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POLARIZATION OF THE ZODIACAL LIGHT: FIRST RESULTS FROM SKYLAB

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Abstract. A brief description is given of the Skylab ten color photoelectric photometer and the programs of measurements made during Skylab missions SL-2 and SL-3. Results obtained on the polarized brightness of zodiacal light at five points on the antisolar hemisphere are discussed and compared with other published data for the north celestial pole, south ecliptic pole, at elongation 90 degrees on the ecliptic, and at two places near the north galactic pole.

Introduction. The Skylab ten color photoelectric polarimeter was designed to measure the surface brightness and direction and amount of polarization of the zodiacal light. The photometer and a 16mm camera were attached to an alt-azimuth mount at the end of a universal extension mechanism that could be deployed up to 5.5m out either the solar or antisolar scientific airlock of the Saturn workshop. Loss of the spacecraft meteoroid shield during launch removed the availability of the solar airlock for this experiment. Thus all observations with the photometer were made from the antisolar scientific airlock.

The Instrument. A brief description of the instrument will suffice here as a more detailed description is available elsewhere (Weinberg et al., 1975). The photometer consisted of a sunshield, a telescope cap with attached Pm 147-activated phosphor source for instrument performance monitoring, Fabry optics with a 6.35cm primary objective, two six position wheels each containing 5 interference filters and an open position, an HN32 rotating polaroid, a wheel with six field of view/neutral density filter combinations and a detector package.

The detector package contained an EMR 541E photomultiplier (with selected S-20 response), a high voltage supply, and an output voltage differential amplifier with time constant of approximately 2 msec. A thermoelectric cooler kept the photomultiplier photocathode at a temperature of approximately $-10^{o}C$; this temperature along with that of the filters and the cap source were monitored.

The photomultiplier output was sampled at 320 sps (nominal 2^8 bit words) while a similar channel was used to record the polaroid position pulse generated once per cycle as the HN32

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polaroid rotated at approximately 2 RPS. These two channels, together with other instrument data sampled less frequently, were stored by an onboard digital tape recorder and subsequently telemetered, or were telemetered to the ground in real time. The elevation and azimuth of the pointing direction of the photometer were recorded 20 and 10 times per second, respectively; however, in this paper we have used the right ascension and declination obtained from the camera photographs with an accuracy of better than $\pm 0.1^{o}$.

Instrument Calibration. The calibration has been based on the signals measured during the scanning programs as the stars Vega, Arcturus and Spica traversed the field of view. Each of these stars was scanned at least twice at all ten wavelengths except 8200A, and the photometer star signal was related to the star's magnitude at each filter wavelength. The magnitude was obtained from a reciprocal wavelength curve fit to the Johnson, et al. (1966) and Mitchell and Johnson (1969) photometric data. Conversion to a calibration in units of $S_{10}(V)$* was obtained using the absolute flux of Vega given by Hayes and Latham (1975), the absolute solar flux given by Johnson (1954), an apparent solar visual magnitude of -26.73 (Stebbins and Kron, 1957) and the angular area of the field of view. We estimate the uncertainty of our calibration at each wavelength as not greater than: 8200A$\pm$20%; 4000A$+10\%_{-20}$; 4760A$+6\%_{-12}$; 6300A$\pm$10% and $\pm$6% at all other wavelengths. Further details of the Skylab photometer calibration are given in Sparrow et al. (1975).

Observational Programs. An automatic programmer was included to operate the photometer manually or in any of seven automatic modes:

0 calibration
1 fixed position
2 vertical circle (scan in elevation h at fixed azimuth)
3 almucantar (scan in azimuth at fixed elevation)
4 limited-area sky map (almucantars separated 2.8 degrees in h)
5 all-sky map (almucantars separated 5.6 degrees in h)
6 stowage position return.

A description of the instrument is given by Weinberg, et al. (1975). Table 2 in Weinberg (1976) lists the observing programs which were performed with the photometer during the first (SL-2) and second (SL-3) missions. The 6 degree angular diameter field was used for most of the observations. Figure 1 illustrates the areas of the antisolar hemisphere for which useful data have been obtained from SL-2, including the five fixed pointing programs whose results are given here.

Data Analysis and Some Preliminary Results. The photomultiplier data are being analyzed by means of a least squares fit to an expression of the form PMT output = $A + Bt + C \sin(\omega t + D)$, where the frequency ω is determined from the polaroid position-pulse repetition rate. The

*the equivalent number of tenth magnitude (V) stars of solar spectral type per square degree (see preceding paper).

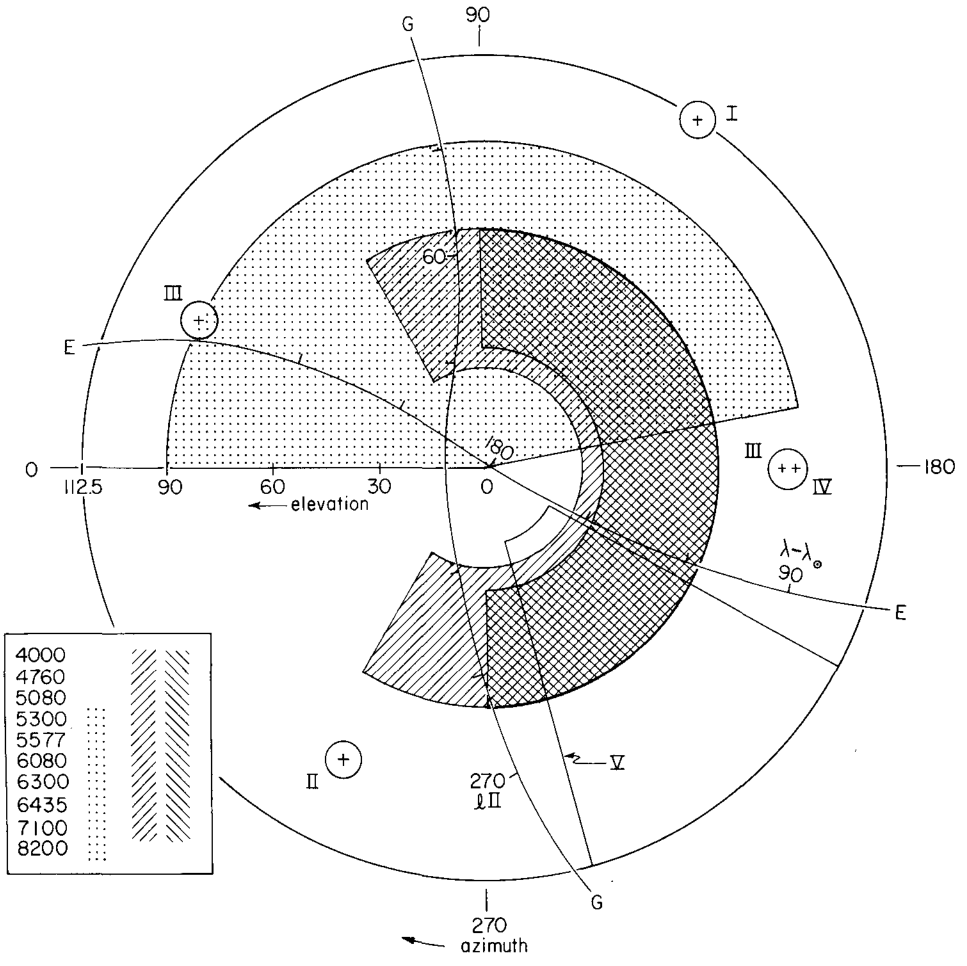

Fig. 1. Regions of the antisolar hemisphere for which useful data were obtained during SL-2. G and E show the positions of the galactic equator and ecliptic, respectively. ℓ^{II} refers to System II galactic longitude in degrees and $\lambda - \lambda_{\odot}$ refers to the ecliptic longitude of the observed point with respect to the sun, in degrees. The inset shows the filters used with the sky-mapping programs.

phase angle D can be transposed to give the direction of the plane of polarization of the measured light. Comparison with that expected from zodiacal light gives some measure of confidence that additional components of polarized light are not contributing to the measured signal. This is particularly relevant since the SL-2 observations were taken when the moon was between 88% and 100% illuminated. For this paper, no analysis has been attempted during times when:

1. The spacecraft was in daylight;
2. The spacecraft was in the vicinity of the south Atlantic anomaly;
3. The photometer pointed below the spacecraft horizontal;

4. The photometer pointed within 60 degrees of the moon.

During these fixed pointing programs the photometer cycled through each of the 10 filters a number of times. Each color measurement took 10 seconds; between filters the shutter remained closed for 2 or 4 seconds to provide measurements of dark current. Unfortunately not all of the repetitions at each color, satisfactory according to the above four criteria, are presently suitable for analysis. This is caused by the introduction of an amplitude change compression factor (K3) during transmission of the data between ground stations prior to preparation of the experimenter tapes. This resulted in removal of all changes in photomultiplier output voltage that did not equal or exceed 80 mv (4 bits compared to full scale 256 bits) for some periods of data. Since the amplitude of the sinusoidal component was often less than this, some of the information on the polarized component of the zodiacal light was thereby lost from these periods of time. Regenerated experimenter tapes with no data compression (Kl), expected to be available soon, will eliminate this problem.

For each of the fixed pointing programs, data without the amplitude change compression factor have been analyzed where available; for those periods where it was not available, we have used the K3 data as indicated in Table 1. It is anticipated that for these time periods, an

TABLE 1

Zodiacal Light Polarized Brightness

Central Wavelength	$\Delta\lambda$	"north celestial pole"	"south ecliptic pole"	"90 deg elongation on ecliptic"	"north galactic pole"	"north galactic pole"
		ϵ β	ϵ β	ϵ β	ϵ β	ϵ β
A	A	67.5° 66.0°	94.9° -84.9°	89.0° 4.7°	96.3° 29.3°	93.6° 30.9°
		$S_{10}(V)$	$S_{10}(V)$	$S_{10}(V)$	$S_{10}(V)$	$S_{10}(V)$
4001	110.0	23.1	16.1	30.2	--	20.5(2)
4748	47.5	18.0	11.0	25.3	16.9	16.1(2)
5068	49.7	20.4	12.7	26.7	18.9	17.8
5294	61.0	19.0	14.2(1)	25.8	17.6	18.8
5562	17.0	20.0	13.2(1)	27.5	--	19.3
6063	83.0	19.5	12.4(1)	26.0	17.4	18.5
6286	20.0	19.3	12.6	30.1	--	17.8
6427	108.2	18.6	9.2(1)	25.8	16.8	19.0
7093	135.0	20.9	13.9	28.3	19.0	19.0
8160	222.0	16.1	8.8	19.4	13.2	14.4(2)
Mean values		19.5 ± .2	12.4 ± .2	26.5 ± .3	17.1 ± .3	18.1 ± .2
Number of 10 second intervals/color		7 (mixed)	1 (Kl)	6 (mostly Kl)	1 (K3)	2 (Kl)

(1) 6 or 7 seconds of data only
(2) 10 seconds of data only

improvement in precision will be achieved when the new experimenter tapes (without the compression factor) are analyzed. During 4 of the 5 programs discussed here, the instrument pointing direction remained constant within $\pm 0.1^{\circ}$ in right ascension and declination; during the final fixed pointing program, a spacecraft reorientation procedure was in progress and the pointing direction changed by about 5° during the course of the program. The photometer pointing direction is presently taken to be the same as that of the camera. The prelaunch boresite measurement coupled with the analysis of star crossings will enable any offset to be determined.

The results obtained from the five fixed pointing programs are shown in Table 1. It is apparent that the color of the polarized component of the zodiacal light is close to that of the sun.

TABLE 2

Zodiacal Light Polarized Brightness

Author(s)	Color	"90 deg elongation on ecliptic" $S_{10}(V)$	"north ecliptic pole" $S_{10}(V)$	"north celestial pole" $S_{10}(V)$
Behr and Siedentopf (1953)	5430A visual (1)	22 (2)		
Elsässer (1958) (3)	visual	40		
Peterson (1961)	4355A blue (4)	33		
	5425A green (4)	46		
Beggs, et al. (1964)	blue	35 (5)		
Weinberg (1964)	5300A	46		
Dumont (1965) Dumont and Sanchez (1966)	5000A	28 (6)	9.7 - 12.6 (7)	
Gillett (1966)	astronomical blue	28 (8)		
Wolstencroft and Rose (1967)	7030A and astron. blue (8)(9)		26.5	
Ingham and Jameson (1968)	5100A		10.7	
Sparrow and Ney (1968)	astronomical visual		10.5	
Weinberg, et al. (1968)	5080A			17 (10)
Jameson (1970)	5100A	22	12	16 (11)
Sparrow and Ney (1972)	4180A	30 (8)	10.9 (8)	
Divari and Krylova (1973)	5300A 5800A		14.3 20.6	
Frey, et al. (1974)	5000A	36 (12)		
Dumont and Sanchez (1975)	4600A and 5020A	27.2		
Present study	10 colors	26.5	12.4	19.5
	ϵ, β	89, 4.7	94.9, 84.9	67.5, 66.0

Notes to Table 2:

(1) Authors give surface brightness at λeff = 5430A and degree of polarization at "visual".
(2) Obtained from product of surface brightness and degree of polarization.
(3) Values obtained from Elsässer (1963).
(4) Author gives surface brightness at λeff = 4355A and 5425A and degree of polarization at "blue" and "green".
(5) Authors apparently used different instruments for measurement of surface brightness and degree of polarization; the spectral response is not given for either instrument.
(6) Obtained from product of degree of polarization quoted in paper and surface brightness read from curve through combined easterly and westerly observations.
(7) Quoted in Dumont and Sanchez (1970).
(8) Calculated using solar color index.
(9) Authors averaged surface brightness in S_{10}(V) from λeff = 7030A and astronomical blue; multiplying it by their interpolated degree of polarization at 7030A gave 26.5S_{10}(V).
(10) Based on correcting the observed polarized brightness for atmospheric extinction and scattering and subtracting a polarized brightness of 4 S_{10}(V) which arises from atmospheric scattering (Dumont and Sanchez, 1975).
(11) Interpolated from table of polarized brightness as functions of $\lambda - \lambda_{\odot}, \beta$ to same celestial pole coordinates as Skylab observations.
(12) Value read from plot given in paper.

We believe the somewhat higher values in Table 1 at 4000A (15%) and the lower values at 8200A (25%) to be connected to the difficulties of calibration in the region of the convergence of the Balmer and of the Paschen lines. The 10% lower values at 4760A may be a consequence of our use of the solar irradiance values of Johnson (1954), which differ by about this amount from those given by Labs and Neckel (1970) at this wavelength.

The mean values given at the bottom of Table 1 have been transposed to Table 2 to compare with other published values for the polarized component of the zodiacal light on the ecliptic at 90° elongation ϵ, at the north celestial pole and at the ecliptic pole. No distinction has been made between measurements made at the north and south ecliptic poles.

New experimenter tapes with no compression would make it possible to obtain the polarized brightness of zodiacal light over much of the antisolar hemisphere. A search would be made for a polarized component associated with the L_4 and L_5 lunar libration regions. Studies are in progress of color differences in the polarization reversal at large elongations.

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