A STUDY OF THE POLARIZATION OF SKYLIGHT

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Summary

Results of polarization observations of cloudless daylight skies over Salisbury South Australia, are presented. The measurements were made in a narrow wavelength range centred at 5450 Å. When clear atmospheric conditions prevailed, the maximum degree of polarization was approximately 0·65, but this was observed to fall to 0·45 on an exceptionally hazy day.

The effects of polarization of skylight on object-to-background contrast are also studied. It is shown that the contrast of certain objects viewed against a sky background can be significantly increased by the use of polarization techniques.

I. Introduction

The polarization work was carried out as part of a research programme on factors that affect the detection of distant objects. The phenomenon of polarization of skylight makes possible the differential attenuation of sky background and object illumination. In some instances, this leads to a significant improvement in object-to-background contrast.

The polarization measurements were proposed as little work of this nature has been carried out in Australia. The observations were carried out at Salisbury, South Australia, with a telephotometer associated with a photoresistive detector. The present investigation has been confined to a wavelength range centred on 5450 Å by the inclusion of an interference filter having a half-width of 86 Å.

II. Theory

A theoretical treatment of polarization has been presented by Landsberg (1956).† In the general case, the endpoint of the electric vector of polarized radiation describes an ellipse. The complete state of polarization can be deduced by measuring the four Stokes intensity parameters I_p, Q, U, and V. If the major and minor axes of the

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† Landsberg, H. E. (Ed.) (1956).—"Advances in Geophysics." (Academic Press: New York.)

ellipse, of length a and b respectively, are inclined at an angle χ to the horizontal and vertical axes, then

$$Q = (a^2-b^2)\cos 2\chi\,, \tag{1}$$

$$U = (a^2-b^2)\sin 2\chi\,, \tag{2}$$

$$V = I_{\mathrm{p}} \sin 2\beta\,, \tag{3}$$

where β is the ellipticity ($\tan\beta = b/a$). Furthermore, if elliptically polarized radiation of intensity I_{p} is mixed with unpolarized radiation of intensity I_{u}, the degree of polarization P is defined by the equation

$$P = I_{\mathrm{p}}/(I_{\mathrm{p}}+I_{\mathrm{u}}) = (Q^2+U^2+V^2)^{\frac{1}{2}}/I\,, \tag{4}$$

where $I = I_{\mathrm{p}}+I_{\mathrm{u}}$ is the total intensity.

With the above definitions, it is possible to assess the advantages of using polarizing techniques to enhance the contrast and hence the detection of objects that are highlighted against the sky. Now the total intensity of the sky radiation is

$$I = I_{\mathrm{u}}+I_{\mathrm{p}} = I_{\mathrm{u}}+(a^2+b^2) \tag{5}$$

and the contrast of an object of intensity I_{t} is given by

$$C = I_{\mathrm{t}}/I - 1 = I_{\mathrm{t}}/(I_{\mathrm{u}}+a^2+b^2)-1\,. \tag{6}$$

When a polarizing filter is placed before the detector in the crossed position, the background intensity is reduced to a minimum, i.e.

$$I = \tfrac{1}{2}I_{\mathrm{u}}+b^2\,,$$

while the object intensity, assumed unpolarized, is reduced to $\frac{1}{2}I_{\mathrm{t}}$. The contrast is therefore given by

$$C' = \frac{\frac{1}{2}I_{\mathrm{t}}}{\frac{1}{2}I_{\mathrm{u}}+b^2}-1 = \frac{I_{\mathrm{t}}}{I_{\mathrm{u}}+2b^2}-1\,. \tag{7}$$

Equations (6) and (7) can be combined to give

$$\frac{C'+1}{C+1} = \frac{I_{\mathrm{u}}+a^2+b^2}{I_{\mathrm{u}}+2b^2}\,,$$

which by means of equations (2) and (5) can be written as

$$\frac{C'+1}{C+1} = \frac{1}{1-U/(I\sin 2\chi)}\,. \tag{8}$$

This expression can be used to determine the resulting improvement in contrast. When sky radiation is approximately plane polarized (a fact confirmed by the present study) the ellipticity β tends to zero and U will be equal to $I_p \sin 2\chi$. Equation (8) can then be written in the form

$$C' = (C+P)/(1-P), \tag{9}$$

where P is the degree of polarization I_p/I. The contrast improvement factor is then

$$C'/C = (C+P)/C(1-P), \tag{10}$$

and the actual increase in contrast that can be obtained is

$$C'-C = P(1+C)/(1-P). \tag{11}$$

III. Experimental Procedure

Landsberg (1956) has shown how the Stokes polarization parameters can be directly measured with a retardation plate of known relative retardation ϵ, followed by an analyser (Polaroid for example) and a photometer. The present intensity measurements were made with a telephotometer consisting essentially of a $3\frac{3}{4}$ in. focal length $f/2\cdot5$ objective lens and a focal plane diaphragm that limits the field of view to 3°. A narrow band interference filter of halfwidth 86 Å centred on 5450 Å and located before the diaphragm confined the study to this region of the spectral band. The detector was an ORP11 cadmium sulphide photoconductive cell placed 0·5 in. behind the diaphragm. The telephotometer was attached to an altazimuth mount on a tripod, enabling the instrument to be pointed at any part of the sky. A long sunshield placed in front of the telephotometer eliminated stray reflections.

Initially, the four Stokes parameters were obtained at 10° intervals in the vertical plane containing the Sun and zenith. It was found that a tape recorder considerably reduced the time taken to record the readings. Adjustment was made to the computation of V, firstly because the retardation ϵ of the quarter-wave plate for wavelengths about 5450 Å was not $\frac{1}{2}\pi$ but 79°, and secondly because the transmission of the plate was 90%. Thus V was computed by the expression

$$V = \frac{0\cdot190U+\frac{10}{9}\{I(\frac{3}{4}\pi,\epsilon)-I(\frac{1}{4}\pi,\epsilon)\}}{0\cdot982}, \tag{12}$$

where $I(\psi,\epsilon)$ denotes the intensity measured when the plane of transmission of the analyser is deviated from the vertical by the angle ψ. On February 1, 8, and 9, 1966, the Stokes parameters were measured at discrete points over the total hemisphere. Measurements were made at intervals of 15° in elevation and 22·5° in azimuth.

IV. Results

The ellipticity β usually varied between 0° and 5° but in some cases was as high as 15° to 20°. The theory for a molecular atmosphere predicts that all polarized light will be plane polarized so that $\beta = 0°$. Light scattered from large aerosol particles would not be plane polarized and so the ellipticity should give a measure of the density of aerosol particles in the atmosphere.

Since the polarized component is essentially plane polarized, the values of P and χ are sufficient to describe the state of polarization. When the vertical plane containing the Sun and zenith is considered, it can be shown that the plane of

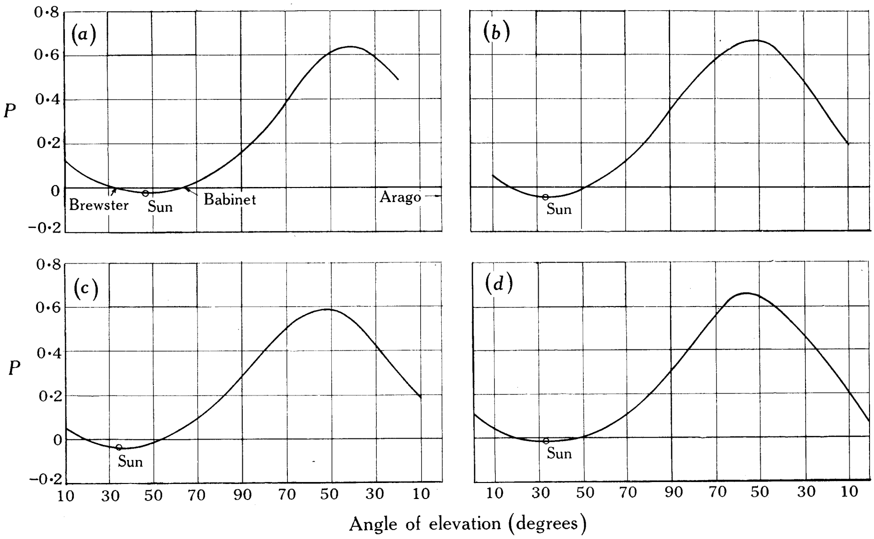

Fig. 1.—Degree of polarization P as a function of elevation angle in the plane containing the Sun and zenith for clear conditions:

(*a*) 1518 C.A.S.T., Feb. 1, 1966; (*b*) 1622 C.A.S.T., Feb. 1, 1966;
(*c*) 1615 C.A.S.T., Feb. 7, 1966; (*d*) 1615 C.A.S.T., Feb. 8, 1966.

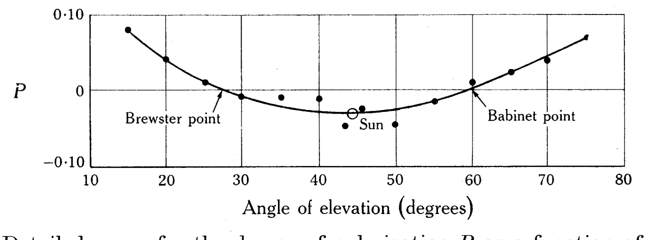

Fig. 2.—Detailed curve for the degree of polarization P as a function of elevation angle in the plane containing the Sun and zenith showing the Babinet and Brewster points (for clear conditions at 1530 C.A.S.T. on Feb. 1, 1966).

polarization is at either $\chi = \frac{1}{2}\pi$ or 0° (Landsberg 1956). This information can be associated with P (always $\geqslant 0$) by the introduction of either a positive or negative sign. Over most elevation angles $\chi = \frac{1}{2}\pi$ ($Q < 0$) and the positive sign is allocated to P. The negative sign is allocated for the condition $\chi = 0°$ ($Q > 0$).

The results of the scans in the vertical plane containing the Sun and zenith are presented in terms of the degree of polarization P in Figures 1–3. The maximum degree of polarization $P_{\max}$ under normal conditions was found to be about 0·65 and this occurred approximately 93° diametrically opposite the Sun. Theoretical curves

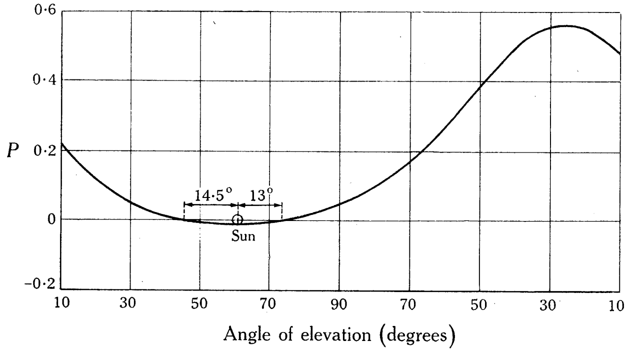

Fig. 3.—Degree of polarization P as a function of elevation angle in the plane containing the Sun and zenith for hazy conditions at 1107 C.A.S.T. on February 9, 1966.

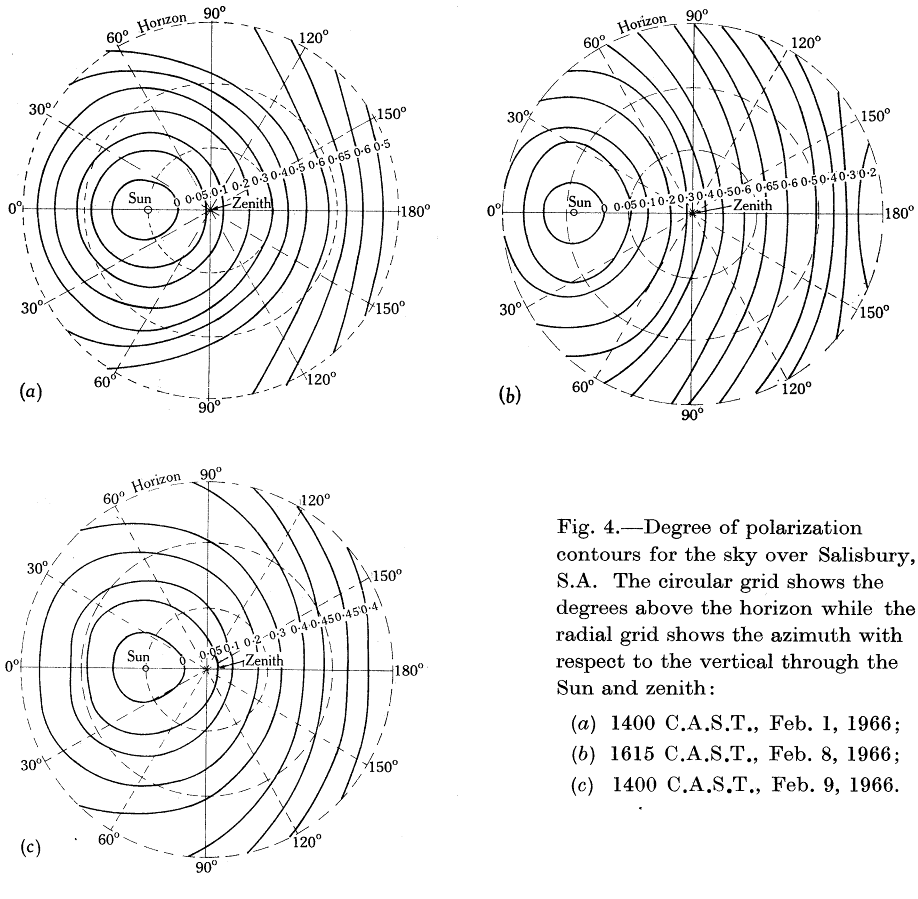

Fig. 4.—Degree of polarization contours for the sky over Salisbury, S.A. The circular grid shows the degrees above the horizon while the radial grid shows the azimuth with respect to the vertical through the Sun and zenith:

(*a*) 1400 C.A.S.T., Feb. 1, 1966;

(*b*) 1615 C.A.S.T., Feb. 8, 1966;

(*c*) 1400 C.A.S.T., Feb. 9, 1966.

have been published by Sekera (Landsberg 1956) for the case of a Rayleigh or pure molecular atmosphere. The theoretical results show that $P_{\max}$ occurs about 87° diametrically opposite the Sun, and that the maximum value of P depends on the optical thickness of the atmosphere. Evidently, the presence of aerosol particles reduces $P_{\max}$ and causes its position to be further from the Sun. These conclusions are illustrated in the results for February 9, the day of an extensive bushfire in the locality (see Fig. 4(*c*)). The increase in density of the aerosol particles caused $P_{\max}$ to drop from 0·65 to 0·46. Reflection from the ground has the effect of reducing the maximum and raising the minimum degrees of polarization; it also affects the position of $P_{\max}$. An increase in albedo of the ground tends to decrease the angular spacing of the Sun and $P_{\max}$. Comparison of the experimental results with Sekera's data indicates that the ground in the vicinity of Salisbury has an average albedo of 0·25.

Figures 1–3 show three positions in the sky (called "neutral points") where $P = 0$. The Babinet and Brewster points exist for higher solar elevations, and the Babinet and Arago points for the Sun close to the horizon. A detailed graph showing the Babinet and Brewster points is given in Figure 2, which shows that they are 15° and 18° away from the Sun respectively. The positions of the neutral points depend on the optical thickness of the atmosphere and not on reflection of radiation from the ground. Comparison of these results with Sekera's data indicates that the presence of aerosol particles tends to space the Babinet and Brewster points further apart. Quantitative comparisons of the experimental results with Sekera's theoretical predictions are not possible because the computed curves apply to a Rayleigh atmosphere. It would be necessary to know the size, type, and density of aerosol particles to predict P for a hazy but more realistic atmosphere.

On three occasions the Stokes parameters were obtained at points over the entire hemisphere. Graphical representations of the degree of polarization P are shown in Figures 4(*a*)–4(*c*). Readings are taken over one-half of the hemisphere only because the Stokes parameters are symmetrical about the vertical plane through the Sun and zenith. The shapes of the contours agree well with the computed curves of Sekera.

V. Conclusions

Results have been presented of the polarization of skylight measured at Salisbury, South Australia, in February 1966. While general characteristics agreed with theoretical predictions, the magnitudes differed due to the presence of aerosols in the atmosphere.

The figures show that the maximum value observed for P, the degree of polarization, was 0·67. Under these circumstances equation (9) becomes

$$C' = 3C+2\,, \tag{13}$$

and it will be apparent that a significant improvement in contrast can be expected if proper use is made of the polarized nature of the radiation. The contrast of all highlighted objects will be improved and in some instances objects that are in silhouette will be converted to highlights of increased numerical contrast.

Consider the special case of a high-contrast highlighted object. The contrast is improved by a factor of three by the use of a correctly oriented analyser. As lower contrasts are considered, the improvement factor C'/C increases until at $C = 0$ it is infinite; but of course this then has little meaning. Of greater interest is the actual increase in contrast obtained. Equation (11) shows that when $C \to 0$, $C' = 2$, which is a very significant increase. Objects that, under normal viewing conditions, appear as silhouettes of contrast within the range 0 to $-0 \cdot 5$ will be seen as highlights of increased numerical contrast.

When distant objects are considered, the contribution of path radiance to the overall apparent radiance can be significant. When this is so the improvement in contrast that results will be less pronounced.

In the light of the results so far obtained, a more extensive survey of the phenomenon of polarization is proposed. The seasonal variation of polarization will also be investigated.

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