NASA CR 103434

Univ Hawaii

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Current Problems in the Zodiacal Light.

A brief summary is given of modern photometric observations of the zodiacal light. Differences among observers are examined in terms of real variations in zodiacal light and of differences in techniques of reduction and observation. In a preliminary analysis of nightglow data from the Haleakala Observatory, we find no evidence for a significant component of dust in the earth-moon environment.

COSPAR Paper b.1
May 1969 Prague

Since the recorded beginning of zodiacal light observations in the 17th century, there has been continued mention of short- and long-term changes, pulsations, irregularities, temporary invisibility, color effects, zodiacal twilight and false zodiacal light, lunar zodiacal light, and so forth. The belief has persisted that modern photographic and photoelectric observations would "remove" these effects, but there is evidence that at least some of these may remain.

1. MODERN PHOTOMETRIC OBSERVATIONS

The plane-polarized nightglow radiation is completely specified for a given wavelength by the orientation of the plane of polarization of the E-vector (χ), the total observed degree of polarization (p_{tot}), the total observed brightness (B_{obs}), and the observed brightness of the polarized component (B_{pol}). These quantities are related by

$$p_{tot} = \frac{\sum_j B_{pol,j}}{\sum_j B_{obs,j}} \neq \sum_j p_j \quad , \qquad (1)$$

or

$$p_{tot} = \frac{(I_\perp - I_\parallel)_{ZL} + \sum_i (I_\perp - I_\parallel)_i}{(I_\perp + I_\parallel)_{ZL} + \sum_i (I_\perp + I_\parallel)_i} \quad , \qquad (2)$$

where $I_\perp$ and $I_\parallel$ are orthogonal components of brightness (radiance) having their electric vectors perpendicular and parallel, respectively, to the plane through the source, the earth, and the observed point. ZL and i refer to the zodiacal light and other brightness components, respectively, and $j = ZL + i$.

The sum of the component degrees of polarization is not equal to the total polarization, p_{tot} (Equation (1)). Therefore, while the degree of polarization of one or more of the components may be small compared to that of the zodiacal light, the brightnesses of the polarized components are not. In particular, a 'bright' airglow line with its small degree of polarization has a brightness in polarized light, B_{pol}, that is considerably higher than that of the 'faint' zodiacal light with its higher degree of polarization[1]. Broad-band detection does not, therefore, permit the assumption that $\sum_i (I_\perp - I_\parallel)_i = 0$ in Equation (2).

If zodiacal light were the only source of polarization, measurement of B_{obs} and p_{tot} would give the brightness of the polarized component of zodiacal light directly - at any wavelength and over the sky. This situation does prevail under certain circumstances: through the use, at a suitable observing site, of narrow-band systems which avoid airglow line emission, regions near the horizon, and low galactic latitudes. The brightness of the polarized component and the measured orientation of the plane of polarization give two of the three parameters required to specify the zodiacal light radiation field. Knowledge of these two parameters assists in deriving the third (total brightness); i.e., separating the components in the denominator of Equation (2)[2]. This approach is being applied to multi-color observations obtained at the Haleakala Observatory[3].

Recent emphasis has been on determining the brightness and polarization as a function of wavelength - perhaps the most fundamental observational parameters of the zodiacal light. Difficulties associated with low light-level photometry and with the separation of zodiacal light from airglow and starlight have resulted in most of these studies involving the bright regions of the zodiacal light (from 30 to 90 deg elongation in the ecliptic).

In Figure 1 we have collected representative post-1950 results for the brightness of the zodiacal light between elongations of 25 and 110 deg in the ecliptic[4-14]. To indicate more clearly the divergence of results, we have included results only in the visible spectral region. Note, in particular, the large spread in results and the sharp decrease of brightness toward larger elongations obtained by Divari and his collaborators. Contrary to the findings of these same observers, we now have conclusive evidence that the zodiacal light does indeed extend to high ecliptic latitudes[15].

Taken alone this spread of results is sufficient to discourage any analysis in terms of the nature and distribution of the scattering material, and the use of an unweighted average is not meaningful. When combined with polarization observations, however, the situation is improved. As noted by Blackwell, et al.[16], there is a tendency for those authors who find large polarizations to find low brightnesses and vice versa, thereby suggesting errors of reduction more than of observation.

In Figure 2 we have collected, without regard for wavelength, the distributions of polarization degree in the ecliptic prior to 1967[17-21]. Recent polarization observations by Gillett[22] and by Wolstencroft and Rose[23] agree with those obtained by Weinberg[9] and by Dumont and Sanchez[21].

Of particular interest is the fact that most investigators find a maximum degree of polarization near 60 to 70 deg elongation. For a geocentric dust cloud we would expect to find a maximum degree of polarization at 90 deg elongation.

Negative polarization[i] has been found between neutral points (zero polarization) at 165 and 180 deg elongation in the ecliptic[9,23]. Subsequently it was found that the position of the neutral point is wavelength dependent; it moves closer to the sun with increasing wavelength[24]. The observed wavelengths and the approximate positions of the neutral points in the ecliptic are given in Table I.

Table I. Neutral point positions in the ecliptic.

wavelength, Å	elongation of neutral point, deg
5080	165-175
6080	138-154
7100	133-144
8200	102-122

The polarization is small in regions around the neutral point, and it is not possible to delineate position except by a range of

i. For negative polarization the electric vector is parallel to the scattering plane; i.e., $I_{\parallel} > I_{\perp}$.

elongation. There appears to be less polarization at the longer wavelengths, and it is possible that the indicated neutral point positions for 7100 and 8200Å may just be where the polarization tends to zero; i.e., there may not be negative polarization at the longer wavelengths. Small dielectric particles are probably required to produce this negative polarization, and such particles also produce enhanced brightness in the back-scattering (Gegenschein) domain. It is interesting to note that in a recent study of the color and polarization of light from reflection nebulae[25] it was found that dielectric spheres predict a shift of the neutral point with wavelength in the same sense as that which we observe in the zodiacal light.

2. REAL VARIATIONS OR DIFFERENCES IN TECHNIQUES?

A number of factors can contribute to the differences in values obtained for the brightness and polarization of the zodiacal light:

a. The lack of a dark-sky, low-latitude, high altitude site;
b. The lack of a proven method for separating zodiacal light from airglow and starlight - especially at high geographic latitudes and when using broad-band systems;
c. Difficulties associated with absolute calibration;
d. Limited observational coverage in time and over the sky;
e. The lack of a satisfactory formulation for the effects of tropospheric scattering - especially near the horizon; and
f. Real changes in the zodiacal light.

The difficulties and possible errors of observation and reduction have been discussed frequently, and factor-of-two differences are easily possible (and have occurred even in observations obtained by the same group). We shall examine here the evidence for solar-associated fluctuations in the zodiacal light.

Investigations of the zodiacal light have generally involved observing for short intervals and have dealt with averages over the period during which observations were obtained. This has arisen partly because it is difficult to separate diurnal variations of the airglow from possible changes in the zodiacal light, especially since concurrent measurements of airglow line emission have not been made properly, if at all, until the more recent investigations. The principal evidence supporting short-term, solar-associated variations is the observation by Blackwell and Ingham[19] of increased brightness two days following a 3+ solar flare. No changes were detected in observations from OSO-2 during solar minimum in 1965[22].

To examine the question of solar-cycle variations in brightness, we have plotted in Figures 3 and 4 (with different scales) those observations shown in Figure 1 and other post-1950 results in the visible spectral region[20,26-33]. The brightness, in 10th magnitude (visual) stars per square degree, is plotted at 5-degree intervals of elongation between 40 and 100 degrees for each of the investigations. The length of each line is based on the period of observation. The dashed lines represent an average of results obtained during the fall of 1962 and the winter of 1964[29]. We have omitted elongations of 30 and 35 degrees where there are few results, there are large gaps between observations, and the scatter is high (especially in the period near solar maximum).

Several factors are apparent from investigation of Figures 3 and 4:

a. There is considerable scatter in the results and a short time per reported observation in the period near solar maximum;
b. There is fair agreement among the more lengthy and more recent studies; and
c. If all observations are given equal weight, there is an apparent relation between solar activity (indicated by relative sunspot number[34]) and zodiacal light brightness.

Critical to such an analysis are the broad-band results near solar maximum, most of which were obtained by Divari and his collaborators. It is relevant to note that there are large variations internal to these results and that Divari concludes, from analysis of this same data, that a large fraction of the zodiacal light arises from scattering by particles in the vicinity of the earth.

Asaad[35] concludes that the zodiacal light increases with decreasing solar activity by a factor of about 2; i.e., that nearly all differences are based on real variations in the zodiacal light. He attributes the decrease in brightness (and a purported increase in polarization[i])[36] to effects of the solar wind, or of the corpuscular radiation, or of alignment of particles by interplanetary magnetic fields. No details are given as to how any of these processes can significantly change the number or kinds of particles or their spatial distribution in the short times characteristic of a solar cycle.

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i. There are relatively few polarization studies that have measured the direction of polarization and avoided the complications of airglow line emissions[1]. When additional observations are available, analysis of differences among observers of polarization will be better performed with the brightness of the polarized component, rather than with the degree of polarization which is a derived quantity subject to errors of reduction and of observation.

One cannot equate the results of short-term, broad-band studies with results obtained by narrow-band studies over long periods of time. A single, consistent body of observations from one location is better suited to investigations of long- and short-period variations.

Weill[37] and Dufay[38], from analyses of zenith and celestial pole observations at Haute Provence between 1953 and 1966, find that the zodiacal light varies by 25 percent, with a maximum in 1960 and 1961 and a minimum in 1956 and 1957. Tanabe[39], however, finds no appreciable change in brightness of the Gegenschein from observations performed at three locations between January 1957 and January 1963. Observations from Haleakala Observatory between November 1961 and November 1968 will be similarly examined.

3. RELATED PROBLEM AREAS

In October 1967 we obtained observations at the Haleakala Observatory of the same bright regions of the morning zodiacal light on thirteen out of a possible fourteen nights. A similar sequence was obtained in February 1968 of the evening zodiacal light. These programs were timed on successive nights to insure that the only change in scattering geometry is the daily motion of the sun. The program generally involved scanning in azimuth at 5080Å and returning along the same path at 5577Å - for each degree of elevation between 5 and 30 degrees.

An example of this program is shown in Figure 5 for observations on eight nights between 18 February and 29 February 1968. Copies of the strip-chart recordings are used to make a map of the region on successive nights. Note the similar and relatively featureless

5577Å airglow levels on these nights and the absence of 5577Å enhancement in the zodiacal light. This, and the vertical position of the ecliptic, makes it possible to examine directly the positions of maximum zodiacal light brightness. We find no evidence for short-term changes in the position of the axis of zodiacal light (see, also, Saito and Huruhata[40]). Other observations will be similarly evaluated for position variations and for variations in brightness.

From an analysis of visual and photoelectric observations in Southern Russia between 1946 and 1955, Divari[41] finds that the zodiacal light achieves a maximum brightness near new moon and near full moon. In a subsequent analysis of photoelectric observations conducted in Egypt and Russia between 1955 and 1958, Divari and Komarnitskaya[42] relate the position of the axis of zodiacal light to the ecliptic latitude of the moon.

Another possible manifestation of near-earth dust in enhancement associated with the L_4 and L_5 libration regions in the system earth-moon-particle. In a preliminary analysis of photoelectric, photographic, and visual observations at the Haleakala Observatory on 18 nights between March 1966 and July 1968, we are unable to detect the presence of a photometric enhancement that could be attributed to lunar libration clouds.

ACKNOWLEDGEMENTS

Assistance has been provided by H. Mack Mann, Peter Hutchison, and David Beeson. This research has received support from the National Aeronautics and Space Administration (~~grant NsG-676~~) and from the Atmospheric Sciences Section, National Science Foundation (grants GA-1528 and GA-12400). NGR-12-001-004

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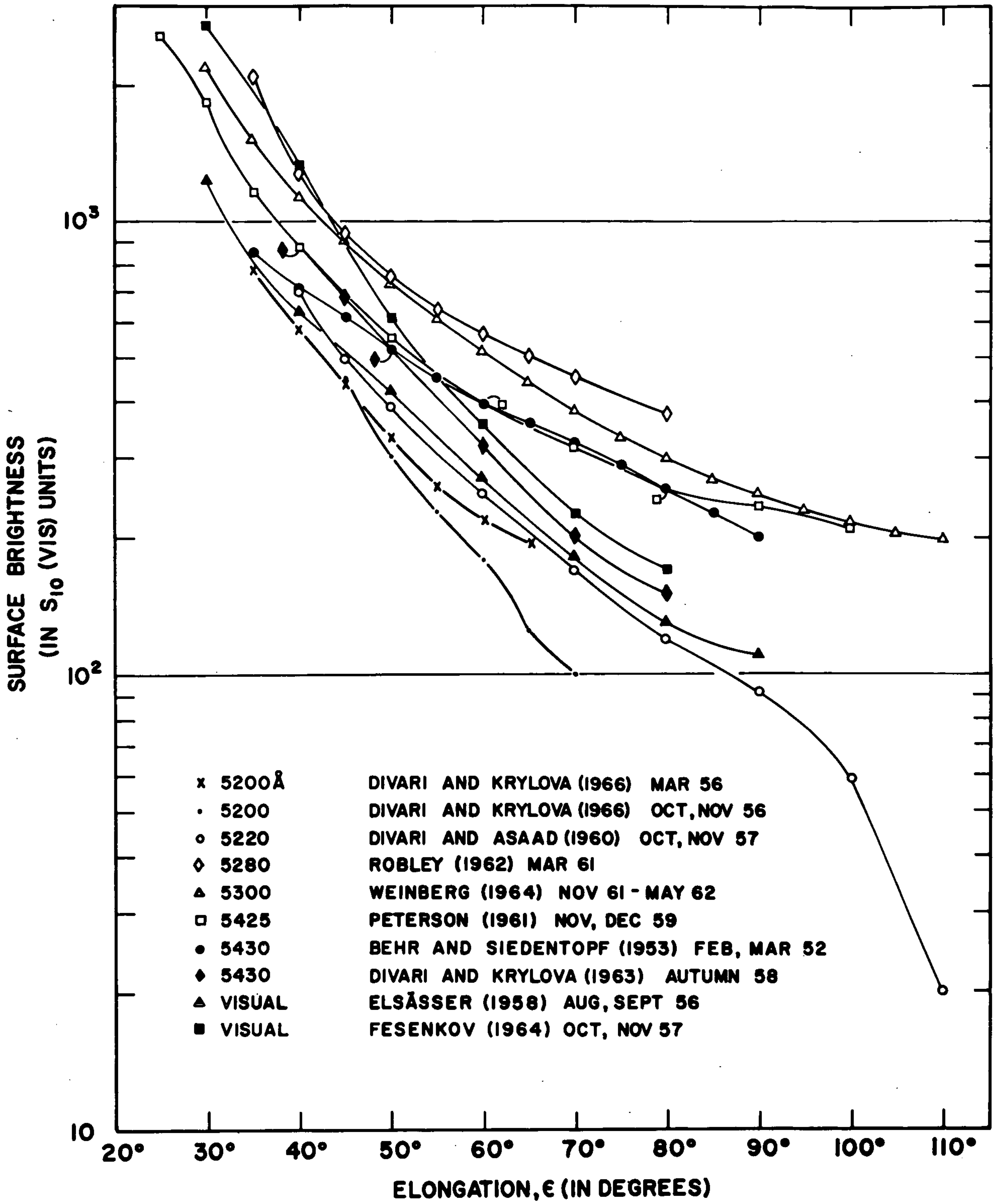

Figure 1. Representative post-1950 results on the brightness of the zodiacal light in the ecliptic.

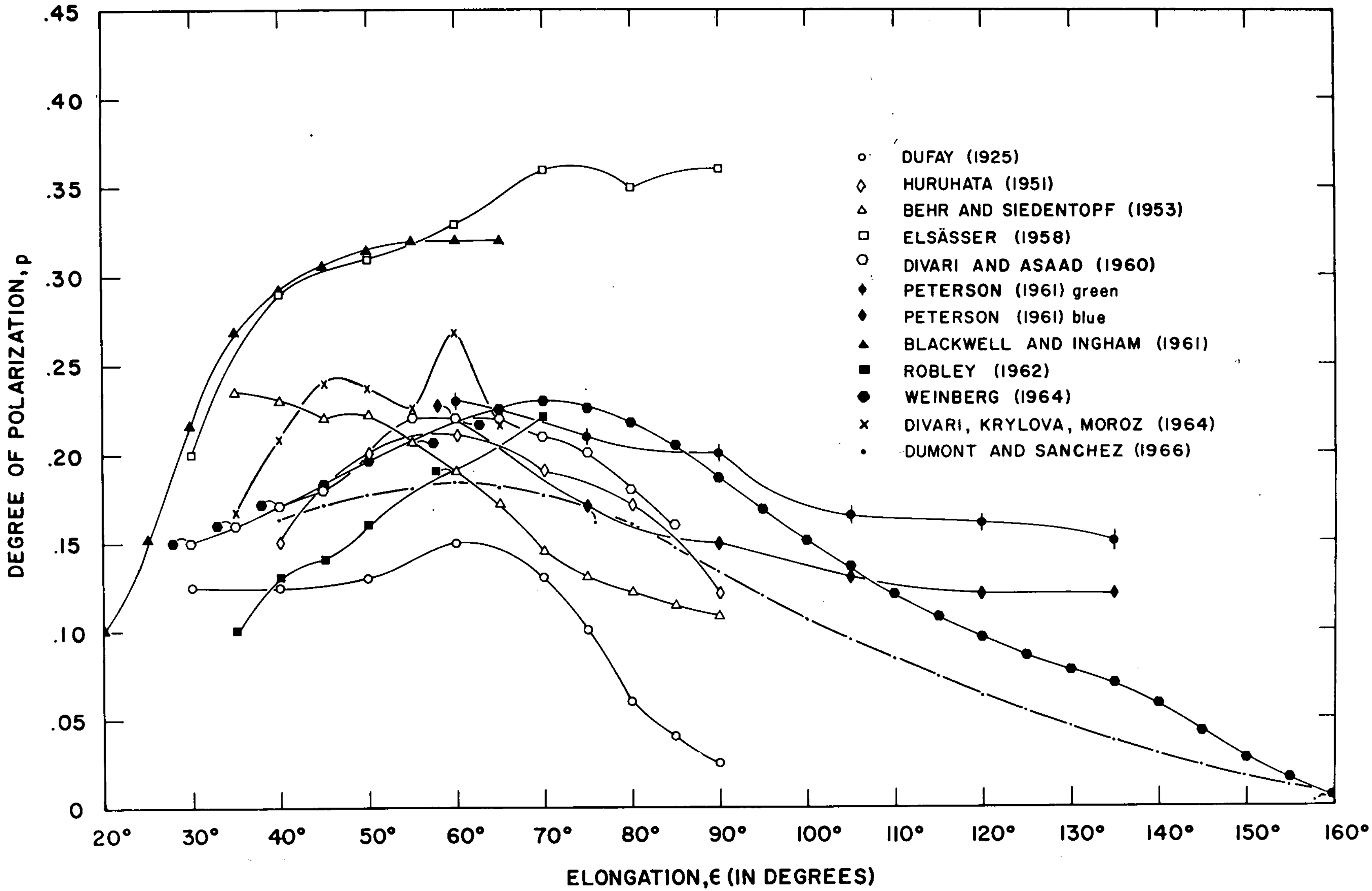

Figure 2. The degree of polarization of the zodiacal light in the ecliptic.

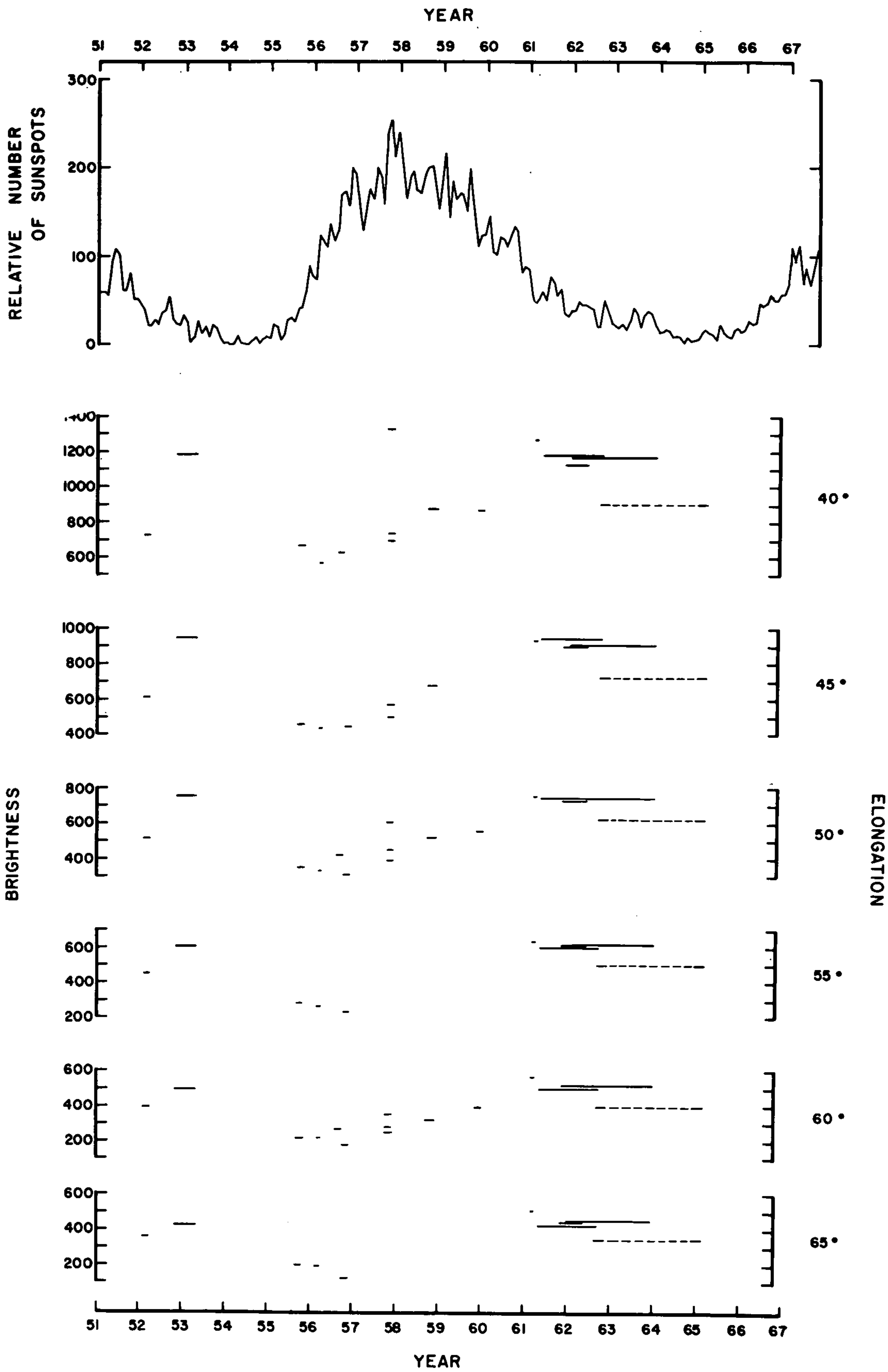

Figure 3. Post-1950 results on the brightness of the zodiacal light - versus year and relative sunspot number and for elongations 40 - 65°.

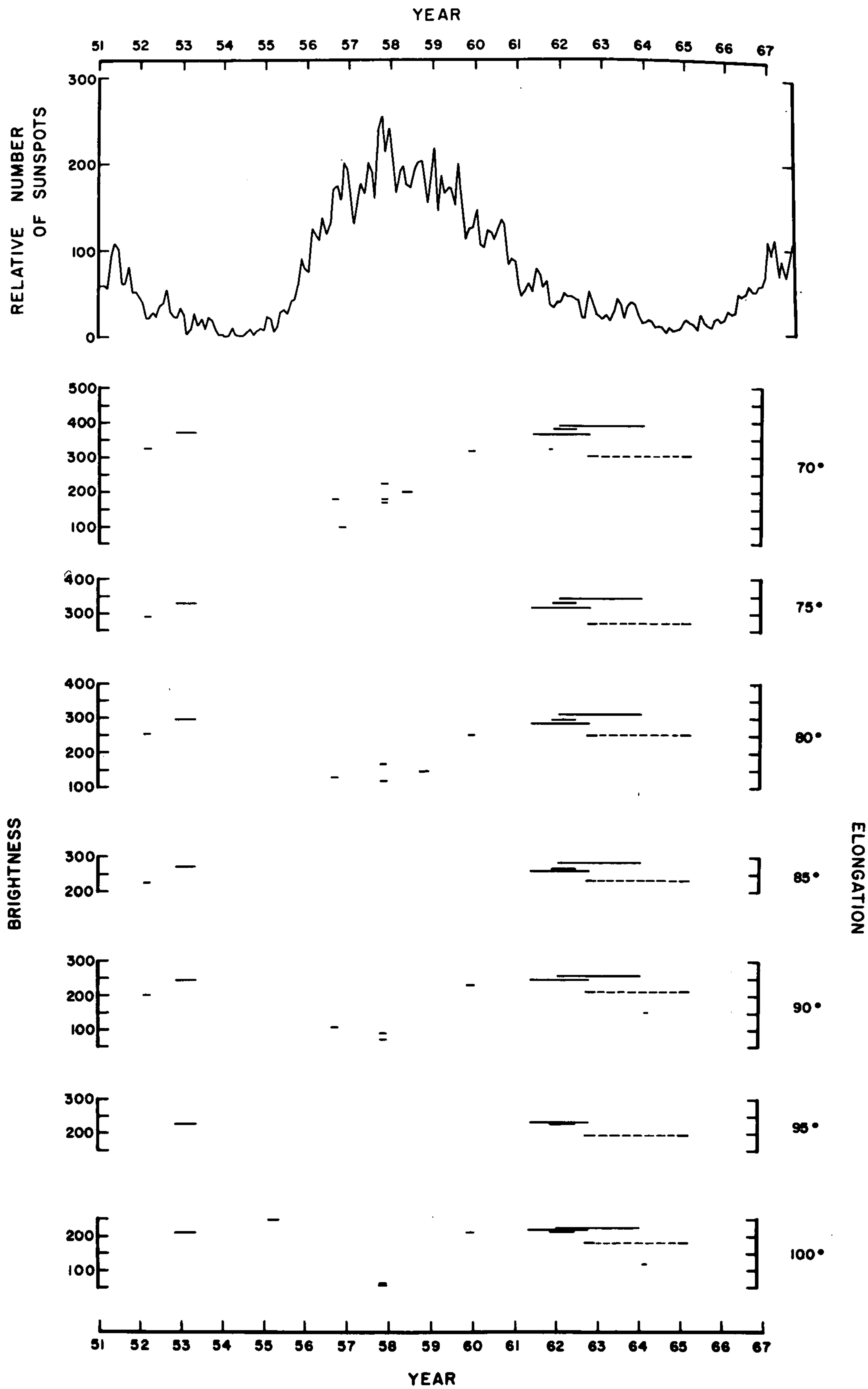

Figure 4. Post-1950 results on the brightness of the zodiacal light - versus year and relative sunspot number and for elongations 70 - 100°.

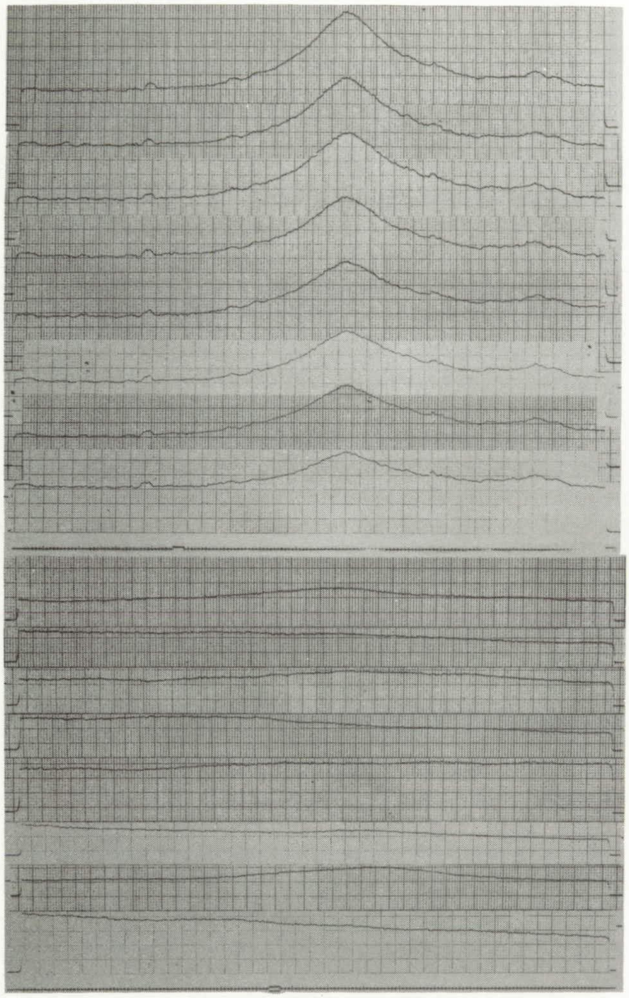

Figure 5. A map of identical regions of the sky at 13° elevation on eight nights between 18 February and 29 February 1968 - at 5080Å (above) and 5577Å over a range of 160° azimuth.