1 ZODIACAL LIGHT

1.1 OBSERVATIONS FROM SPACE

1.1.1 SPACE OBSERVATIONS OF THE ZODIACAL LIGHT

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Abstract. A listing and discussion are given of balloon, rocket, satellite, and space probe observations of the zodiacal light. The paucity of space observations in several critical areas (e.g., in the ultraviolet and near the sun) is noted and suggestions are made for experiments to meet these needs.

Figure 1 shows the zodiacal light as it typically appears at a low, northern latitude site in the mid-January morning sky. This photograph was taken in January 1967, several weeks before the first international symposium on interplanetary dust and the zodiacal light. At that time there were relatively few space observations, and most of our knowledge of the zodiacal light was derived from ground based observations. In recent years there has been an increasing number of space experiments, and it is most appropriate to have a second meeting at this time and in this place, where interplanetary dust and zodiacal light have been studied intensively for a number of years and where several important space experiments have recently been performed:

1. The first observations of the inner zodiacal light during the day and outside of eclipse (Leinert, et al. 1974a);
2. Multicolor observations of the zodiacal light from a balloon (Frey, et al. 1974; Hofmann, et al. 1973);
3. A zodiacal light experiment (Leinert, et al. 1974b) and a micrometeoroid detection experiment (Dietzel, et al. 1973) on Helios A, the first probe of the inner solar system; and
4. Near-earth and interplanetary measurements of micrometeoroids from HEOS 2 (Hoffmann, et al. 1975).

From Ground to Space. As the results of different ground observers came into better agreement and more opportunities arose for space observations, attempts were made to verify earlier zodiacal light results and to make observations not able to be made from the ground. One reason for going into space is illustrated in Figure 2 which shows the F-corona/inner zodiacal light as photographed from lunar orbit during the Apollo 15 mission (Mercer, et al. 1973b). This region is masked by twilight and is not observable from the ground (the apex of the cone in the Apollo photograph is approximately 20 degrees from the sun; i.e., it would be behind the outcropping of rocks shown in Figure 1). Having gone "from ground to space", it is appropriate for the author to enumerate the reasons for going (and, subsequently, to indicate what may be found when

Fig. 1. Photograph of the morning zodiacal light by P. B. Hutchison; Mt. Haleakala, Hawaii, 12 January 1967. 100 sec exposure on Kodak Tri-X. The outcropping of rock at the base of the zodiacal light cone is approximately 20 degrees from the sun.

Fig. 2. Apollo 15 photograph of the F-corona/inner zodiacal light from lunar orbit using a 70mm Hasselblad electric camera and Kodak 2485 film. Mercury, at 28 degrees from the sun, and Regulus are seen above the apex of the light cone.

one gets there):

1. To observe near the sun. Zodiacal light observations must avoid twilight, and corrections for airglow continuum and scattered light are uncertain closer than 10 degrees to the horizon. Therefore, observations from the ground are essentially restricted to elongations greater than 30 degrees.
2. To observe in the ultraviolet. Observations are difficult even in the blue and near ultraviolet. Atmospheric absorption is high, and there are relatively few windows that are free of airglow line and band emission.
3. To observe in the near infrared and parts of the infrared that are obscured by atmospheric emission and absorption.
4. To measure the change in zodiacal light with heliocentric distance in and out of the ecliptic and, thereby, to derive information on the spatial distribution of interplanetary dust.
5. To perform combined micrometeoroid/zodiacal light experiments.
6. To avoid uncertainties arising from airglow line and continuum emission, atmospheric scattering and extinction, and light pollution.
7. To increase the useable observing time by avoiding bad weather, the moon, and the personal equation.
8. To avoid confusion from the changing celestial aspect inherent in ground observations.

Although many of these difficulties are removed in space observations, a new, in many ways more difficult, set appears:

1. Limitations on location, weight, volume, power, and data rate.
2. Instrument design, test, and delivery are often based on system delivery schedules rather than on engineering or scientific readiness, resulting in insufficient time or access to the instrument for testing and calibration prior to launch.
3. Launch can abort or the instrument can fail, with little or no chance for repair.
4. Scheduling difficulties or degradation of data can result from spacecraft maneuvers, changes in experiment or mission priorities, contamination (spacecraft corona or particulate deposition), competition for astronaut time, interior vehicle lighting, etc.
5. Inadequate vehicle or instrument pointing information.
6. Effects of vehicle mechanical or electrical limitations or failures on instrument operation.
7. Environmental effects such as temperature variations associated with cyclic day-night-day operation, radiation effects during passage through the South Atlantic anomaly, ultraviolet degradation of optical components, high or low temperature operation, etc.
8. Stray light from direct or indirect solar radiation (Leinert and Klüppelberg 1974).
9. There are often long delays in getting correct data tapes.
10. In many cases, insufficient funds or time are provided for data analysis.

This represents a formidable set of obstacles, and without extensive engineering and scientific assistance one is certain to have several years of lower scientific productivity. In spite of these difficulties, a number of experimenters have survived and a great deal of new information from space experiments is now available on the observational characteristics of the zodiacal light.

To discuss every observation of zodiacal light from space in detail would be outside the scope of this paper and probably of limited value. A listing of these observations can, however, help to show what experiments have been performed and which areas require additional study. Therefore, we present in the next section an annotated listing of space observations of the zodiacal light and follow that with a discussion of selected results and with suggestions for additional experiments.

Table 1

An Annotated Listing of Space Observations of the Zodiacal Light

Institution	Date of Observation	Type of Observation or Detector	Wavelength Coverage	Polarization*	Selected References	Notes
A. Balloons.						
Univ. of Minnesota	1962-1965	photographic, PMT's	broadband: blue, visual	x	Gillett (1966); Gillett, et al. (1964)	1
Univ. of New Mexico	1965, 1966	PMT	broadband: 4000, 4350, 5500A	x	Regener and Vande Noord (1967); VandeNoord (1970)	2
MPI - Astronomy, Heidelberg and Heidelberg Observ.	1970	PMT	medium band: 5500	x	Gabsdil (1971)	3i
	1972	PbS	broadband: 2.4μ		Hofmann, et al. (1973)	3ii
	1972	PMT's	medium band: 3500, 5000, 7100, 8200	x	Frey, et al. (1974)	3iii

Notes:
1. The first space observations of the zodiacal light.
2. Observations of the inner zodiacal light, 25 to 50 degrees elongation, during solar minimum. No correlation was found with solar activity or lunar age, although the evening zodiacal light was found to be 30% brighter than the morning zodiacal light.
3. These observations were performed with the balloon-borne telescope THISBE. No deviation from solar color was found between 3500A and 2.4μ. Polarization observations at 5000A (iii), from 80 to 180 degrees elongation in the ecliptic, confirmed the existence of negative polarization** at large elongations.

* x indicates that polarization observations were made, although not necessarily at all of the indicated wavelengths.
** Electric vector parallel to the scattering plane.

Table 1, continued

An Annotated Listing of Space Observations of the Zodiacal Light

Institution	Date of Observation	Type of Detector	Wavelength Coverage	Polarization*	Selected References	Notes
B. Rockets.						
Kitt Peak National Observatory	Sept 1964	PMT	medium band: 4500, 7030A	x	Wolstencroft and Rose (1967)	1
University of Wisconsin	Sept 1964	PMT	2200 to 2900 and 4170; 7 colors		Lillie (1968, 1972)	2
Tokyo Astronomical Observatory	July 1965	PMT	medium band: 4300, 5300, 6000		Tanabe and Huruhata (1967)	3
Nagoya University	Jan 1969	PbS	broad band: .52, 1.23, 1.57, 2.16μ		Hayakawa, et al. (1970); Nishimura (1973)	4
Cornell University	Dec 1970	copper doped germanium	5-16 μ 12-14μ 16-23μ		Soifer, et al. (1971)	5
MPI - Astronomy, Heidelberg and Heidelberg Observ.	July 1971	PMT	broad band: 4680, 4755, 5915	x	Leinert, et al. (1974a)	6
Los Alamos Scientific Laboratory	July 1972 eclipse	PMT	medium band: 3500, 4500, 5500, 6500	x	Sandford, et al. (1973)	7

* x indicates that polarization observations were made, although not necessarily at all of the indicated wavelengths.

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Table 1, continued

An Annotated Listing of Space Observations of the Zodiacal Light

Institution	Mission or Spacecraft	Date of Observation	Type of Observation or Detector	Polarization*	Selected References	Notes
C. Satellites. (1) Manned						
University of Minnesota	Gemini 5	Aug 1965	photographic, Kodak Tri-X		Ney and Huch (1965)	1
University of Minnesota	Gemini 9	June 1966	photographic, Kodak Tri-X		Ney (1966)	
NASA and Dudley Observatory	Apollo 14	Jan 1971	photographic, Kodak 2485		Dunkelman, et al. (1971)	2
Dudley Observatory, NASA, High Altitude Observatory	Apollo 15	July-Aug 1971	photographic, Kodak 2485		Mercer, et al. (1973b)	2
High Altitude Observ. and NASA	Apollo 16	April 1972	photographic, Kodak 2485		MacQueen, et al. (1973b)	2
NASA and Dudley Observatory	Apollo 16	April 1972	photographic, Kodak 2485		Dunkelman, et al. (1972)	2
Dudley Observatory and NASA	Apollo 17	Dec 1972	photographic; broad band - blue and red	x	Mercer, et al. (1973a)	2i
High Altitude Observ. and NASA	Apollo 17	Dec 1972	photographic, Kodak 2485		MacQueen, et al. (1973a)	2
Johns Hopkins University	Apollo 17	Dec 1972	ultraviolet spectrometer		Fastie, et al. (1973)	3

* x indicates that polarization observations were made, although not necessarily at all of the indicated wavelengths.

Table 1, continued

An Annotated Listing of Space Observations of the Zodiacal Light

Institution	Mission or Spacecraft	Date of Observation	Detector	Wavelength Coverage	Polarization*	Selected References	Notes
C. Satellites. (1) Manned, continued							
State Univ. of NY at Albany and Dudley Observatory	Skylab	June, Aug 1973	PMT	narrow to medium band: 4000 to 8200A, 10 colors	x	Weinberg, et al. (1975)	4
NASA, State Univ. of NY at Albany, Dudley Observatory	Skylab	Aug 1973	Kodak 2485 film	visual		Kessler, Zook, Mercer, and Weinberg (unpub.)	5
(2) Unmanned							
University of Minnesota	OSO-B2	Feb 1965-Nov 1965	PMT	broad band: blue, visual	x	Sparrow and Ney (1968)	1
California Institute of Technology	Surveyor 6 Surveyor 7	Nov 1967 Jan 1968	camera/vidicon	visual		Bohlin (1971)	2
University of Wisconsin	OAO-2	Dec 1968-	PMT	medium band: 1050 to 4250, 12 colors		Lillie (1972)	3
University of Minnesota	OSO-5	Jan 1969-	PMT	broad band: 4180, 5410, V, R, 6820	x	Burnett, et al. (1972)	4
Rutgers University	OSO-6	Aug 1969-Jan 1972	PMT	medium band: 4000, 5000, 6100	x	Roach, et al. (1972)	5
Service d'Aeronomie du CNRS	D2A (Tournesol)	Apr 1971-June 1973	PMT	narrow band: 6530		Levasseur and Blamont (1973a,b)	6

* x indicates that polarization observations were made, although not necessarily at all of the indicated wavelengths.

Table 1, continued

An Annotated Listing of Space Observations of the Zodiacal Light

Institution	Mission or Spacefraft	Date of Observation	Detector	Wavelength Coverage	Polarization*	Selected References	Notes
D. Space Probes.							
Soviet unmanned interplanetary station, Venus-3		Nov-Dec 1965	nitrous oxide filled Geiger counters	1050-1340A 1225-1340		Kurt and Syunyaev (1967)	1
University of Arizona, State Univ. of NY at Albany, Dudley Observatory	Pioneer 10 Pioneer 11	Mar 1972- Apr 1973-	dual-channel Channeltrons	broad band: blue, red	x	Weinberg, et al. (1973)	2
General Electric, Philadelphia	Pioneer 10 Pioneer 11	Mar 1972- Apr 1973-	PMT's	broadband, visual		Zook and Soberman (1974)	3
MPI - Astronomy, Heidelberg and Heidelberg Observatory	Helios A	Dec 1974-	PMT's	UBV	x	Leinert, et al. (1974b)	4

* x indicates that polarization observations were made, although not necessarily at all of the indicated wavelengths.

Notes to Table 1B:

1. The first observations of the brightness and polarization of the zodiacal light from above the scattering atmosphere. Negative polarization was found at large elongations, and circular polarization was found between 40 and 65 degrees elongation near the ecliptic. The zodiacal light was found to be bluer than the sun at elongations beyond 110 degrees and 15 per cent brighter at the south ecliptic pole than at the north ecliptic pole. The absolute brightnesses were substantially higher than those found in most ground observations.
2. First ultraviolet observations of the zodiacal light. The brightness of zodiacal light was found to increase sharply below 2500A.
3. First rocket observations of the inner zodiacal light, 15 to 41 degrees elongation. Brightnesses were found to increase sharply at small elongations (toward the horizon), suggesting that the observations were undercorrected for airglow emission at these elongations.
4. First infrared observations of the zodiacal light. Except for a weak enhancement at 1.6μ, the zodiacal light was found to have the color of the sun from .52μ to 2.16μ.
5. Thermal emission was detected in the zodiacal light at 160 degrees elongation near the ecliptic.
6. The first observations of the inner zodiacal light during the day and outside of eclipse. Observations were made in 360 degree circles around the sun at elongations 15, 21, and 30 degrees. The zodiacal light was found to be slightly red compared to the sun, and the minimum to maximum brightness ratios for each circle were found to be approximately .32, in agreement with results at 90 degrees elongation (Sparrow and Ney 1972; Dumont and Sanchez 1973). The degree of polarization in the plane of symmetry was found to be higher than expected from ground based observations, and it showed a large decrease away from this plane.
7. Observations were made at 12 elongations, 0 to 30 degrees, east and west of the eclipsed sun. The data were degraded by scattered light and by a trajectory error, but brightness observations west of the sun were less affected and suggest a reddening at very small elongations.

Notes to Table 1C(1):

1. The first photographs of zodiacal light and Gegenschein from a manned spacecraft.
2. The Apollo photography of the F-corona and zodiacal light was carried out from Command Modules while in the "double umbra"; i.e., that dark region free from sunlight and earthshine. Cameras used: Maurer 16mm, Nikon 35mm, Hasselblad 70mm. During Apollo 17, the first measurements were made of color and polarization (2i). Preliminary results showed the zodiacal light within 15 degrees of the sun near the ecliptic to be brighter in the red than in the blue and to be less bright in the red for all other regions.
3. Twice during lunar orbit the lunar atmosphere ultraviolet spectrometer was used to measure the inner zodiacal light. Although a preliminary analysis is said here to generally support the OAO-2 observations (i.e., enhanced brightness at short wavelengths), Lillie, in a private communication to C. Leinert (Leinert 1975), reports no excess brightness in the zodiacal light at 1470A.
4. This experiment is discussed later in this paper.
5. Photographs were taken of a region of sky containing the Gegenschein using equipment of Skylab experiment T025 (externally occulted coronagraph with the occulter rotated out of position and a 35mm Nikon camera).

Notes to Table 1C(2):

1. Observations of brightness and polarization at 90 degrees elongation for ecliptic latitudes from 50 degrees to the north pole. No changes greater than 10 per cent were detected in the polarized brightness, including observations during periods of strong magnetic index, K_p.
2. Inadequate calibration precluded polarimetry and absolute photometry, although some relative photometry of the F-corona/inner zodiacal light was accomplished by normalizing the Surveyor data to published mean values for the corona.
3. Fixed position, all-sky observations made during satellite night. The zodiacal light was found to be redder than the sun for wavelengths above 2500A with a sharp increase in brightness below 2500A.

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Notes to Table 1C(2), continued:

4. Long-term multicolor observations of brightness and polarization at 90 degrees elongation for all ecliptic latitudes. No difference was found between zodiacal light brightnesses at northern and southern ecliptic latitudes, and no changes were found with solar activity, lunar phase, the orbital plane of Comet Encke, or an annual cycle (Burnett, 1976).
5. Three-color observations of brightness and polarization at 5-degree intervals of elongation from 180 to ± 10 degrees. Observations were only possible during satellite day, and stray light has limited analysis to observations near the anti-solar point. Large, short-term changes were observed in the direction and amount of polarization (Roach, et al. 1974) and in the brightness in this region, the suggestion being made that the latter changes are a result of scattering by dust in the "general region of the earth-moon system" (Roach, et al. 1973).
6. Observations of brightness at 90 degrees elongation for all ecliptic latitudes. Observed short and long period changes were ascribed to local meteor streams and the changing position of the earth with respect to the invariant plane, respectively. Burnett, et al. (1974) attribute at least part of the short term changes to scattered moonlight.

Notes to Table 1D:

1. 2×10^{-12} ergs/cm^2 sec ster A is given as an upper limit for the intensity of zodiacal light at 1300A.
2. This experiment is discussed later in this paper.
3. Brightness measurements in the zodiacal light mode of the Asteroid Meteoroid Detector have been made periodically from both spacecraft since launch (see, also, Soberman, et al., 1976).
4. The first observations of the zodiacal light inside the earth's orbit (perihelion near 0.3 AU). Measurements of brightness and polarization with three photometers, fixed at 75, 60, and 0 (toward the south ecliptic pole) degrees with respect to the spacecraft spin axis (Pitz, et al., 1976, Link et al., 1976).

Table 1 illustrates the enormous growth in space observations of the zodiacal light in just the past decade - and their diversity. At the same time, there have been relatively few ground based observations of the zodiacal light, especially during the past five years. In spite of this space activity, several important areas have still received little or no study: polarization measurements in the ultraviolet and infrared, observations near the sun, and all-sky observations (color and polarization).

Selected Results and a Look at the Future

1. Observations from Skylab. Multicolor observations of sky brightness and polarization over large regions of the antisolar hemisphere were obtained with a photoelectric polarimeter during Skylab missions SL-2 and SL-3 (Weinberg, et al. 1975). The original plan to also observe the solar hemisphere, to within 15 degrees of the sun, had to be abandoned following the loss of use of a solar-pointing scientific airlock after launch. The instrument was extended outside the spacecraft and could be operated in fixed-position or sky scanning modes. Table 2 summarizes observing programs performed with the photometer during the Skylab missions (see, also, Figure 1 in Sparrow, et al.; 1976). The availbility of only limited amounts of valid data has restricted analysis to parts of fixed position (Mode 1) programs. Preliminary results have been derived on the spacecraft corona (there were levels of sky brightness in

daylight only five per cent above those at night) and on the polarized brightness of the zodiacal light (Sparrow, et al.; 1976). Much of the data have just been made available (September-October 1975) in useable form, and it will now be possible to derive results for the scanning programs and to complete the analysis of fixed position data.

Table 2

Observations with the Skylab Photometer

Mission	Mission day	1973 date	Mode		Program*
SL-2	19	June 12	4		sky map (7 colors, 5300-8200)
	19	12	1	I	north celestial pole
	19	12	1	II	south ecliptic pole
	19	12	1	III	contamination, 2 parts: night/day, day/night
	22	15	4		sky map (9 colors, 4000-7100)
	22	15	1	IV	north galactic pole
	22	15	2	V	elevation scans
	22	15	4**		sky map (4000, 4760)
	23	16	4**		sky map (7 colors, 5080-7100)
	23	16	3		azimuth scans (5 colors, 4000-5577)
	23	16	3**		azimuth scans
	24	17	3**		azimuth scans
SL-3	5	August 1	4**		sky map (4000)
	6	2	4**		sky map (4760)
	7	3	1		Gegenschein (5 colors, 4000-5577)
	7	3	1		contamination, night/day
	7	3	1		night/day scan, gravity-oriented
	7	3	1		Gegenschein
	7	3	2**		elevation scans
	8	4	2**		elevation scans

*10-color observations, unless otherwise indicated.
**Program started one day and ended the following day.

2. Observations from Pioneers 10 and 11. Imaging photopolarimeters on the Pioneer 10 and 11 probes are being used by our group to map sky brightness and polarization in the blue and red from heliocentric distances beyond 1 AU. The combination of telescope stepping and spacecraft roll produces sky data for the entire sky between 28 and 170 degrees (near the antisun direction) from the spacecraft spin axis in a sky map or grid of observations consisting of 78 data rolls and 64 effective fields of view per roll per color. Since the spin axis moves slowly on the celestial sphere, most of the sky within approximately 30 degrees of the sun is eventually covered with a resolution better than

the 1.8 degree roll-to-roll (cone angle) separation of fields of view in a single sky map. Figure 3 shows the trajectories for Pioneers 10 and 11 and the spacecraft positions from where sky maps were made. Measurements are continuing with both spacecraft.

Major results to date: The Gegenschein was observed when the spacecraft antisun direction was 3.4 degrees from the earth antisun direction and when the spacecraft was 1.011 AU from the sun (Weinberg, et al. 1973). Brightnesses in the ecliptic at elongations greater than 90 degrees show no change (i.e., negligible zodiacal light) beyond 3.3 AU (Hanner, et al. 1974). Observations from beyond the asteroid belt are being used to derive a map of the background starlight in two colors with high spatial resolution (Weinberg, et al. 1974). Observations from 1 to 3 AU are being used to derive

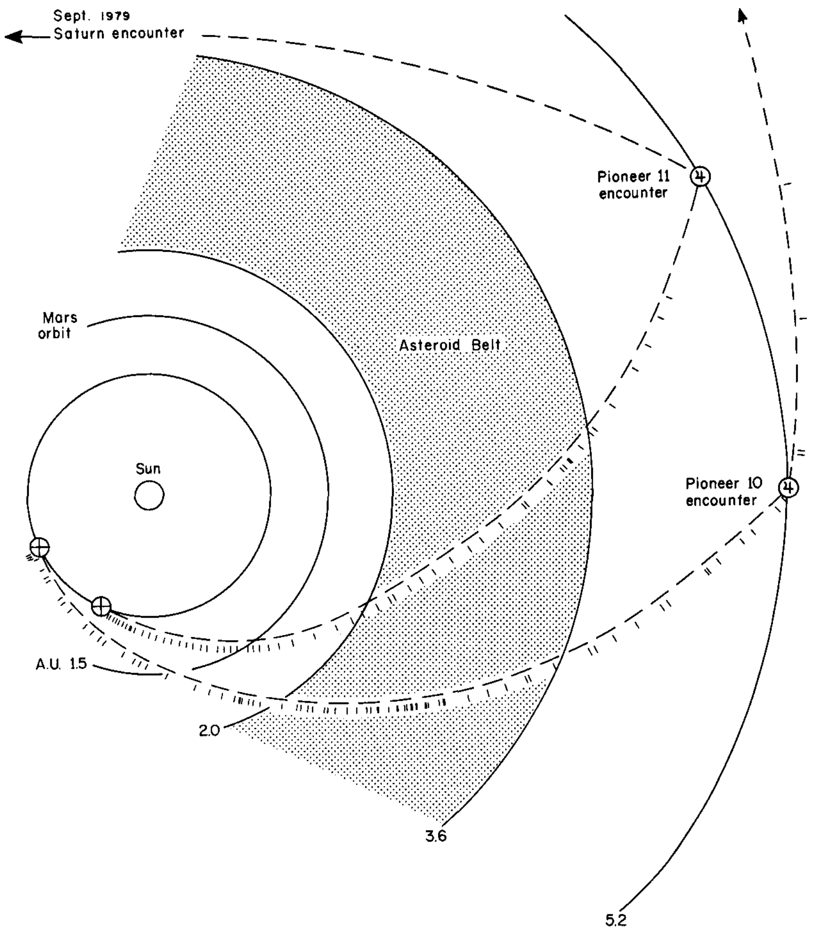

Fig. 3. Trajectories and celestial aspect for Pioneers 10 and 11. Tick marks along the trajectories indicate spacecraft positions from where sky maps were made with the imaging photopolarimeters.

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the change in zodiacal light brightness with heliocentric distance (Hanner, et al.; 1976).

3. Wavelength Coverage. Multicolor brightness observations by Peterson (1967), Nishimura (1973), Hofmann, et al. (1973), Frey, et al. (1974), and others show the zodiacal light to have the color of the sun from the near ultraviolet out to 2.4μ. Similarly, Sparrow, et al. (1976) find the polarized brightness of the zodiacal light to have the solar color in the visible. Therefore, the degree of polarization is not wavelength dependent in the visible. Additional information on the sizes of the particles would be available from polarization observations in the ultraviolet, especially if the degree of polarization was found to change with wavelength in that region. No polarization observations have been made in the ultraviolet, although balloon observations of brightness and polarization are planned by A. Frey, rocket observations are planned by E. Pitz and by C. F. Lillie, and observations of brightness are planned from the French satellite D2B (Maucherat and Cruvellier; 1976; Llebaria, 1976). Limited ultraviolet-visible observations of the zodiacal light may be possible with a photopolarimeter during the cruise phase of the Mariner Jupiter-Saturn missions (Lillie 1974). Additional observations in the ultraviolet and infrared might disclose signatures or features (e.g., 2200A in the UV and 10μ in the IR) and, thereby, provide more direct information on the nature and sizes of the particles that give rise to the zodiacal light.

4. Spatial Coverage. As noted earlier, ground observations are restricted to elongations greater than 30 degrees, which means that they cannot see the effects of particles closer than 0.5 AU to the sun. Although extremely difficult to observe, brightness and polarization observations from the ultraviolet to the infrared in an annulus from 5 to 30 degrees from the sun probably contain more information on the nature of the particles than any other region. There are relatively few all-sky observations beyond 30 degrees elongation, even in the visible. The information-laden regions at large elongations, for example, are underobserved, and accurate observations of brightness, polarization, and color extending into the ultraviolet are not yet available.

Zodiacal light observations from Pioneer 10 and 11 and from Helios can provide information on the spatial distribution of interplanetary dust throughout the region from 0.3 to 3.3 AU (Hanner and Leinert 1972). Dumont (1972, 1973), Leinert (1975), and others have discussed inversion of the brightness integral to obtain information on the spatial distribution and scattering properties of the particles. It is generally assumed that the scattering properties do not depend on heliocentric distance, R, although this restriction is probably not realistic, especially in the inner solar system. If Pioneer 10 and 11 observations of polarization versus elongation (beyond 90 degrees) differ with R, it is likely that the scattering properties do change with heliocentric distance.

Concluding Remarks

Observations close to the sun can best provide information on the nature and sizes of the zodiacal dust, on possible solar storm effects, and on the vaporization zone; ultraviolet observations of brightness and polarization over a large range of elongations can provide information on the sizes and, perhaps, composition of the zodiacal dust;

more extensive observations in the ultraviolet and infrared may provide signatures or features characteristic of particular materials.

We now have preliminary results on the spatial extent of the zodiacal light and its appearance from the inner solar system to the asteroid belt and more consistent results on its brightness from the near ultraviolet to the near infrared. If we are to go beyond understanding its observational characteristics and derive information on the particles that give rise to the zodiacal light, we must have the aforementioned observations and further laboratory and theoretical studies of the properties of small and moderate size particles of different shapes.

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