Reprinted from "The Proceedings of the Indian Academy of Sciences",
Vol. XLIII, No. 2, Sec. A, 1956

ON THE INTENSITY AND POLARISATION OF THE LIGHT FROM THE SKY DURING TWILIGHT

BY J. V. DAVE AND K. R. RAMANATHAN, F.A.SC.

Received December 24, 1955

1. INTRODUCTION

THE object of this paper is to present the results of some new homogeneous measurements of the brightness of the clear zenith sky taken at Mt. Abu (24° 26′ N; 72° 43′ E) with a photon multiplier and six narrow band filters for different values of solar depression from 0° to 20° together with some measurements of polarisation, discuss the results in the light of our present knowledge of the upper atmosphere and attempt on broad lines an explanation of the optical phenomena observed during the transition between day and night.

2. EXPERIMENTAL ARRANGEMENTS

An R.C.A. photomultiplier 931–A, selected for small dark current, was used with an A.C. operated D.C. power-supply stabilised by a degenerative type of electronic regulation. The photomultiplier output current was amplified by a balanced-bridge stabilised D.C. amplifier. The sensitivity of the amplifier could be changed successively by factors of about 10 by introducing different resistances varying from 10^3 to 10^8 ohms in its grid circuit. The exact scaling factor from one stage to the next was determined by illuminating the photocathode by a beam of constant intensity and noting the reading in each successive stage. No attempt was made to measure the absolute values of the intensities; only relative intensities were determined. For values of output current less than 400 microamperes, the current was found to be proportional to the intensity of light falling on the photocathode. For higher outputs, the correction due to the non-linearity of the variation of output against input voltage was measured and applied. The effect of varying the orientation of the plane of polarisation of the incident beam on the sensitivity of the photomultiplier was tested and found to be negligible.

Suitable optical filters were used to transmit different parts of the spectrum. The components and characteristics of the filters are shown in Table I. The figures take into account the spectral sensitivity of the photomultiplier. It will be noted that with the green, yellow and red filters, the effective transmissions are about 200 A centred approximately at the respective lines of the airglow spectrum.

Proc. Ind. Acad. Sci. A 43, 67–78, 1956.

TABLE I

Components and effective transmissions of optical filters when used with RCA Photomultiplier 931 *A*

Brief name for filter	Components	Half band-width of transmission	Maximum transmission
U	Chance OX 1	3300–3850	3700–32%
V	Chance OV 1	3640–4050	3850–44%
B	Chance OY 18 and OB 10 ..	4350–4800	4600–9½%
G	I.F. *plus* ON 16 *plus* Plastic Yellow	5530–5750	5600–3½%
Y	I.F. *plus* Chance OY 1	5800–6000	5870–2%
R	I.F. *plus* Plastic Red	6150–6400	6300–1%
J	Polaroid	4000–5500	4600–40%

I. F. stands for interference filter obtained from Messrs. Barr and Stroud.

For the measurement of polarisation, a polaroid of type J was placed in the path of the radiation so as to measure (1) the intensity I_R of the component perpendicular to the sun's meridian and (2) the intensity I_L of the component parallel to it. Both the intensities were measured within a time interval of 5 seconds. The percentage polarisation was calculated from the formula,

$$P = \frac{I_R - I_L}{I_R + I_L} \times 100.$$

3. RESULTS

(*a*) *Intensity.*—Observations were made only on cloudless clear skies. Only one narrow-band filter was used on any particular morning or evening. Meter readings were noted at regular intervals of half a minute except during late twilight when the rate of change of intensity was very small. Frequent check was made on the zero reading and photomultiplier voltage. After applying linearity and zero shift corrections, the corrected meter readings were multiplied by appropriate scaling factors so that the final values were proportional to the intensity of the light falling on the photocathode.

The readings taken on different *clear* days with the same filter were found to agree well when the photomultiplier voltage was kept very steady.

The actual readings for the same solar depression were found to differ in certain ranges on some days. This might have been due to small changes in photomultiplier voltage, changes in the scattering and absorption of light by dust and haze in the atmosphere and changes in the emission of the air-

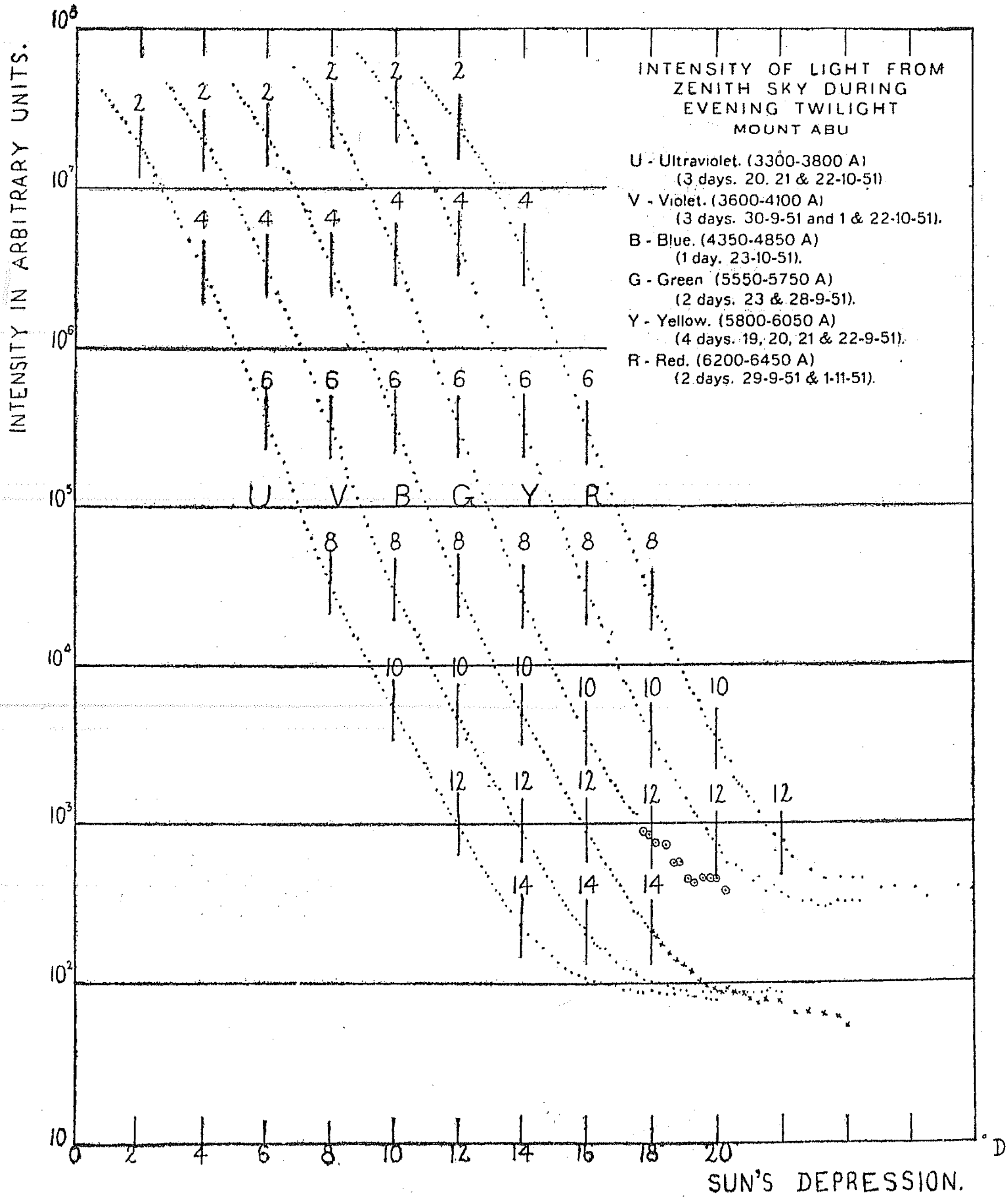

FIG. 1. Intensity of the light from the zenith sky in evening twilight in defined regions of the spectrum.

2

glow lines. For comparing the course of the variation on different days and in different wave-lengths, the readings were reduced to a common standard by multiplying the values on a particular morning or evening by a factor which would make the readings on all the occasions have the same value at a solar depression of 5°. The means of the intensities observed on different days with the same filter and for the same solar depressions, were calculated.

The average values of the observed intensities of the zenith sky in arbitrary units during evening twilight in different portions of the spectrum are plotted against solar depression in Fig. 1. The intensity scale is logarithmic. The following are the main features of zenith sky brightness during twilight:

(1) The curves for the different wave-lengths from the near ultra-violet to red are *generally* similar from D = 0 to D = 12°, but in the shorter wave-lengths, the rate of decrease of intensity with increasing solar depression becomes markedly less when D is about 8°.

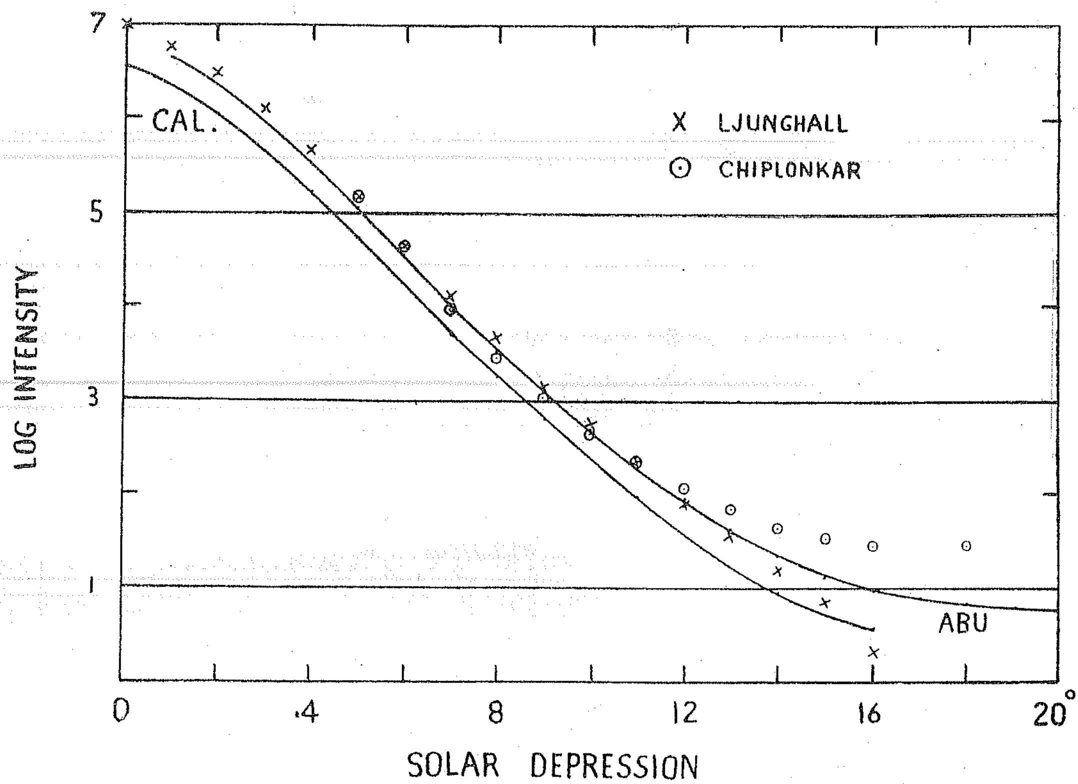

FIG. 2. Comparison of twilight zenith sky intensities as measured in different places.
ABU 4600 A.
CAL. 4400 A. Ashburn (Cactus Peak, California).
× Composite. Ljunghall (Helwan and other places).
⊙ Visual including green. Chiplonkar and Ranade (Sinhagad, Poona).

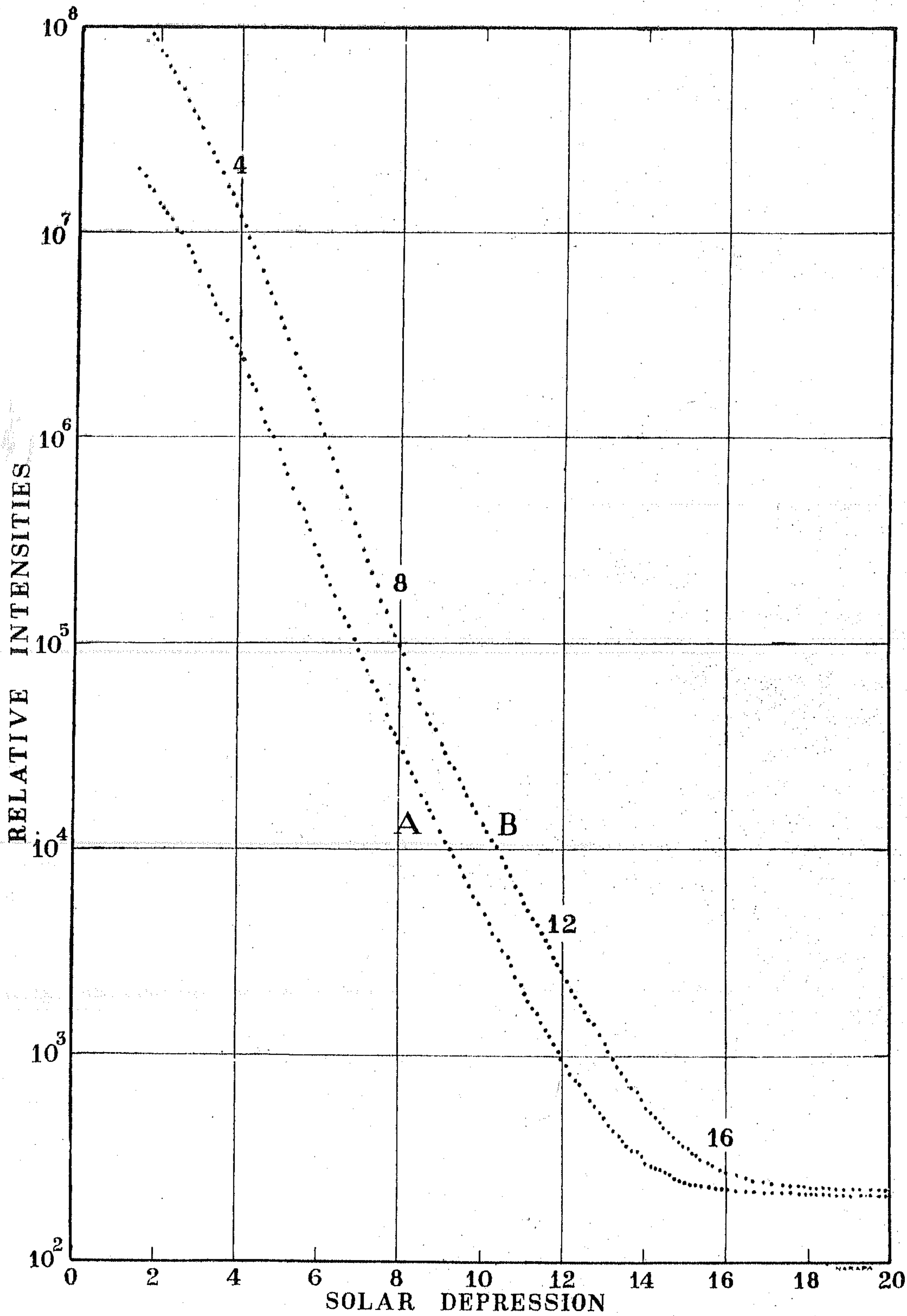

FIG. 3. Intensity of **parallel and perpendicular** components of zenith sky light during morning twilight (4000–5700 **A**).

A. Parallel **component**. **B.** Perpendicular component.

(2) While the intensities of the ultraviolet, violet and blue flatten out when the sun's depression is 16° to 18°, the intensities of the green, yellow and red which include bright lines in the night airglow flatten out when D is 13° to 14° at a higher level of relative intensity.

(3) In the green and the red, there were observed on many days a reduction in the rate of fall of intensity when D was about 12° suggesting a temporary brightening near the boundary of earth's shadow. This requires further examination.

For comparison, the values of zenith sky intensities observed during twilight by other observers are plotted side by side with the Abu values. Ashburn's measurements[1] in California were made with a phototube and filters and come closest to Abu values. The observations of Chiplonkar and Ranade[2] were made at Sinhagad near Poona with a visual photometer including the oxygen green line. Ljunghall's[3] curve is composite being made up of his own observations at Helwan with a photocell and filter and of the old visual observations of Dufay and others.

(*b*) *Polarisation.*—Observations of I_L and I_R for studying the polarisation of the sky were taken on a number of mornings and evenings: (1) with the polaroid alone (which transmits the violet, the blue and the green including an appreciable fraction of the green line 5577 A) and (2) with polaroid and blue filter.

In Fig. 3 are plotted the values of I_L and I_R for different solar depressions during morning twilight with polaroid alone. The corresponding curves for evening twilight taken with polaroid and blue filter for the spectral region 4350–4850 A, are essentially similar.

The values of the percentage polarisation as calculated from the values of I_L and I_R are plotted in Fig. 4. Curves B and C represent the values obtained in the effective spectral region 4350–4850 A for evening and morning twilight respectively, while the curves D and E are for the spectral region 4000–5700 A.

The curves showing zenith sky polarisation against solar depression are in general agreement with those obtained by Robley[4] visually at Pic du Midi. His observations extended to 16° and are also shown in Fig. 4, curve A. From Fig. 4, the following points are clear. When observations were taken with a blue filter, the zenith sky polarisation remained more or less steady at about 70% till D was 5°, and then showed a pronounced fall till D was $8\frac{1}{2}$°. Between $8\frac{1}{2}$° and 12° solar depression, the polarisation again showed a plateau at 45% to 50%, after which it declined rapidly so that when D was greater than 18°, the zenith sky was practically unpolarised.

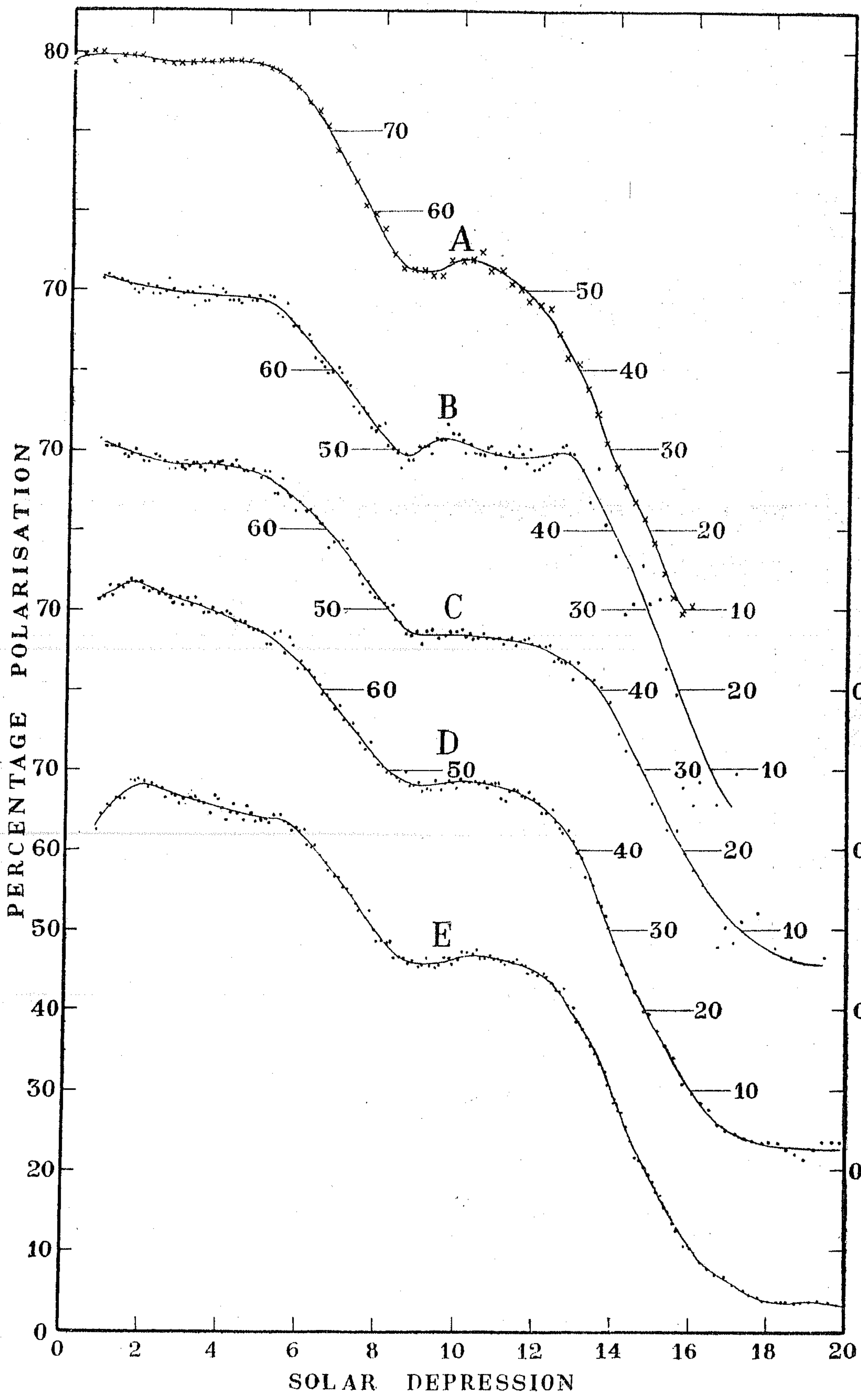

FIG. 4. Percentage polarisation of the light from the zenith sky during twilight.
A. Robley, Visual. Pic du Midi (1950)
B. 4350–4850 Evening. Mt. Abu.
C. 4350–4850 Morning. Mt. Abu.
D. 4000–5700 Evening. Mt. Abu.
E. 4000–5700 Morning. Mt. Abu.

Robley's curve shows similar variations, but the initial polarisation at low values of solar depression is higher, due no doubt to the clearer skies over Pic du Midi.

The curves obtained with the polaroid alone without the blue filter show similar features but the changes of polarisation are less sharp.

The polarisations at points 30° from the zenith in the vertical plane through the sun were measured both towards the sun and away from the sun

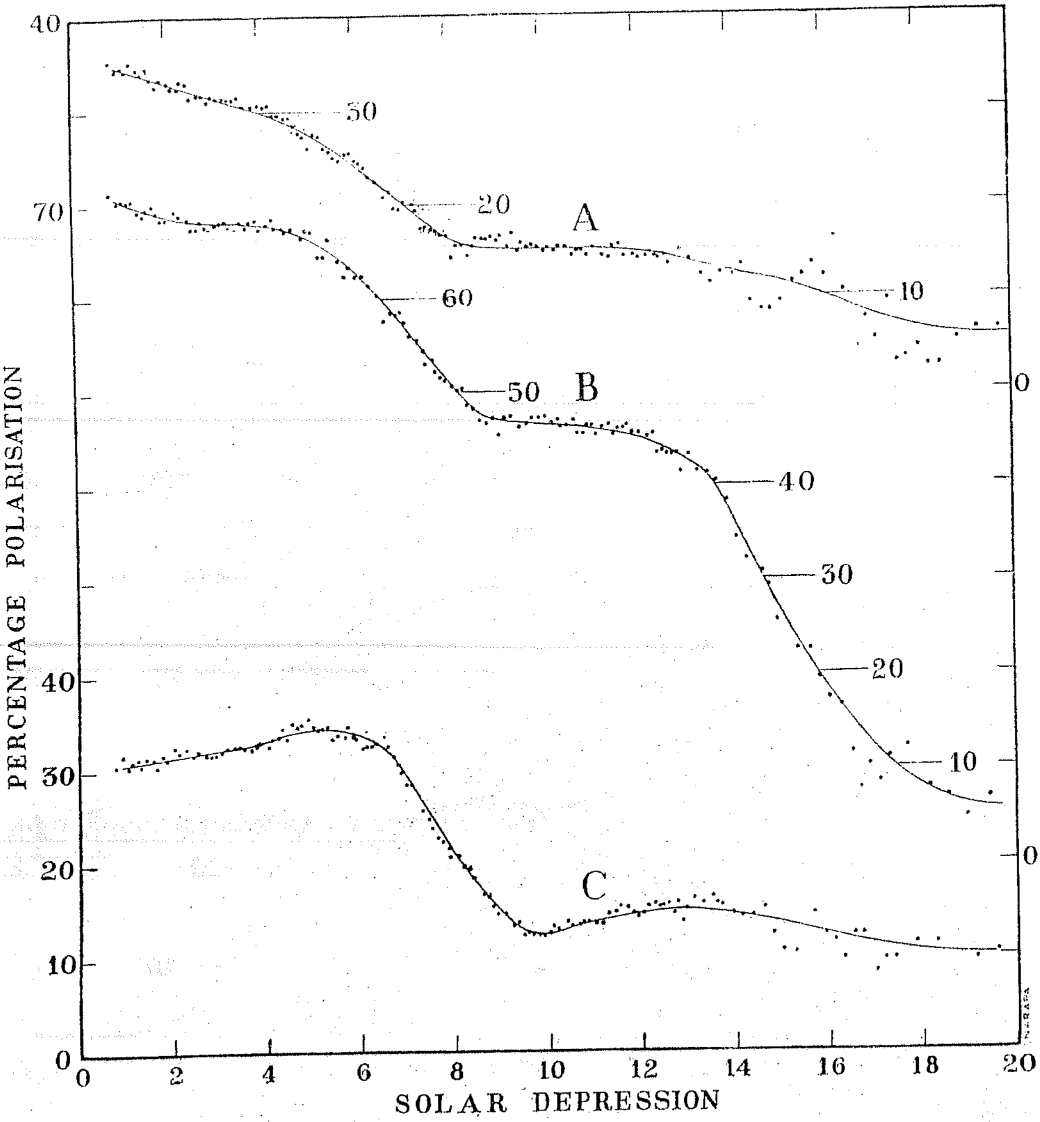

FIG. 5. Percentage polarisation of skylight in morning twilight (4350–4850).
A. 30° from the zenith away from the sun.
B. At zenith.
C. 30° from the zenith towards the sun.

on different days during morning twilight. The values of the polarisation calculated from the observed values of I_L and I_R are plotted in Fig. 5. Curves B, A and C represent the variations of polarisation with solar depression at zenith, 30° from the zenith towards the sun and at 30° from the zenith on the anti-sunside respectively.

It will be observed that the changes in sky polarisation 30° away from the zenith but towards the sun are sharper than those at the same angular distance from the zenith on the anti-sunside. The corresponding changes occur as may be expected, first on the anti-sunside, then at the zenith, and lastly on the sunside; the flattening out of the polarisation curve occurs at 9·5° on the sunside, at 9° at the zenith and at 8·5° on the anti-sunside.

To explain the humps in the polarisation curves requires further analysis of secondary scattered light.

4. Discussion

When the sun is a few degrees below the horizon, the upper part of the atmosphere is directly illuminated by the sun's rays, while the lower part lies in the shadow of the earth. The shadow region is however illuminated by scattered radiation from the sky all round, particularly from the hemisphere towards the sun. The light from the zenith sky is therefore made up of the primary scattered light from the upper part of the atmosphere and secondary (and multiple) scattered light. Owing to the greater air density in the lower part of the atmosphere, however, the main secondary scattered light would come from layers lower down in the atmosphere than the primary scattered light. As a consequence, as the sun goes down, the primary scattered light would decrease at a much faster rate than the secondary scattered light.

The observed variation of the brightness of the zenith sky with the depression D of the sun below the horizon agrees with the view that the sky illumination during twilight is only in part due to primary scattered light P. If it were due mainly to P, the variation of the sky brightness with D would be similar to the variation of the amount of air above the lower boundary of the directly illuminated upper atmosphere, that is, of the pressure at the shadow boundary. In Fig. 6 are drawn the curves of brightness RR and BB, of the zenith sky observed at Abu in the red (6300 A) and the blue (4600 A) and also the curve of pressure PP at the shadow limit. The height of the earth's shadow above the ground (for 4500 A) corresponding to different values of D are taken from Ljunghall's paper. Ljunghall assumes that above 6 km., the attenuation of light in the atmosphere is due only to molecular scattering while at lower levels, the coefficient increases, becoming at ground level 2–2·5 times the value for molecular scattering. The refraction due to the atmosphere has been neglected. It will be seen from Fig. 6 that while the curves of BB and RR follow approximately the curve of PP down to a

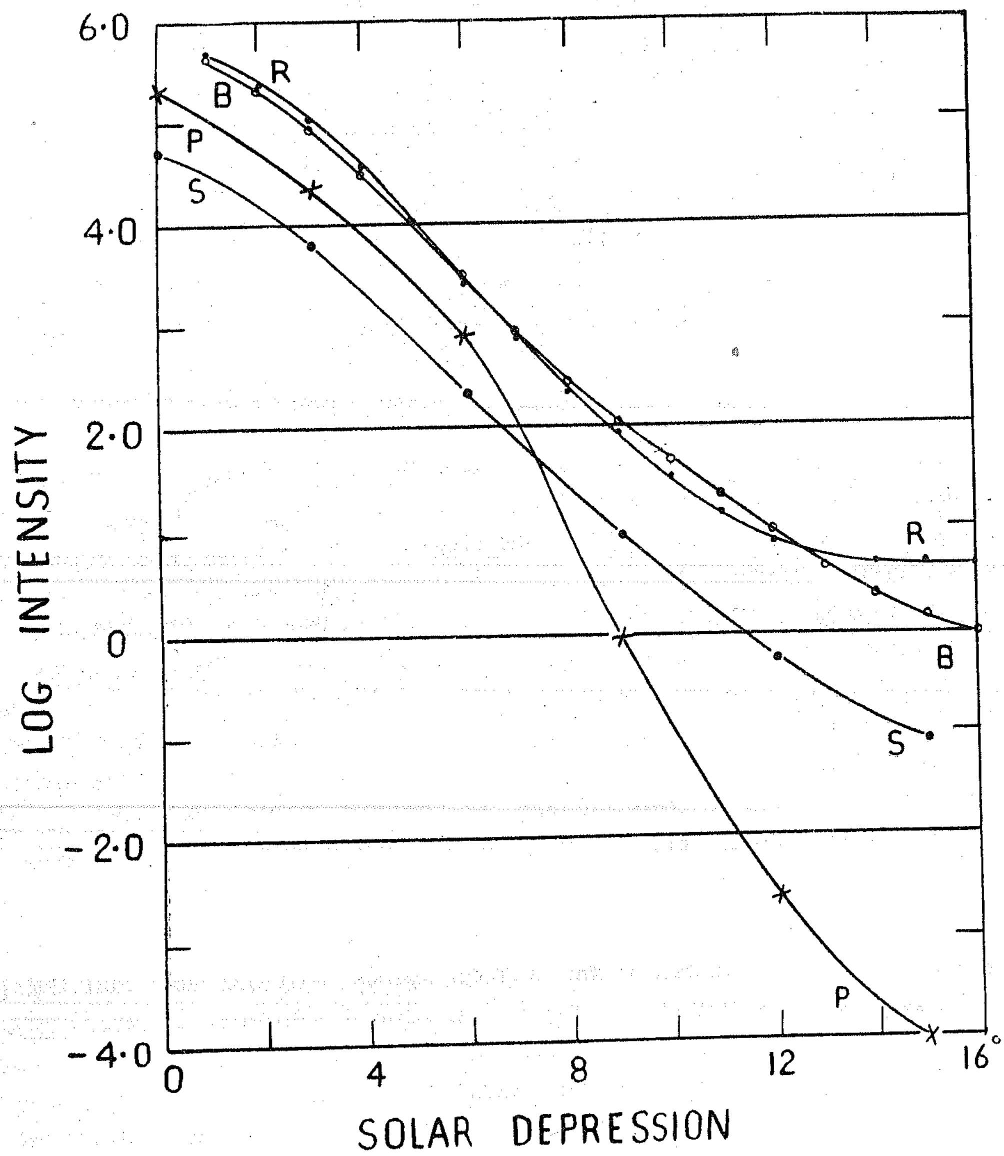

FIG. 6. Comparison of the observed zenith sky intensity with pressure at the base of the illuminated layer.

RR Observed intensity at 6300 A.
BB Observed intensity at 4600 A.
PP Pressure at the base of illuminated layer. Height of base as given by Ljunghall.
SS Integrated illumination at ground level due to scattered light from the whole sky during twilight.

solar depression of about 6°, they deviate more and more from it at greater values of D.

At solar depressions of 12° and 15°, the values of BB are more than a thousand times greater. Many years ago, it was suggested by Hulburt[5] that secondary scattering plays an important part in twilight illumination. He showed that when the solar depression exceeds 8°, the light scattered from the zenith sky from the lower part of the atmosphere lying within the shadow of the earth but illuminated secondarily by the twilight glow is comparable in amount to the light scattered by the upper part of the atmosphere directly lit by the sun's rays. We now find that the discrepancy is enormous; can all this be explained by multiple scattering? From observations now available, it is possible to make an estimate of the relative contributions of primary and multiply scattered light to the brightness of the zenith sky during twilight.

Koomen[6] and others have given values of sky brightness measured in different azimuths and altitudes at Sacramento Peak in New Mexico (2800 m. above sea-level) for different values of sun's depression down to 15° below horizon. From these measurements, one can by numerical integration estimate the illumination due to scattered light from the whole sky at the point of observation on the earth's surface. This has been done and the following are the results.

Sun's depression below horizon	Illumination due to skylight at ground
0°	180 candles/ft.^{2}
3°	22·6
6°	0·76
9°	0·031
12°	0·0017
15°	0·00027

The values in column 2 are plotted in Fig. 6 as curve SS.

We may assume as a *first approximation* that the scattered light incident after sunset or before sunrise on a vertical column of the atmosphere above the observer will vary similarly to the integrated illumination at ground as given in column 2 above. PP and SS will then represent respectively the relative variations of primary and secondary scattered light from the atmosphere during twilight. It is known that when the sun is on the horizon, *i.e.*, at D = 0, the secondary scattered light from the zenith for 4500 A is nearly 0·25 of the primary scattered light, but we do not know how this ratio will change when D increases. In what proportions the primary and secondary should be combined at different times after sunset is a matter for investigation.

5. Polarisation of Light from Zenith Sky during Twilight

The view that secondary scattering is the main factor responsible for extending the twilight period is borne out by the measurements of polarisation of the sky during twilight. Robley first showed from his observations at Pic du Midi that the polarisation of the clear zenith sky during twilight fell rapidly when D increased to more than 6° but that it later attained a steady value of 50% to 55% when the sun's depression was between 9° and 12°. These observations have been corroborated by our Abu observations (Fig. 4). When the secondary scattering also becomes insignificant, the light from the zenith sky is only scattered starlight and light from the airglow and is practically unpolarised. This happens when D is 16° to 18° for blue light. Robley found that with red light for which the secondary scattering would be much smaller, the first dip in polarisation and the plateau between D = 9° and D = 12° were inconspicuous. It may be observed that the sky illumination during evening twilight, especially in its later half, is markedly anisotropic, the light coming from the direction of the sun being much greater than from other directions. This light, when secondarily scattered downward by the atmosphere above the observer, will naturally have a large polarisation.

Quantitative checking of these ideas with observation requires the calculation of the intensity and polarisation of secondary scattered light by the spherical atmosphere when the sun is below the horizon. The calculations have been made and will be the subject of communication of Part II.

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