OAO-2 OBSERVATIONS OF THE ZODIACAL LIGHT

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ABSTRACT

Photometric measurements of the night sky brightness have been obtained at twelve wavelengths between 1000 Å and 4300 Å from above the earth's atmosphere. A preliminary analysis of the data reveals a component of the sky brightness with ecliptic symmetry and an intensity distribution similar to that of the zodiacal light.

At wavelengths greater than 2500 Å this component is significantly redder than the sun and has the energy distribution of a G8 star. At wavelengths shorter than 2500 Å this component is bluer than the sun and has the energy distribution of an early B-star.

At the longer wavelengths the zodiacal light isophotes have a shape similar to those obtained from ground-based observations by Smith, Roach and Owen (1965). At shorter wavelengths the isophotes tend toward radial symmetry with respect to the sun.

The ultraviolet spectrum of the zodiacal light can be closely approximated with a two component model in which one component has an albedo proportional to the wavelength (λ) and the other component has a scattering efficiency proportional to λ^{-19}.

The observations at 4250 Å indicate a zodiacal light intensity of 30 ± 3 stars of magnitude B = 10.0 per square degree [$S_{10}(B)$] at the north ecliptic pole. This ecliptic pole intensity is about 35 $S_{10}(B)$ fainter than that indicated by ground-based observations, but is in good agreement with the balloon measurements of Gillette (1966) and the satellite observations of Sparrow and Ney (1968). The source of this discrepancy is unknown.

I. INTRODUCTION

Ground-based observations of the zodiacal light are hampered by the low light levels involved and by emission, scattering and absorption in the earth's atmosphere. These highly variable atmospheric sources contribute 30-40% of the zenith sky brightness at 5300 Å (Roach 1964). Thus it is not surprising that the absolute brightness of the zodiacal light is uncertain by more than a factor of two (Wolstencroft and Roach 1969, Roosen 1971). The same difficulties have produced measurements of the color of the zodiacal light which vary from spectral type F5 to G8 (Peterson 1967).

In the past decade it has become possible to measure the surface brightness of the night sky from above the earth's atmosphere with rocket and satellite-borne instruments and to extend these measurements into the ultraviolet region of the spectrum.

In this paper we report a preliminary analysis of observations of the zodiacal light in the 1600-4300 Å spectral region obtained with the Wisconsin Experiment Package of the Orbiting Astronomical Observatory (OAO-2).

II. THE OBSERVATIONAL MATERIAL

a) Instrumentation

The Wisconsin Experiment Package (WEP) has four 8-inch photometric telescopes which can be used to measure the surface brightness of the sky at twelve wavelengths in the 1050-4250 Å region of the spectrum. The instrumentation and operation of this package has been described in detail by Code et al. (1970). Briefly, each 8-inch telescope has a photometer with a five-position filter wheel containing three medium-band filters, a dark slide and a Cerenkov radiation calibration source. Using the 10-arc minute diameter field-of-view, it is possible to measure the surface brightness of the night sky at all wavelengths with a 64-second integration time.

b) Observing Sequence

A typical observing sequence consists of eleven readings with each photometer: two dark readings, a calibration reading and eight (3-2-3) filter readings. The filter readings are made at different gain settings to avoid ambiguities in the digital data. A complete sequence lasts from 24 to 32 minutes and takes an entire spacecraft night. Since orbit 3000, the dark readings have been made at the beginning and end of the sequence to determine the time dependence of the radiation-belt induced dark current.

c) Observations

OAO-2 can point to discrete regions of the sky with an accuracy of ±1 arc-minute, but it has no capability for continuous sky scans. The sky brightness data for this program have been obtained in two ways:

1) During routine photometry of discrete objects such as stars, planets and galaxies, it is necessary to measure and remove the contribution of the sky background. Thus, a large number of sky observations have been obtained near specific targets.

2) In addition, a number of observations of sky background areas selected for known star counts or uniform distribution in galactic and ecliptic coordinates have been obtained.

III. RESULTS

a) Shape

We have identified the zodiacal light component in our data in two ways:

1) by selecting observations obtained in a short period of time at high galactic latitudes which cover a large range of ecliptic coordinates and assuming the variations in sky brightness are due to zodiacal light; and

2) by selecting observations of the same sky region obtained over a period of weeks or months and identifying the component which varies with time with the zodiacal light.

An example of the first method is shown in Figures 1 and 2. We plot net digital counts at four wavelengths versus ecliptic latitude and longitude $(\lambda - \lambda_{\odot})$. The data were obtained on February 17, 1969 by measuring sky brightness along the ecliptic at 10° intervals from 50° to 80° from the sun and at ±15° and ±30° ecliptic latitude at 50° ecliptic longitude. The sky areas were selected to exclude all stars brighter than $10^{m}.0$ and all areas have galactic latitudes $b_{II} < -40°$ except the (50°, 30°) area at $b_{II} = -25°$.

At 4250 Å the sky brightness contours show a strong ecliptic symmetry. When these data are plotted against the 5300 Å zodiacal light brightness predicted from the tables of Smith, Roach and Owen (1965) [SRO] one finds a linear relationship with no deviation greater than 3% from a straight line. This suggests there are no large differences between the intensity distribution of the zodiacal light at 4250 Å and that at 5300 Å which is consistent with neutral scattering by the interplanetary dust particles.

The observations at 3330 and 2980 Å also show brightness

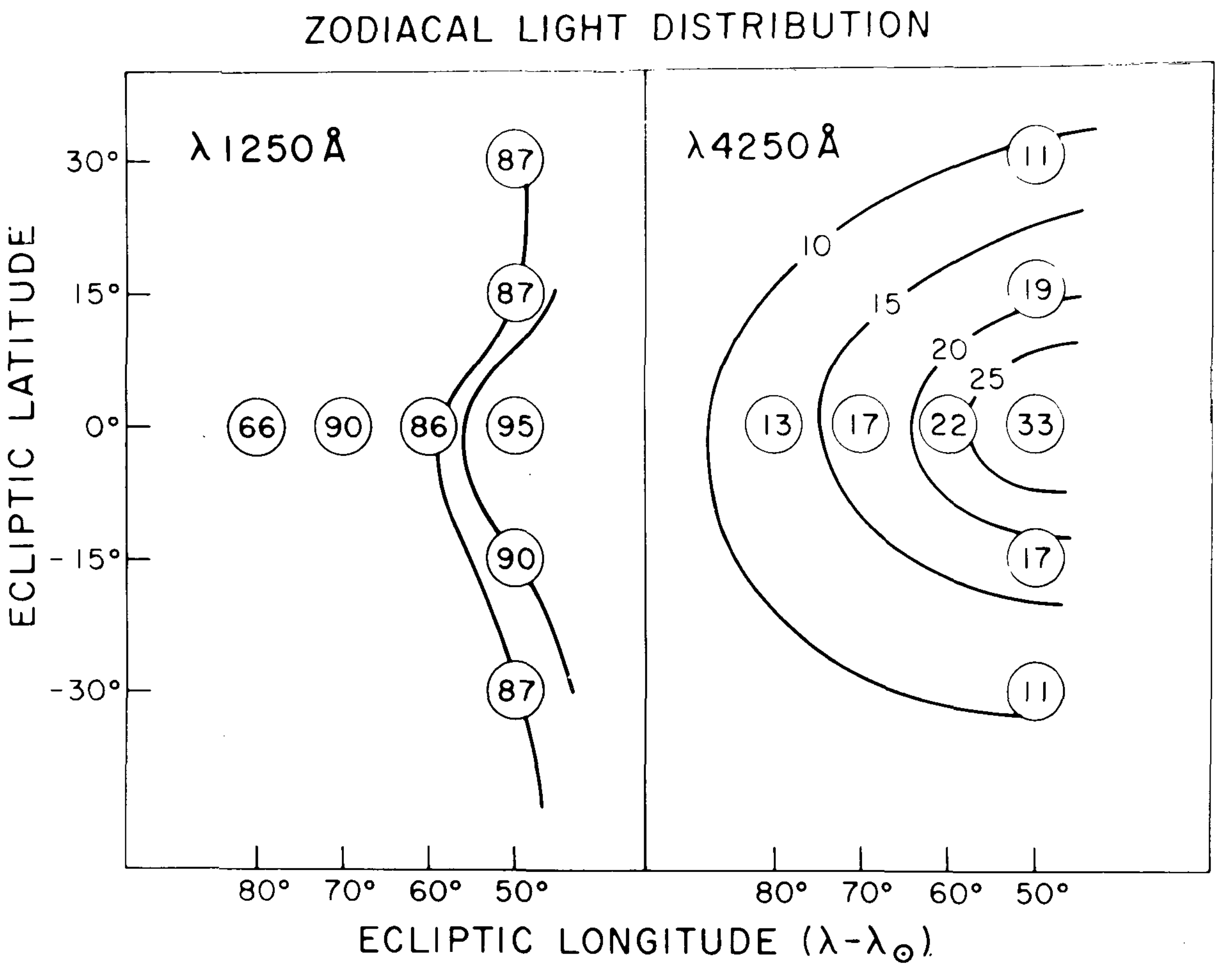

Figure 1.—The sky brightness at 4250 Å and 1250 Å is plotted vs. position in ecliptic coordinates. The brightness data is in digital counts and includes the contribution of stars fainter than 10th magnitude and the geocorona.

contours with ecliptic symmetry and agree well with the 4250 Å data. There is, however, a tendency toward less elliptical, more circular contour lines with decreasing wavelength. This trend seems to continue for data at 2500 and 2200 Å.

The observations at 1250 Å include a strong contribution from L_α emission in the geocorona which may amount to 80% of the measured sky brightness (Thomas and Krassa 1971). One can see an ecliptic symmetry in the data, but further interpretation will require a detailed model of the geocorona.

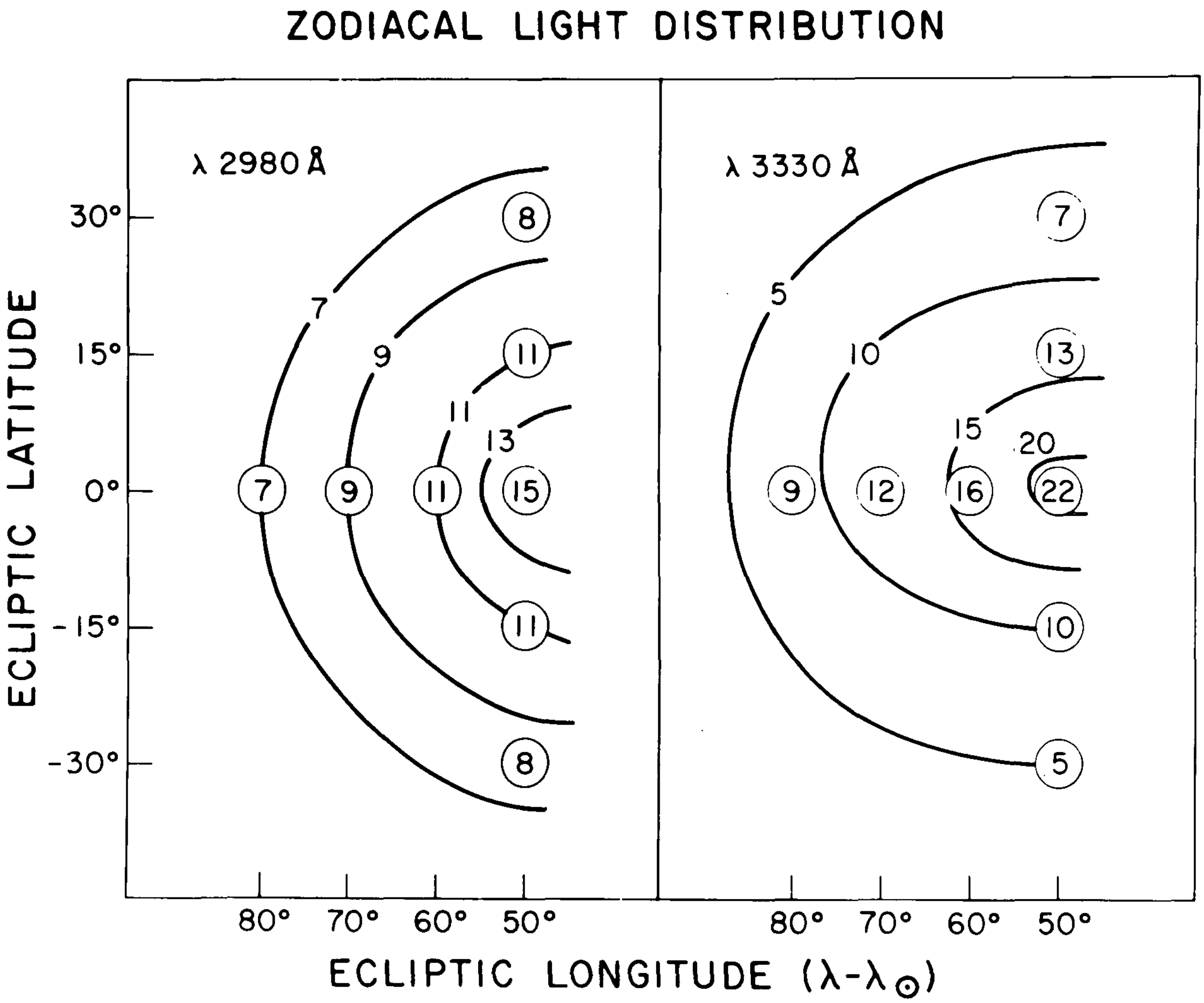

Figure 2.—The sky brightness at 3330 Å and 2980 Å is plotted vs. position in ecliptic coordinates.

b) Color

An example of the second method is shown in Figure 3 which presents observations of the sky near Nova Serpens 1970 obtained over a period of seven weeks in February and March of 1970. We plot net digital counts versus the zodiacal light intensity predicted by ground-based observations at 5300 Å [SRO] in units of stars of magnitude B = $10^{m}_{.}0$ per square degree [S_{10}(B)]. Here we assume

$$1\ S_{10}(V) = 1.69\ S_{10}(B)$$

(Roach and Smith 1964).

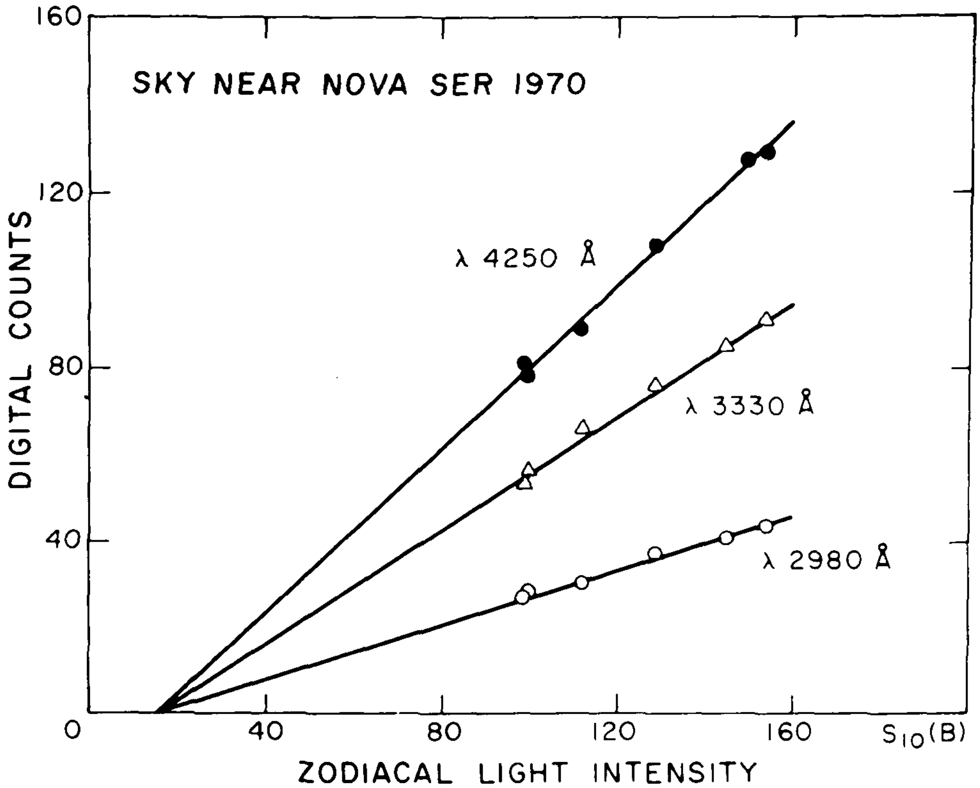

Figure 3.—Observations of the sky brightness near Nova Serpens 1970 for a period of seven weeks are plotted against the zodiacal light intensity predicted from the observations of Smith, Roach and Owen (1965). Digital counts are plotted vs. the number of stars of magnitude B = 10^{m}0 per square degree.

Here again, we find a linear relationship between ground and space observations. From the slope of these lines we can find the number of digital counts to be expected at each OAO wavelength for a given zodiacal light intensity. If we then divide by the number of digital counts observed for some comparison star, we have a spectrum of the zodiacal light in the instrumental system of the spacecraft. The results of this calculation are shown in Figure 4. We have chosen an A1 V star, θ Lep, for a comparison standard, because it is not too bright to be observed with Stellar 1 and its ultraviolet energy distribution is nearly constant with wavelength. We also show curves for several other stars compared to θ Lep.

The zodiacal light data for Figure 4 are average values for three separate series of observations. The data is listed in

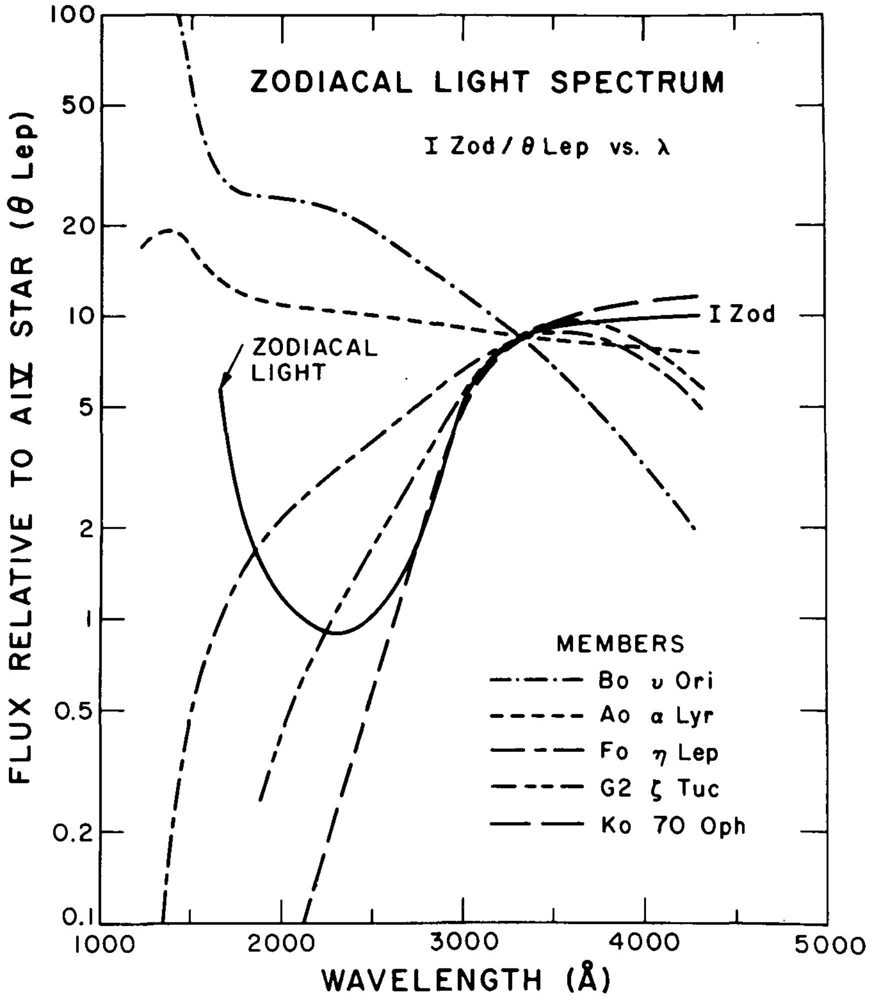

Figure 4.—The flux ratio of the zodiacal light, relative to θ Lep, an A1 V star, is compared with the flux ratios of a grid of main sequence stars. The curves are normalized to an arbitrary value at 4250 Å.

Table 1 in which we give the slope of the relationship between the OAO net digital counts at gain E4 versus zodiacal light intensity predicted from SRO in S_{10}(B). The estimate of probable error is based on the internal consistency of the data. The next two columns give the net digital counts observed for θ Lepus and β Hydrus, the comparison stars for Figures 4 and 5. The last column gives the ratio of the zodiacal flux at each wavelength to that from β Hyi, normalized to 4250 Å.

From an examination of Figure 4 it is apparent that the zodiacal light is redder than the sun in the 2500-4300 Å region

Table 1. Zodiacal Light Spectrum

λ	Slope	P.e.	θ Lep	β Hyi	$F_z/F_{\beta Hyi}$
4250 Å	52.45*	4.5%	343,380†	983,800†	1.00
3330	4.75	7.6	36,650	111,100	0.766
2980	2.18	2.2	29,500	53,250	0.729
2940	0.907	13.0	15,380	27,970	0.580
2380	0.119	18.8	6,400	2,300	0.919
2040	0.275	18.7	4,880	3,070	1.613
2460	0.140	10.0	9,600	3,890	0.638
1920	0.106	31.2	2,110	126	15.0
1680	0.0251	73.2	357	22	203.

*Digital counts at gain E4 per S_{10}(B)

†Net digital counts less sky at gain E4

with an energy distribution similar to that of a star of spectral type G8. Below 2500 Å the zodiacal light is much bluer than the sun, approaching an early B-star in its energy distribution.

The flux ratio of the zodiacal light relative to the sun is shown in Figure 5. The results obtained earlier by Lillie (1968) with data from an Aerobee rocket are presented for comparison, as well as a rocket measurement due to Sudbury and Ingham (1970). The "sun" for the OAO data is β Hyi, a G2 IV star [$B - v \approx 0^m.62$] whose energy distribution is quite similar to that of the sun in the ultraviolet (Code 1971). The agreement between the observations is quite good, considering the low light levels involved and the difficulty in removing the contribution of starlight to the rocket data.

Earlier reports of an upturn in the zodiacal light intensity below 2500 Å (Lillie 1968) are confirmed by the OAO measurements and extended to shorter wavelengths. It is interesting to note that the zodiacal light spectrum can be reproduced by a two component model of the interplanetary dust cloud in which one component has an albedo proportional to the wavelength, λ, while the other component has a scattering efficiency proportional to λ to the -19th power.

The reason for this upturn is unknown. It does not seem to be a phase effect, since the rocket observations are for the entire night sky and the OAO data is the average for several points at elongations from 50° to 120° from the sun. And the wavelength dependence is too high for small particle scattering.

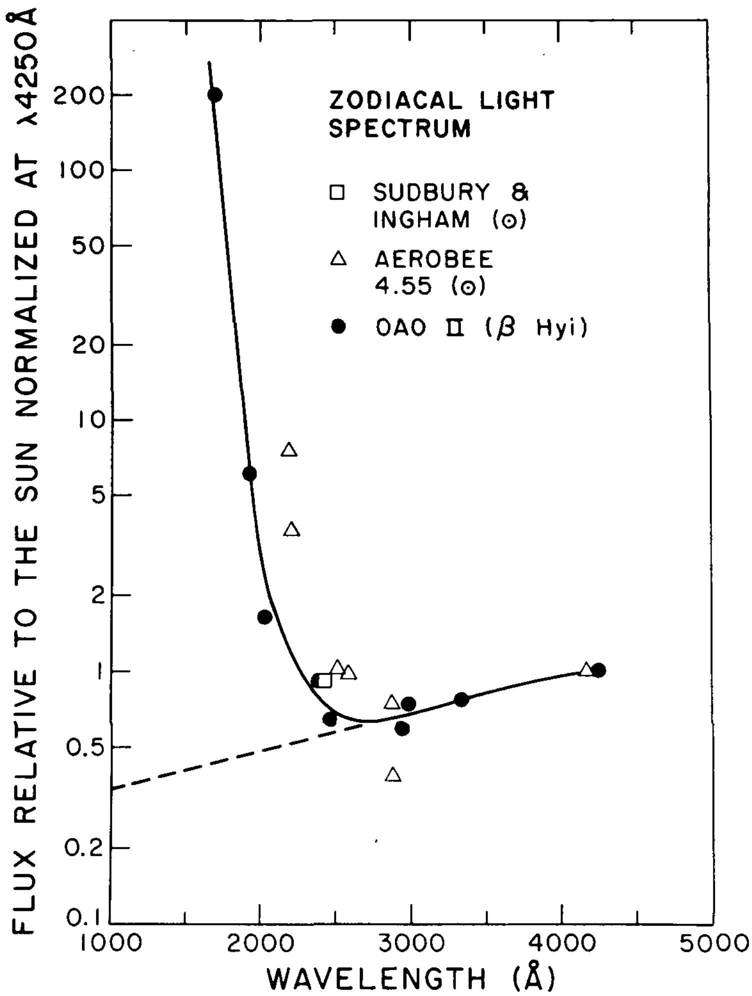

Figure 5.—Flux ratios for the zodiacal light relative to the sun from OAO-2 data and data from Aerobee 4.55. The curves are normalized at 4250 Å.

The most likely explanation is that the effect is produced by the plasma oscillations in small particles which Gilra (1972) has suggested to explain the "bump" in the interstellar extinction curve at 2200 Å. This feature in the extinction curve (Bless and Savage 1972) shows a sharp decrease in extinction around 2000 Å with a wavelength dependency of about λ to the -20 to -24. In this interpretation of the data the λ dependency would be due to large (micron-sized) particles, while the λ^{-19} component would be due to very small particles with little or no coating.

It is also of interest to note that the zodiacal light isophotes in Figures 1 and 2 seem to become more radially symmetric below 3000 Å. This would be consistent with a two component model in which large particles of asteroidal origin are found near the ecliptic, while small particles of cometary origin form a spherical halo around the sun.

c) Brightness

(i) General

The difficulty of measuring the absolute brightness of the zodiacal light has been discussed in detail by Wolstencroft and Roach (1969). The principal sources of error in this determination are uncertainties (a) in the absolute calibration of the photometer, and (b) in the subtraction of other sources of background radiation.

The second source of error is not too significant for the OAO observations because atmospheric emission, scattering and absorption can be ignored and the small field of view of the OAO photometers makes it possible to reject the contribution of stars brighter than 10th magnitude. In sky regions at high galactic latitude 90% of the observed background is typically due to zodiacal light.

The usual method of calibrating sky brightness photometers is to observe stars whose energy distribution is known as they drift through the field of view (Roach and Smith 1964). This provides a test for vignetting and a measurement of the photometer's absolute sensitivity.

(ii) OAO Data

Extensive tests with the OAO photometers indicate a uniform response ±5% across the field of view for Stellars 1-3, and ±10% for Stellar 4. The choice of a star for calibration at 4250 Å is complicated by the broad band-pass of the filter (860 Å) and the uncertain spectrum of the sky background. The relationship between (B - V) and (m_{4250} - V) is non-linear and corrections range up to $0\overset{m}{.}26$ for late-type giant stars. (The correction for main sequence stars is much smaller, however.) The adopted calibration

$$1 \text{ digital count at Gain E2} = 1.18\ S_{10}(B)$$

is based on the average transformation from m_{4250} to B for six main sequence stars ranging in spectral type from B2 V to G2 V. This average agrees within $0\overset{m}{.}01$ with the transformation for 70 Oph, a K0 V star, whose energy distribution closely resembles that of the zodiacal light in the 3000-4500 Å region, as shown in Figure 3.

The results of applying this calibration to five sky background areas of particular interest are shown in Table 2. In successive columns we list the area designation, its ecliptic latitude, ecliptic longitude, the sky brightness observed by OAO, the contribution due to starlight, the zodiacal light component ($I_{obs} - I_{star} = I_{zod}$) and the zodiacal light according to Smith, Roach and Owen (1965) converted to S_{10}(B) assuming the ratio $S_{10}(V)/S_{10}(B) = 1.69$.

Table 2. Zodiacal Light Brightness

Sky Area	β	$\lambda-\lambda_0$	I_{obs}	I_{star}	I_{zod}	SRO
# 5	0°	50°	312*	11*	301*	454*
7	0	60	208	13	195	302
9	0	70	161	13	148	224
11	0	80	123	12	111	166
NEP	90	0	53	23	30	65

*Brightness in S_{10}(B)

The contribution of direct starlight was calculated using the tables of Roach and Megill (1961) for stars fainter than 10th magnitude and converted with the relationship

$$1\ S_{10}(B) = 0.903\ S_{10}(pg)$$

(Wolstencroft and Rose 1967).

The contribution due to diffusely scattered starlight was included by multiplying the star counts by 1.34 (Lillie 1968).

(iii) Comparison in the Ecliptic Plane

The first four entries in Table 2 are for the data points in the ecliptic plane shown in Figure 1.

An examination of the table indicates the factor 1.69 is not correct for the conversion of S_{10}(V) to S_{10}(B); it should be 2.55 for sky areas 5 - 11, i.e., the zodiacal light is much redder than the sun.

We can check this result by assuming both the OAO and SRO observations are correct at 4250 and 5300 Å respectively. Using the absolute calibration of the WEP photometer: 1 E4 count = 2.38×10^{-16} ergs/cm^2-sec-Å from the observation of A0 V stars and the calibration

$$1 \; S_{10}(V) = 1.31 \times 10^{-13} \frac{\text{ergs}}{\text{cm}^2\text{-sec-Å}}$$

(Roach and Smith 1964), we find the zodiacal light flux at 4250 Å is 0.59 times the flux we predict from the solar energy distribution and the SRO 5300 Å observations. This compares with the value 0.57 found by Lillie (1968) with rocket observations at 4170 Å.

If we extrapolate the OAO observations in the ecliptic to an elongation of 45°, we find a brightness of 363 S_{10}(B) or 925 S_{10}(V) if 2.55 is the correct conversion factor. This value may be compared with the mean value of 857 ± 147 S_{10}(V) for eight previous investigations (Wolstencroft and Roach 1969).

(iv) Comparison at the Ecliptic Pole

The surface brightness of the zodiacal light at the ecliptic pole provides a sensitive test for models of the interplanetary dust cloud. Ground-based measurements disagree by factors of 2 or more, but space measurements seem to be converging to the value of 30 ± 3 S_{10}(B) which was found in this investigation. The results of previous photoelectric determinations are shown in Table 3.

We note that the result of Sparrow and Ney (1971) would be reduced by 5 or 6 S_{10}(B) if allowance were made for a diffuse galactic light component. Part of the disagreement between observers may be due to the use of the solar color index to convert observations from the visual to the blue photometric system. But there still seems to be an excess of 15 to 20 S_{10}(B) in the ground-based observations over those from space. The source of this discrepancy is not known, but may be scattering by aerosols or airglow from altitudes greater than 200 km.

IV. CONCLUSIONS

The purpose of this paper was to present some preliminary results from the OAO-2 observations of the zodiacal light. The main conclusions which can be drawn at this stage of the investigation are:

1. The surface brightness of the zodiacal light at 4250 Å is equal to 30 ± 3 stars of magnitude B = $10^{m}_{.}0$ per square degree [S_{10}(B)]; in the ecliptic at 45° elongation the brightness is 363 S_{10}(B).

2. The color of the zodiacal light is redder than the sun between 4300 and 2500 Å, resembling that of a G8 star. Below 2500 Å the zodiacal light is bluer than the sun, with the col-

or of an early B star.

3. The spectrum of the zodiacal light can be approximated with a two component model, one component having an albedo proportional to λ, the other with a scattering efficiency proportionate to λ^{-19} power.

Table 3. Surface Brightness of Zodiacal Light at the Ecliptic Pole

Author	Brightness	Location†
Elvey and Roach (1937)	40 $S_{10}(B)$	G
Beggs *et al.* (1964)	105*	G
Weinberg (1964)	110*	G
Smith, Roach and Owen (1965)	65*	G
Dumont (1965)	41*	G
Wolstencroft and Rose (1967)	92	R
Gillett (1966)	27#	B
Sparrow and Ney (1968)	30	S
Lillie (1968)	30	R
Sparrow and Ney (1971)	35	S
Present Study	30	S

* Value determined from observations in visual assuming $[S_{10}(V)]/[S_{10}(B)] = 1.69$

\# Value extrapolated from balloon observations with model calculations

† G = Ground, R = Rocket, B = Balloon, S = Satellite

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