A Program of Ground-Based Studies of the Zodiacal Light*

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Rather than open the Symposium on a negative note by emphasizing the discordance of zodiacal light results, I will outline some recent results from the Haleakala program and current studies in several critical areas.

The Haleakala Program

Measurements of the zodiacal light were begun at Haleakala in 1961 with a single color photoelectric polarimeter (5300Å; Weinberg, 1964). Since March 1965, when the program was adapted to a multicolor study in the visible and near infrared, we have obtained observations on 275 nights. We expect to continue certain aspects of both the routine and special observing programs through solar maximum. From this we hope to obtain information on both short- and long-term fluctuations in the nightglow and to provide a ground-based backup for the numerous balloon, rocket, and satellite experiments now planned or in operation.

The multiplier phototube now in regular use is a red-sensitive, EMR S-20 (Table I) which will cover the range from approximately 3500Å to 9000Å without using prismatic light injection. Tests are being conducted with an S-1 multiplier phototube as a prelude to our construction of a near infrared photoelectric polarimeter.

Wavelength discrimination is provided by sequential observation with narrow-band interference filters. In practice the characteristics of such filters (Table II) will vary with temperature and over the filter surface, and it is necessary to measure the characteristics in an optical configuration similar to that in which the filters are to be used. For the very narrow filters one must beware of shifts with time of the band position. Additional

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details of the instrument and programs will be described in an Observatory report now in preparation.

Recent Results

1. Non-zodiacal light sources of polarization in the nightglow.

The nightglow can be specified by the total or observed brightness (B_{obs}), the brightness of the polarized component (B_{pol}), the orientation of the plane of polarization (χ), and the total degree of polarization (p_{tot}) .[i] These quantities are related[ii] by

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

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 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 $j = ZL + i$. In studies of the nightglow continuum it is usually assumed

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[i] The ellipticity is small and is ignored in this treatment.

[ii] This is given incorrectly in previous publications (Weinberg; 1963, 1964).

that all or most of the polarization arises from zodiacal light. Accordingly, $\sum_i (I_\perp - I_\parallel)_i = 0$, and the problem is reduced to separating the components in the denominator of equation (2).

Recent studies at Haleakala indicate that there are, however, non-zodiacal light sources of appreciable polarization (both astronomical and atmospheric) in the nightglow. Of particular interest is the polarization associated with the 6300Å and, especially, with the 5577Å airglow line emissions. The airglow polarization monotonically increases to a value of several percent near the horizon. In contrast to the strong azimuth-dependence of the astronomical sources of polarization, the airglow polarization is relatively uniform in both orientation and degree.

Figure 1 gives an indication of the origin of this polarization. The diurnal variation of the plane of polarization at 5080Å is primarily associated with the zodiacal light and with the changing position of the sun with respect to the observer and the celestial pole (see, also, Weinberg, 1965). Clearly, the polarization at 5577Å is not solar-oriented. Preliminary calculations (Coulson and Weinberg, 1967) suggest that the 5577Å polarization may be explained by tropospheric scattering of an unpolarized radiation incident on the scattering atmosphere from the E and/or F regions.

Although the degree of polarization is small, the airglow lines are "bright", and the intensity of the polarized component is comparable to that of the zodiacal light. Broad-band detection does not, therefore, permit the assumption that $\sum_i (I_\perp - I_\parallel)_i = 0$ in equation (2). In the following section we discuss methods of separating the terms in the denominator of equation (2). There is every indication that the discordance of results arises from difficulties engendered by different measuring techniques rather than from real changes in the zodiacal light.

2. The separation of zodiacal light from starlight and airglow.

Starlight. We define starlight as the sum total of brightness from integrated starlight, galactic light, and other sources not having their origin in the atmosphere or in interplanetary space. An empirical technique for deriving the starlight is illustrated in Figure 2 where we have plotted the observed brightness at 5300A for part of an almucantar including the peak zodiacal light and regions of both high (I) and low (II) galactic latitude. These regions are bounded by points a, b, c, and d, whose galactic coordinates (b^I, ℓ^I) are also shown in Figure 2. The smooth curve drawn in region I is used as a background for region II above which the differential starlight (the cross-hatched area) is measured. This differential starlight is corrected for atmospheric extinction and scattering and is then added to the integrated starlight, J(V), corresponding to the b^I, ℓ^I of the background or mirror points via a cubic interpolation in tables (Roach and Megill, 1961) based on star counts in the Selected Areas. This sum is termed starlight.

For best results the almucantar scan should be approximately centered on the peak zodiacal light. The central value of azimuth, from which the mirror regions are reckoned, is chosen to approximately bisect the brightness distribution near its peak value. The choice of boundaries is governed by the range of azimuth over which the total brightness is measured, by the position of the plane of the galaxy with respect to the peak zodiacal light, and by how close the mirror points are in ecliptic latitude and elongation. To satisfy these requirements and to assure that differential atmospheric scattering will be minimized, the ecliptic must be within ±5 degrees of the vertical.

Inherent in the technique are the assumptions that (1) the zodiacal light is approximately symmetric about its axis, (2) the airglow continuum is constant over the range of azimuth included in the measurement, and (3) the starlight is constant. The reproducibility of results obtained on different nights indicates that these assumptions are valid. This technique applied to satellite observations made perpendicular to the ecliptic appears to be especially well-suited for giving the non-zodiacal light component over a range of perhaps ±40 degrees of galactic latitude.

We observe small scale structure which is not found in the smoothed star count results, and while existing star count results cannot be used as a base for separating components of the nightglow at low galactic latitudes, the use of the tabular values does not introduce a significant error at high latitudes where the starlight is relatively faint. This technique is being used to derive a map of the starlight at low galactic latitudes.

Airglow. By careful selection of filters the airglow line emission can be avoided. The principal culprit in making an accurate separation of nightglow components is the airglow continuum. We know neither its nature nor its origin, and it is quite possible that it is not there (at some wavelengths).

The airglow line radiations are not enhanced in the zodiacal light; i.e., we observe no enhancement when we scan across the bright regions of zodiacal light with narrow airglow filters (e.g., 5577III and 6300III in Table II). Similarly, we observe no enhancement through suitably-blocked continuum filters when we scan across regions of enhanced airglow line emission.

In a study in progress at Haleakala we compare observations of the continuum with observations of the 5577Å and 6300Å airglow line emissions at the celestial pole. Figure 3 shows the brightness observed through eight filters at the celestial pole on 16/17 December 1966. The small variation seen through the continuum filters is typical even when the line emission varies by a factor of two or greater. Our preliminary results do not confirm the degree of covariance between 5577 line and continuum emission found by other investigators. Analysis of other observations is required before we can assess the effect of line and continuum filter characteristics on the inferred degree of covariance. The 5577 line emission has its principal maximum at 90 km and a secondary maximum in the F-region which coincides with the maximum of the 6300 line emission. Under "normal" conditions the 5577 and 6300 line emissions do not co-vary. When the 6300 line emission is enhanced, and factor-of-ten enhancements are not uncommon at Haleakala, it covaries with the F-region portion of the 5577 line emission. This further complicates the study of line and continuum covariance.

Since the zodiacal light extends over the entire sky, observations at some distance from the ecliptic cannot be used effectively for the purpose of estimating the background. Pending the results of additional studies of nightglow covariance groups, we find that the most successful means of separating components involves subtraction of the starlight by some technique and an examination of the nature of the remainder (zodiacal light plus airglow) with time and over the sky.

3. Comet 1965f and the zodiacal cloud.

Numerous observations before and after perihelion of Comet 1965f make it possible to examine effects resulting from the newly-injected cometary material. We have found no large-scale changes in the zodiacal light in a two-week period including perihelion. Additional data is being analyzed in this manner as part of our continuing study of short- and long-term fluctuations in the nightglow.

Multicolor observations were taken of the nightglow over a 9x20 degree section of the sky containing Comet 1965f during several nights following perihelion. The principal Stokes parameters have been derived at 5300Å both along and normal to the axis throughout the tail of the Comet for one night's observation. Along the axis of the tail the polarization decreases to a neutral point several degrees from the nucleus after which it is negative (electric vector parallel to the scattering plane) throughout the remainder of the tail. This result, as in the case of zodiacal light, requires the presence of dielectric particles. The use of additional observations suggests that it may be possible to delineate a rather small family of allowable solutions for the size distribution of the particles.

4. Lunar libration clouds.

In a cooperative program with the Haleakala satellite tracking station of the SAO we have initiated a program of observations of the libration regions in the earth-moon system. Based on predictions received from SAO, Cambridge, we have searched for clouds L_4 and L_5 on six different occasions. No visual enhancement was evident on any of the six nights. Photoelectric observations by us and photographic observations by the SAO in and around the predicted regions are still being analyzed. In the event that the existence or characteristics of these clouds may be dependent on lunar phase, we plan to observe in and around the predicted regions as often as possible.

Concluding Remarks

The observer is charged with the responsibility for providing new observations to further limit the allowable size and spatial distributions of the zodiacal dust. Existing observations can be interpreted in many ways and allow us to say little about the mass or density distributions of the zodiacal dust although we can differentiate between certain dielectric and metallic component models.

Studies now underway at Haleakala should provide information on short- and long-term changes in the position of the symmetry axis of the zodiacal light in total and polarized light, and on characteristics of the Gegenschein and of the polarized component at large distances from the sun in the plane of the ecliptic. We hope to provide very soon the distribution of brightness and polarization in the ecliptic at eight or more colors in the visible spectrum in the range of 30 to 120 degrees elongation.

By observing over long periods of time and by extending line and continuum covariance studies to many wavelengths in the visible and near infrared it should be possible to infer something of the nature and origin of the airglow continuum. This, in turn, will enable us to derive the wavelength dependence of the principal Stokes parameters of the zodiacal light over the sky.

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Tables

I. Multiplier Phototube Calibration Data (EMR Model 541E-01-14).

II. Interference Filter Characteristics.

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1. Orientation of the plane of polarization in two colors at the celestial pole on 9/10 December 1966.
2. Observed brightness (in 10th mag. vis. stars deg^{-2}) at an elevation of 8 degrees on 11/12 January 1966 for 5300Å.
3. Observed brightness at the celestial pole on 16/17 December 1966. The same brightness scale is used for all colors except 5577II, which has been reduced by a factor of 1.546.

Table I

Multiplier Phototube Calibration Data (EMR Model 541E-01-14)

Test Date	Luminous Sensitivity	% Quantum Efficiency					Dark Current at 10^6 Gain
		4100	4600	5600	6300	8000Å	
6-30-65	231 μA/lumen	24			6.5	1.7	$4\text{x}10^{-9}$ A - 1 hr
7-16-65	226	24			6.5	1.7	$9\text{x}10^{-9}$ - 20 min
9-23-65	236	27			7.0	1.4	$9\text{x}10^{-9}$ - 20 min
11-12-65	237	27			7.0	1.4	$2.2\text{x}10^{-9}$ - 1 hr
12-10-65	237	27.2	21.8	10.4	6.9		
*8- 8-66		22.2	18.4	10.0	6.4		$7.8\text{x}10^{-10}$ - over-night
10-12-66	237	27.1	21.6	11.9	7.3	1.7	$1.6\text{x}10^{-9}$ - "

*relative calibration based on earlier data.

Table II

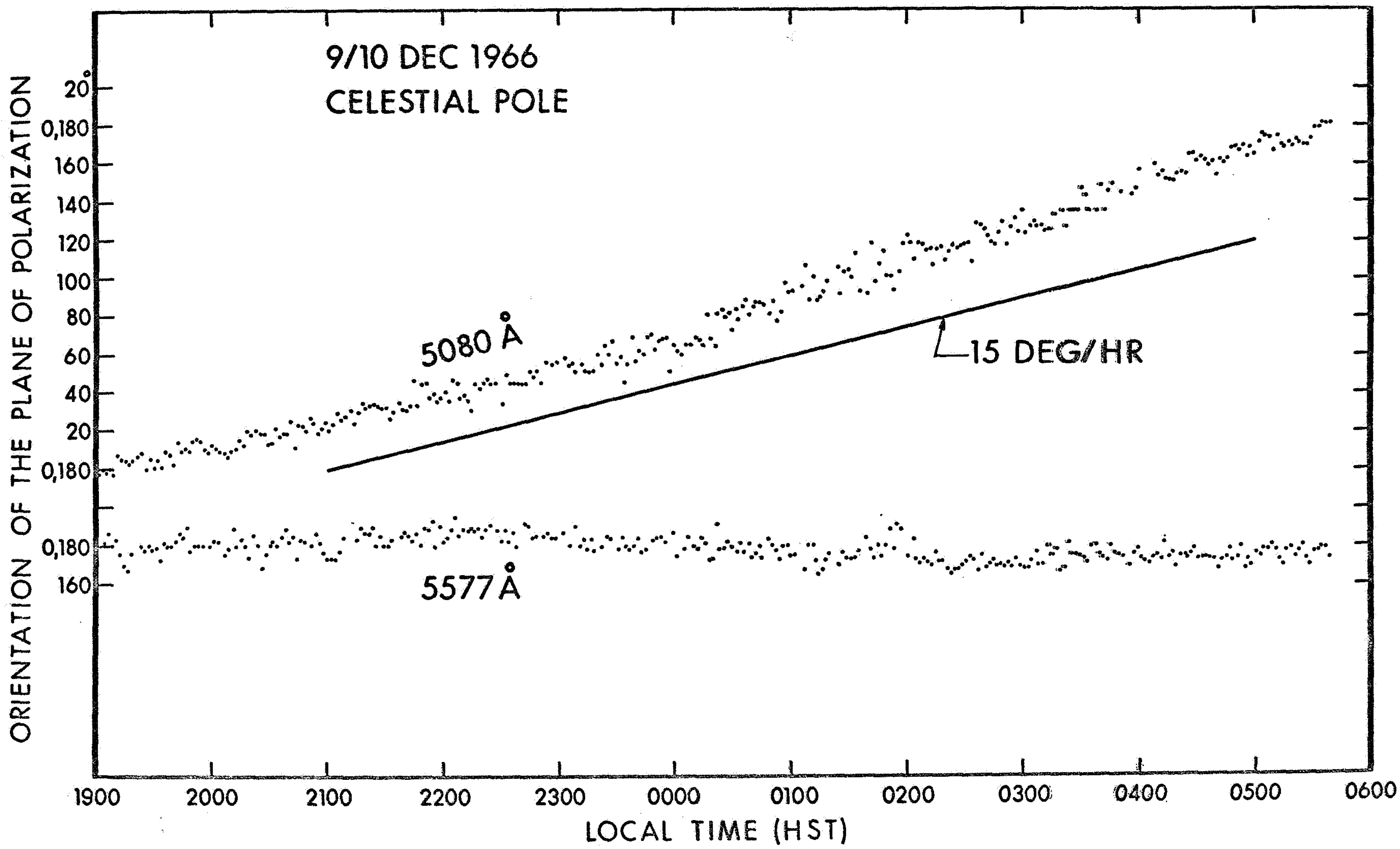
Interference Filter Characteristics

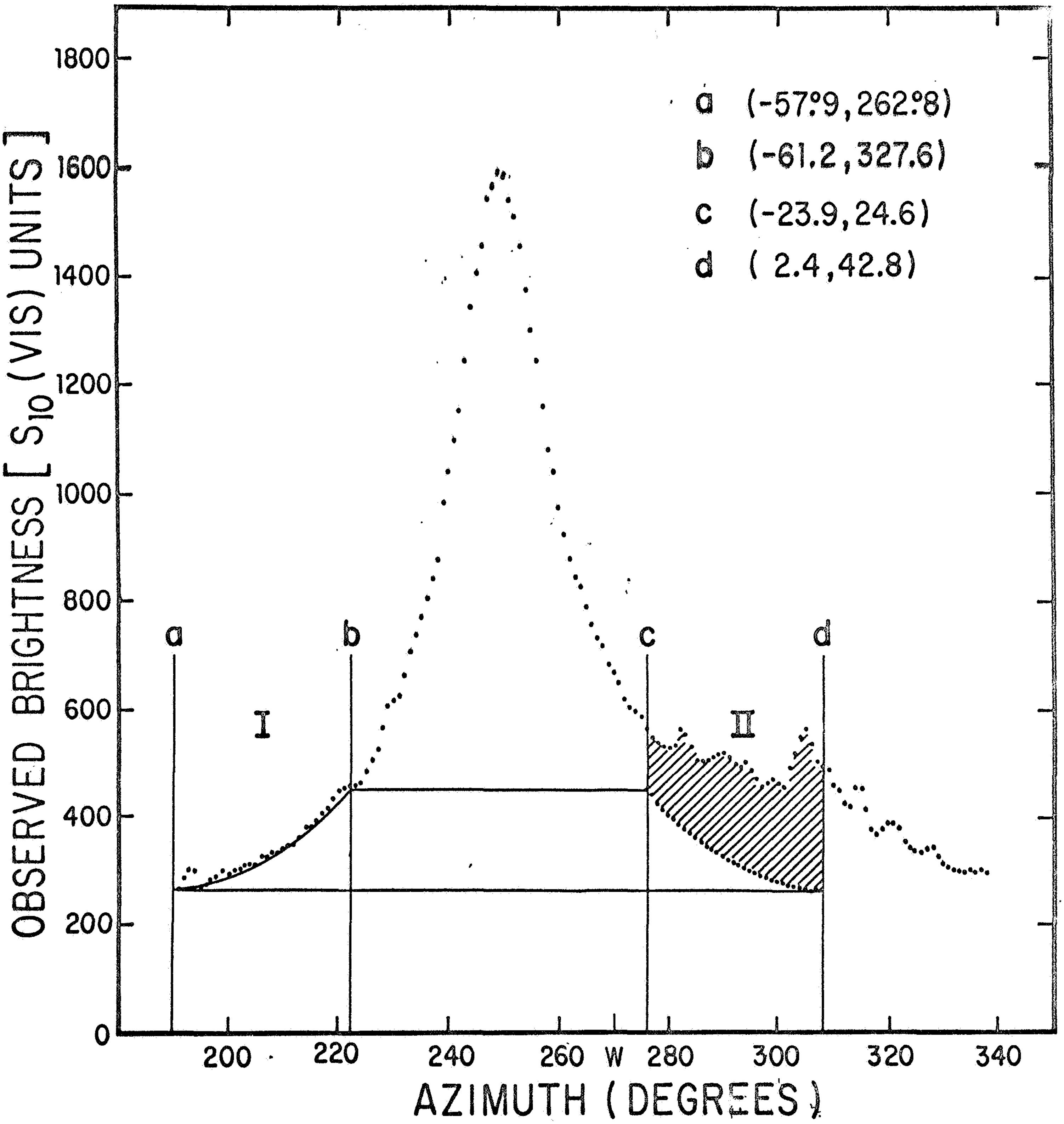
Central Wavelength			
$1/\lambda$, μ^{-1}	λ, Å	Half-Transmission Bandwidth*	Maximum Transmission
2.86	3500	40 Å	61 %
2.50	--4000	10	
2.30	4355	12	38.5
2.10	4760	11	56.3
1.97	5080	30	64.0
1.89	5300	62	78.2
1.83	5450	20	57.5
1.79	5577I	23	55.2
	IB	12.2	54.1
	II	10.8	56.7
	IIB	7.1	39.8
	III	5.7	41.4
1.74	5752	24.0	42.1
1.64	6080	17.0	65.1
1.59	6300I	31.7	56.3
	IA	22.9	53.6
	II	10.0	41.0
	IIA	9.2	44.8
	III	4.6	36.3
1.55	6437	12.4	55.3
1.48	6745	21.0	57.6
1.41	7100	23.5	59.9
1.22	8200	51.5	57.8
1.15	8700	53	53
1.08	9250	58	64
1.05	--9550	80	
0.939	--10650	100	

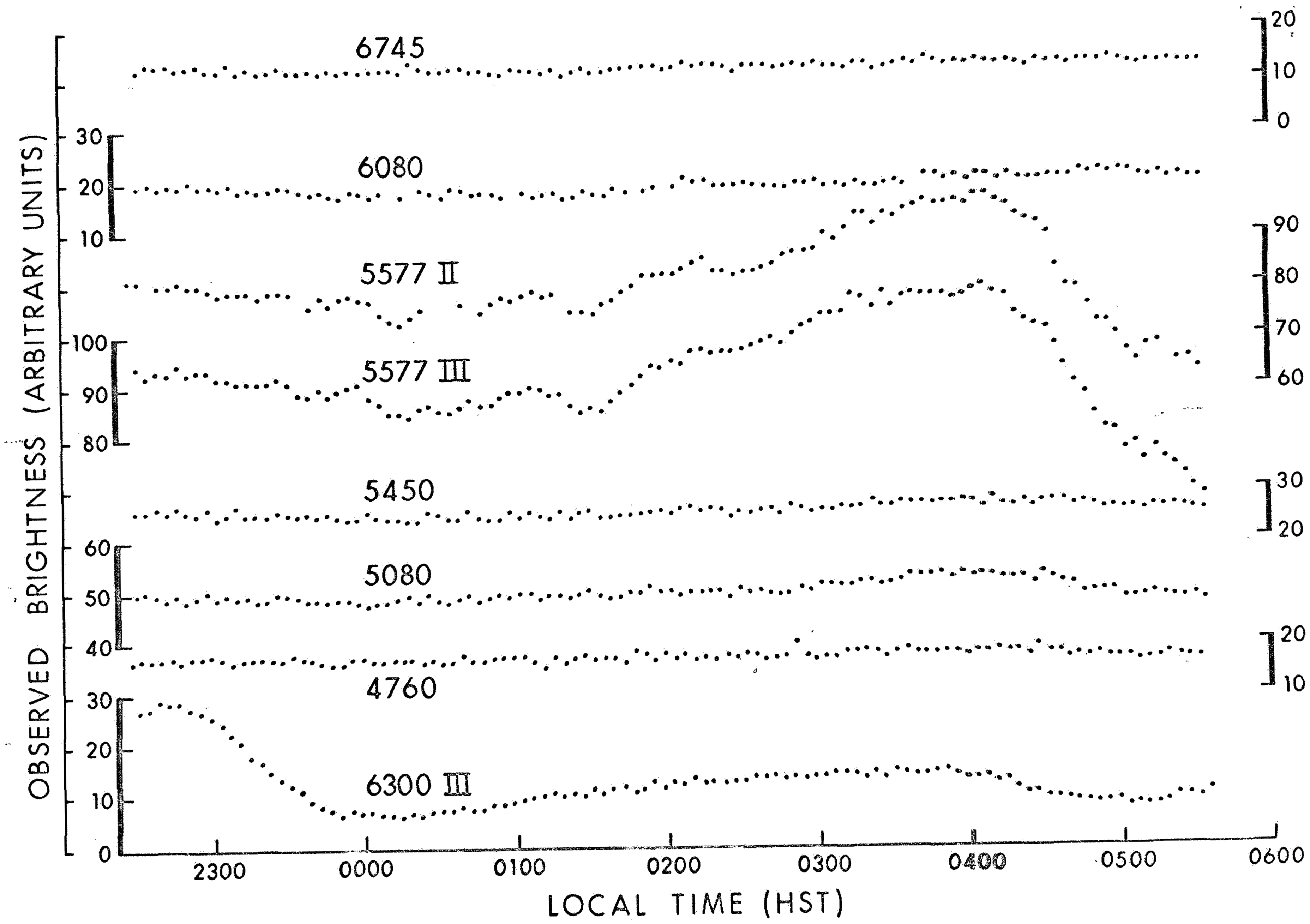
*at center of filter

--on order (also on order are additional filters at 5577, 6300)

These filters (except those at 3500Å and 5300Å) are characterized by excellent off-band rejection (transmission less than 0.005 %).


9/10 DEC 1966
CELESTIAL POLE
5080 Å
5577 Å
15 DEG/HR
ORIENTATION OF THE PLANE OF POLARIZATION
20°
0,180
160
140
120
100
80
60
40
20
0,180
0,180
160
1900
2000
2100
2200
2300
0000
0100
0200
0300
0400
0500
0600
LOCAL TIME (HST)


a (-57°9, 262°8)
b (-61.2, 327.6)
c (-23.9, 24.6)
d (2.4, 42.8)
a
b
c
d
I
II
OBSERVED BRIGHTNESS [S_{10} (VIS) UNITS]
1800
1600
1400
1200
1000
800
600
400
200
0
200
220
240
260
W
280
300
320
340
AZIMUTH (DEGREES)


6745
6080
5577 II
5577 III
5450
5080
4760
6300 III
OBSERVED BRIGHTNESS (ARBITRARY UNITS)
LOCAL TIME (HST)
2300
0000
0100
0200
0300
0400
0500
0600
30
20
10
100
90
80
60
50
40
30
20
10
0
20
10
0
90
80
70
60
30
20
20
10