the solar radiation pressure. Comets as well as asteroids would be able to provide the required mass input.

Direct evidence for the importance of the Poynting-Robertson-effect over the other forces, as the postulated spatial differentiation of meteor streams depending on meteoroid mass, is missing.

The effects of the solar wind on an uncharged particle are a minute contribution to the radial force ($\approx 10^{-3}$ of the radiation pressure), a tangential drag increasing in the average the Poynting-Robertson-effect by 25% and, most important, *sputtering*. Bandermann (1967) calculated the change in radius to be 6×10^{-6} μm yr^{-1} at 1 AU based on measurements of sputtering efficiencies by Wehner *et al.* (1963). Earlier authors overestimated the effect. Sputtering alone would not destroy a particle as fast as the Poynting-Robertson-effect, but with shrinking particle size radiation pressure and Poynting-Robertson-effect become more important.

Interplanetary dust particles most probably are charged to about 10 V positive (Rhee, 1967; Wyatt, 1969) independent of their size. Coulomb collisions with the solar wind protons give rise to the *coulomb drag* which according to Wyatt adds about 50% to the Poynting-Robertson force for typical parameters of the solar wind. The effect of the *Lorentz force* exerted by the magnetic field frozen in the interplanetary plasma is statistical in the sense that the change of sign with the sector structure of the interplanetary magnetic field occurs at much shorter time intervals ($\Delta t \approx 10^6$ s) than corresponds to the gyration of the interplanetary dust particles. Schmidt and Elsässer (1967) showed that the Lorentz force will remove submicron particles ($a \leqslant 0.1$ μm) from the solar system within less than 10 yr, while for a particle of size 1 μm it is already ineffective. Bandermann (1967) discussed the effect of the Lorentz force on the distribution of orbit inclinations, but found it insufficient to account for the observed wide distribution of the particles of the zodiacal cloud. If there were a steady polar component in the interplanetary magnetic field, which is controversial due to the difficulty of the measurement, this would drastically reduce the lifetime of interplanetary dust particles (Belton, 1966). A statistical fluctuation around a mean value of zero already could completely mask the Poynting-Robertson-effect (Bandermann, 1967). The experimental foundation for a quantitative calculation of these striking effects still is insufficient.

Most of the Lorentz force is due to the velocity of the solar wind. This component of the force often is called 'convective drag'. A few minor effects like the Jarkowski-Radziewski effect (see Öpik, 1951) are omitted here.

Usually a cometary vs an asteroidal origin the zodiacal cloud is discussed. The forces mentioned above together with the results of zodiacal light observations give limits to the orbital parameters of possible parent objects. It will be difficult to answer the question on the basis of kinematic arguments, since asteroids and short period comets have similar distribution of orbital parameters. The material could be a discriminating factor. In a study of photographic meteors which are thought to be of cometary material Jacchia *et al.* (1967) found a low density of typically 0.3 g cm^{-3}. This value depends on the method to estimate meteor photometric masses but is in agreement with the predictions of Whipple's comet model. Compact high density and metallic meteoroids would be classified as asteroid fragments. Perhaps first the relation of the zodiacal cloud to the general meteor background should be clarified. The spatial distribution in and outside the ecliptic plane and the apparently low spatial density of micrometeoroids in the asteroid belt indicate that these may be different populations. Going from the more massive objects like asteroids and comets to meteoroids and micrometeoroids the average inclination increases. This apparant dissipation has not been really understood. It suggests a chronological sequence for the interplanetary material, with the general meteor background as an intermediate step on the way from comets or asteroids into the zodiacal cloud.

One would not expect to find traces of the origin of the solar system in the zodiacal cloud. There may be comets releasing micrometeoroids from primordial matter, but these particles are subject to modifications by cosmic rays and solar wind, sputtering and collisions and can hardly be identified among the majority of second or third generation particles.

5.5. Possible interrelation between interstellar and interplanetary dust

This topic has gained new interest by the reported observation of a large ultraviolet excess in the zodiacal light between 160 nm and 220 nm which correlates with the decrease in interstellar absorption in this wavelength range (Lillie, 1972). Öpik (1951) hoped that a comparison between interplanetary and interstellar dust particles could be performed in the zodiacal light, where the brightness along the ecliptic would be almost entirely due to interplanetary particles while at high ecliptic latitudes a large fraction of the light scattering could be due to interstellar grains. Since typically models explaining the zodiacal light give a mass density at 10^{-21} g cm^{-3} at 1 AU in the ecliptic for 'flat' and 10^{-24} g cm^{-3} for 'steep' size distributions (Bandermann, 1967) a typical interstellar cloud with 3×10^{-25} g cm^{-3} (Greenberg, 1969) would possess sufficient scattering material to show up in the zodiacal light, especially if the albedo of the interstellar dust is high as indicated in the observation of dark nebulae (Mattila, 1970b). It cannot be excluded that the Sun is passing through an interstellar cloud but it is improbable that the interstellar dust grains could penetrate into the solar system against the forces associated with the solar wind, interplanetary magnetic field and solar radiation pressure (Greenberg, 1973).

6. Conclusion

During the last ten years the situation has changed in zodiacal light research. While then the observations were sparse and uncertain and could be explained by many models now there is a large amount of reasonably reliable data. An attempt to cover most of the observational aspects in one model, which could clarify the relative significance of the different types of zodiacal light observations, is missing. As a basis for such models more should be known about the light scattering on nonspherical particles. It is expected that the most conclusive results concerning spatial distribution and scattering properties of the interplanetary dust particles will be contributed from the measurements in deep space. Earthbound measurements remain important because of their greater variety and since the deep space measurements facilitate their interpretation. With respect to other methods of studying the interplanetary dust zodiacal light observations are a good measure of the spatial distribution and of large scale *changes* of average physical parameters like size and composition, while the information on material, size distribution and orbits is rather indirect. Only with the aid of micrometeoroid experiments and meteor observations the place of the zodiacal cloud in relation to the meteoritic complex, asteroids and comets probably can be found. Among the open question the particle dynamics is one of the most interesting.

Acknowledgements

My first thanks are to my colleagues H. Link and E. Pitz who made this review possible by taking over a larger part of the daily work of our group. I thank Dr Th. Schmidt and many other colleagues for their helpful comments. The general approach to the subject was mainly influenced by Drs H. Elsässer and J. L. Weinberg. The pictures were produced by Ms Haberbosch, the typing was done by Ms Flamme and Schwander. I am grateful to Centre Nationale de Recherche Scientifique, Blackwell Scientific Publications, University of Chicago Press, American Geophysical Union, Springer Verlag Berlin, Reidel Publishing Company, Optical Society of America, University of Arizona Press and Pergamon Press for permission to reproduce Figures 3, 8, 9, 12, 15, 16, 18, 20–24.

This work was supported in part by Grant RS-21 from Bundesministerium für Forschung und Technologie.

Appendix A

Alphabetic summary of observations presented in Figures 6, 7, 10, 11, 13

Author	Date	Place or vehicle	Wavelength band (nm) or colour system [a]	Observed quantity	Method [b]
Allen (1956)	June 30, 54	Island Syd-Koster, Sweden	400–600	I	pg
Beggs *et al.* (1964)	June/July 61	Chacaltaya 5.2 km	480 (broadband)	I	pe
Blackwell (1955/56)	June 30, 54	Aircraft 9 km	630 (broadband)	I	pg
Blackwell and Petford (1966)	July 20, 63	Aircraft 9 km	656	I, p, I_p	pe
Chiplonkar and Tillu (1967)	Feb. 64	Narayangoon 0.7 km	440, **530**, 600	I, C	pe
Dumont (1965)	Jan./Feb. 64	Teneriffa 2.4 km	502	I, p, I_p	pe
Dumont and Sanchez-Martinez (1966)	Aug.–Dec. 64	Teneriffa 2.4 km	502	I, p, I_p	pe
Frey *et al.* (1974)	May 13/Oct. 23, 72	Balloon 34 km	350, **500**, 710, 800	I, p, I_p, C	pe
Gabsdil (1971)	Oct. 1/2, 70	Balloon 34 km	350, **500**	I, C	pe
Gillett (1967)	1962–65	Balloon 30 km	B	I, p, I_p	pg, pe
	Feb/Oct. 65	Satellite OSO-2	V (?)	I, p, I_p	pe
Gillett *et al.* (1964)	July 20, 63	The Forks, Maine	**475**, 830 (broadband)	I	pe
		Balloon 34 km	400–650	I	pg
Hofmann *et al.* (1973)	Oct. 23, 72	Balloon 34 km	**710**, 2400	I, C	pe
Jameson (1970)	March 68	Jungfraujoch 3.6 km	510	I_p	pe
Leinert *et al.* (1974)	July 2, 71	Rocket 224 km	592 (broadband)	I, C	pe
			468 (broadband)	I, p, I_p	
Levasseur and Blamont (1973)	Apr. 71–June 73	Satellite D2A	653	I	pe
Lillie (1972)	Feb 17, 69	Satellite OAO-2	9 colours, 168 to **425** (broadband)	I, C	pe
	Feb./March 70				
MacQueen (1968)	Jan. 9, 67	Balloon 28 km	2.02–2.47 μm	I	pe
MacQueen *et al.* (1973)	Apr. 22/23, 72	Apollo 16 in lunar orbit	425–700	I	pg
Peterson (1967)	1962/63	McDonald Obs. 2.1 km	12 colours, 360 to 770	I, C	pe
Robley (1962)	Feb./March 61	Pic du Midi 2.9 km	463, **528**, 617	I, p, I_p, C	pe
Rouy *et al.* (1971)	1970	Satellite OSO-6	400, **500**, 600	I	pe
Smith *et al* (1965)	1961/62 9 nights	Haleakala 3.0 km	530	I	pe
Sparrow and Ney (1972)	1969/70	Satellite OSO-5	418, 618 (all broadband)	I, p, I_p, C	pe
Van de Noord (1970)	Nov. 65–March 66	Balloon 30 km	B, **V**	I, p, I_p, C	pe
Waldmeier (1961)	June 30, 54	Island Syd-Koster, Sweden	400, **530**, 610 (all broadband)	I	pg
Weinberg (1964)	Nov. 61–March 62	Haleakala 3.0 km	530	I, p, I_p	pe
Wolstencroft and Brandt (1967)	Aug. 2, 64	Chacaltaya 5.2 km	451, **530**, 707	I, p, I_p, C	pe
Wolstencorft and Rose (1967)	Sept. 15, 64	Rocket 205 km	B, **703**	I, p, I_p, C	pe

[a] Bands in bold face were taken for the figures.
[b] pg=photographic, pe=photoelectric.

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