BRIGHTNESS AND POLARIZATION OF THE ZODIACAL LIGHT: RESULTS OF FIXED-POSITION OBSERVATIONS FROM SKYLAB

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ABSTRACT

In an earlier paper Sparrow *et al.* (1976) found the polarized brightness of zodiacal light to have solar color at five sky positions for which there were fixed-position observations from Skylab: north celestial pole, south ecliptic pole, vernal equinox, and two places near the north galactic pole. The brightness and degree of polarization of zodiacal light at these sky positions are derived using Pioneer 10 observations of background starlight from beyond the asteroid belt (Weinberg *et al.*, 1974; Schuerman *et al.*, 1976) and the assumption that the zodiacal light is also solar color in total light.

Ten-color observations of sky brightness and polarization were made of portions of the antisolar hemisphere from Skylab (Weinberg *et al.*, 1975; Sparrow *et al.*, 1977). Three independent quantities were determined directly from the measurements: total brightness (B_t), polarized brightness (Bp), and orientation of the plane of polarization (χ), the last more precisely referred to as azimuth of vibration. These three quantities are related to the Stokes parameters I, Q, and U, respectively.

Except in regions relatively close to the Milky Way, the observed direction and amount of polarization (χ,B_p) in these space measurements can generally be attributed entirely to zodiacal light. To isolate the zodiacal light brightness, it is necessary to remove the brightness contribution of all discrete or "resolved" stars in each 6° diameter field of view (FOV) and to subtract the background starlight (integrated starlight, diffuse galactic light, light from extragalactic sources). Thus, the zodiacal light total brightness (B_z) is obtained as the residual after a several-step subtraction process. This subtraction process has been the largest single source of error in determining the brightness of zodiacal light in observations from space and, even more so, in observations from the ground.

Skylab observations included sky-scanning and fixed-position measurements, the latter at the north celestial pole, south ecliptic pole, and vernal equinox, and at two positions near the north galactic pole. A number of sequences of filters (Table 1) were used to observe these

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positions, one sequence taking 2 minutes. In the following, we briefly outline our method for evaluating discrete and, especially, background starlight at the Skylab wavelengths, so as to derive the total brightness of zodiacal light at these sky positions. The method will be developed more fully elsewhere, in conjunction with its use to isolate the zodiacal light in Skylab sky-scanning observations.

Omitting absolute calibration and the conversion of analog voltages to relative brightness and polarization, reduction of the Skylab observations involves the following major steps:

1. Determination of instrument pointing. Pointing directions are obtained by combining vehicle attitude data with telemetry data on position in the instrument's reference system and using data derived from photographs with a bore-sighted, 16mm camera. Where there are frames containing at least three or four identifiable stars, pointing is generally known to at least ±0.2°.
2. Determination of the brightness contribution of stars resolved by the instrument. A combined star catalog was generated by editing and merging data in the U.S. Naval Observatory Photoelectric Catalog (Blanco *et al.*, 1968), the Yale Catalogue of Bright Stars (Hoffleit, 1964), and the Moscow General Catalog of Variable Stars. The Skylab spectral transmittance functions were convolved with 40 stellar spectral energy distributions selected from the five luminosity classes given in Mitchell and Johnson (1969). These were used to determine the relationship of the instrument magnitude to the Johnson V magnitude as a function of the B-V color index and spectral luminosity class. This relationship was then used to convert the Johnson V magnitudes of the combined star catalog to instrument magnitudes for each Skylab filter.
3. Separation of background starlight and zodiacal light at Skylab wavelengths. The Pioneer 10/11 Imaging Photopolarimeters were used to periodically measure sky brightness and polarization in the blue (B/W 3950Å-4850Å) and red (5900Å-6900Å) at heliocentric distances beyond 1.002 AU. A two-color map of background starlight over the sky has just been completed using Pioneer 10 observations from beyond the asteroid belt (Weinberg *et al.*, 1974), where the zodiacal light was found to be negligible compared to the background starlight (Hanner *et al.*, 1974; Schuerman *et al.*, 1977). To create this map, the contributions of resolved stars (stars brighter than V magnitude ≃ 6.5) were removed from each of 60,000 FOV's before merging data from sky-mapping observations made at six heliocentric distances between 3.27 AU and 5.15 AU. These data are used to separate background starlight and zodiacal light in those Pioneer 10/11 observations which contain both; *i.e.*, in observations at heliocentric distances less than approximately 3 AU. The Pioneer background starlight data can also be used directly in any other observations having similar spatial and discrete star resolution - and similar wavelengths (blue and red).

Table 1 illustrates our use of Pioneer red background starlight (effective wavelength 6420Å) directly with data at Skylab wavelength 6427Å. Also shown is the method used for other wavelengths in Skylab fixed-position observations at the north celestial pole.

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Table 1. Observed and Derived Results at the North Celestial Pole

(1) Filter central wavelength	(2) χ	(3) B_p	(4) B_t	(5) B_{ds}	(6) B_t-B_{ds}	(7) B_{bs}	(8) B_z
4001Å	24°8	23.8	192	28.0	164	[87]	77
4748Å	27.8	18.5	154	14.3	140	63	77
5068Å	28.0	19.4	164	13.7	150	73	77
5294Å	27.7	18.3	163	12.5	151	74	77
5562Å	27.3	19.3	179	11.2	168	[91]	77
6063Å	26.7	17.9	164	11.3	153	76	77
6286Å	27.0	19.2	221	11.9	209	[132]	77
6427Å ·······	26.6···	18.7···	167···	11.6···	155·····	78····	77
7093Å	28.4	18.9	172	11.3	161	84	77
8160Å	29.4	15.4	187	11.5	176	[99]	77
Mean Values	27°4±.1	18.8±.2					77

Each value of χ, B_p, and B_t is the mean of up to 15 individual measurements.

Table 1 columns and discussion:

(2) Measured orientations of the plane of polarization; these values correspond closely to the electric vector's being perpendicular to the scattering plane.

(3) Polarized brightness (B_p), in $S_{10}(V)$ units. The $S_{10}(V)$ unit is referred to the sun; the brightnesses in this unit will have the same value at all wavelengths for radiation of solar color. Absolute calibrations at 4001Å and 8160Å appear to be high and low, respectively, as noted in a first analysis of these data by Sparrow *et al.* (1976). The mean value is determined using 8 colors only.

(4) Total observed brightnesses (B_t). These include discrete and background starlight, zodiacal light, and airglow emission; the last at 5562Å, 6286Å, and probably 8160Å.

(5) Discrete starlight (B_{ds}).

(6) Total brightness (B_t) minus discrete starlight (B_{ds}). Except for the aforementioned airglow, these differences correspond to background starlight plus zodiacal light.

(7) and (8): Background starlight (B_{bs}) and zodiacal light (B_z), respectively. For B_{bs} Skylab 6427Å is equivalent to Pioneer red, which we found (column (7)) to be 78 $S_{10}(V)$. Thus, $B_t-B_{ds}-B_{bs}=B_z=77$ $S_{10}(V)$. As seen in column (3) (see, also, Sparrow *et al.*, 1976), B_p is close to solar color. If we assume that B_z is also solar color, then $B_z=$ 77 $S_{10}(V)$ at all Skylab wavelengths (column (8)). B_{bs} at the other Skylab wavelengths is obtained from the corresponding differences, (6)-(8). Due to calibration difficulties and airglow emission, the bracketed values of B_{bs} are uncertain. From Pioneer blue data (effective wavelength 4360Å) we find $B_{bs}=57$ $S_{10}(V)$, in good agreement with the trend in Skylab-derived values of B_{bs}; *i.e.*, the results are consistent with the assumption of solar color for B_z.

Table 2 gives the results obtained by applying this method to all fixed-position observations. Each value of χ and B_p is a mean value obtained as shown in Table 1. Only part of the data was available for the earlier analysis of the B_p data by Sparrow *et al.* (1976), which also found

Table 2. Best Estimate of Mean Zodiacal Light - Fixed Position Observations, Skylab Mission SL-2

Target	Coordinates Equatorial α	δ	Ecliptic ε	β	Zodiacal Light χ	B_p	B_z	p
NCP	174°.2	85°.8	67°.2	65°.8	27°.4±.1	18.8±.2	77	.244
SEP	76.2	-66.6	89.8	-84.5	30.8±.3	11.4±.5	50	.228
VE	350.6	1.0	89.9	4.6	29.6±.2	25.6±.4	168	.152
NGP1	190.9	27.6	95.4	29.4	29.8±.4	17.0±.3	110	.154
NGP2	189.8	27.4	92.4	28.8	29.5±.2	17.2±.2	112	.154

B_p to be solar color. Availability of all of the data for our analysis and our use of a different solar-based $S_{10}(V)$ unit account for the slightly lower values of B_p found here. In this paper and in our studies of Pioneer 10/11 data, we follow the $S_{10}(V)$ recommendations of Sparrow and Weinberg (1976). The degree of polarization, p, is derived, not measured. It is obtained from B_p/B_z. The measured and assumed solar colors for B_p and B_z, respectively, mandate that p be grey or independent of wavelength. The p data reconfirm our earlier result (Weinberg and Hahn, 1976) and that of Dumont and Sanchez (1976) that p is greater off the ecliptic than on the ecliptic at these elongations. As noted earlier, this methodology is also being used in the reduction of the Skylab scanning data.

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