THE WAVELENGTH DEPENDENCE OF THE FACULAR EXCESS BRIGHTNESS

G. A. CHAPMAN AND T. E. McGUIRE
Space Sciences Laboratory, Ivan A. Getting Laboratories, The Aerospace Corporation, El Segundo, California
Received 1976 November 22; accepted 1977 April 25

ABSTRACT

It has been shown that solar faculae can produce an apparent solar oblateness. They produced some of the oblateness measured at Princeton in 1966, although how much has not been finally settled. A "classical" test to separate the effects of brightness versus a geometrical oblateness is the color dependence of the brightness. Data is presented here on the color dependence of solar faculae. The excess brightness is well described by a $\lambda^{-1}$ form. The implication for oblateness measurements is discussed.

Subject headings: relativity — Sun: activity — Sun: faculae — Sun: interior — Sun: magnetic fields — Sun: rotation

I. INTRODUCTION

In 1966, Dicke and Goldenberg (1967, 1974) measured an excess solar oblateness that was sufficiently large, $\Delta r/r \approx 4 \times 10^{-5}$, that it represented a serious challenge to general relativity. There have been a number of attempts to explain the excess solar oblateness in terms of faculae or other brightness effects. (See, e.g., Chapman and Ingersoll 1972, 1973; Durney and Werner 1971, Ingersoll and Spiegel 1971; Kandel and Keil 1973. See Dicke 1974 for discussions of these matters.) Dicke and Goldenberg's claim of an excess solar oblateness has been weakened by a number of recent observations which indicate that there is no excess solar oblateness. Hill et al. (1974) found evidence for a time-varying excess brightness and no excess solar oblateness. Williams et al. (1976) and Shapiro, Counselman, and King (1976) have found that the results of the lunar ranging experiment support Einstein's general relativity but not the scalar-tensor theory of Brans and Dicke. Fomalont and Sramek (1975) obtained evidence from gravitational deflection of radio waves that supports Einstein's general relativity but not the scalar-tensor theory. At present there does not appear to be an excess solar oblateness. The nature and origin of the excess brightness is still unresolved.

The excess brightness of Hill et al. (1974) could have caused the apparent excess oblateness reported by Dicke and Goldenberg. Although this excess brightness has not been identified, we feel that solar faculae are a reasonable explanation unless it is specifically shown otherwise.

In measuring the solar oblateness there are several internal checks that can be made to separate the effects of a brightness signal from that of a geometrical oblateness. One of these checks is the color dependence. An excess brightness can be expected to have a pronounced color dependence, whereas a geometrical oblateness cannot depend on color.

Any excess brightness can be expected to have a color dependence, and in this sense faculae are nothing special. However, because of the patchy nature of faculae, some care must be exercised in determining not only the color dependence but also the quantitative effect, on the particular oblateness experiment, of the facular excess brightness. It will generally not be adequate to infer the effect of faculae by exterior means. Experiments which give up, by design, the color discrimination must do an especially good job of determining any excess brightness, including the degree of patchiness.

There is little evidence concerning the color dependence of facular brightness. Statements exist (Stellmacher and Wiehr 1973) that the facular brightness does not depend on wavelength. The main purpose of this paper is to show the wavelength dependence of faculae and to briefly discuss the magnitude of this wavelength dependence on a brightness-induced oblateness signal.

II. OBSERVATIONS

We present observations of the wavelength dependence of photospheric faculae obtained during 1975 August. These observations were obtained at the San Fernando Observatory with the extreme limb photometer (ELP), and refer to facular regions appearing in aperture 1 of the ELP. During these observations, aperture 1 defined an annulus of from 16° to 53° from the solar limb. A second aperture, which extended beyond the solar limb, produced data whose color dependence was consistent with that reported here, but because of greater noise due to seeing distortions of the limb, it has not been included here. The results pertaining to oblateness-like signals in § III refer to the second or limb aperture, but with the same color dependence as for aperture 1.

The measurement of the excess brightness of faculae near the solar limb is severely hampered by the geometrical foreshortening and the rapid change in the limb darkening. The ELP is designed to average over
the extreme solar limb to deal with the foreshortening and limb darkening. One attempts to obtain information on the facular limb darkening by knowing the limb distance of facular regions or measuring the change in light flux as a function of time as the solar rotation varies the limb distance. These effects are still under study and the results will be presented in a future publication.

Systematic observations were carried out in five different bands given in Table 1. The wavelengths and full widths at half-maximum were determined by a convolution of the filter transmission curves, the detector efficiency, the solar spectral shape outside the atmosphere, and the atmospheric transmission given in Allen (1973). The telescope efficiency has not been included. It is fairly uniform except for a decrease in the violet which may give a true wavelength for the blue filter of 0.440 rather than the value of 0.435 \( \mu m \) in Table 1. The basic optical scheme and observing technique are described in Chapman (1975). The observations of the color dependence started and ended with the green filter, and the complete sequence of five colors required about 30 minutes of observing time. Such a sequence was carried out from one to four times on each of four observing days in 1975 August.

Figure 1 presents plots of the limb brightness of a facular region for each of the five colors. The wavelength for each plot increases downward, and each, below the first, is offset downward by 0.04 intensity units for clarity. (The wavelengths are given in Table 1.) The intensity units are arbitrary and each tick mark on the horizontal scale corresponds to 10 steps of the ELP (each step is \( \approx 0.2 \) heliocentric).

The wavelength dependence of the facular excess brightness, \( \Delta I / I \), is shown in Figure 2, normalized to unity for the green filter. The intensity is the average over the length of the slit, and the quantity \( \Delta I / I \) represents the integrated brightness over that part of the facular region within one radian on the observed annulus. Each data point in Figure 2 corresponds to 250 scans around the solar disk, except for the case of \( \lambda = 0.53 \mu m \), which corresponds to 475 scans. The data are well described by a \( \lambda^{-1} \) variation, where we have plotted the smooth line,

\[
R(\lambda) = 0.53 \lambda^{-1},
\]

(1)
FACULAR EXCESS BRIGHTNESS

Fig. 2.—Wavelength variation of the facular excess brightness normalized to 1.0 at \( \lambda = 0.53 \, \mu \text{m} \), where \( R(\lambda) = \Delta I(\lambda)/\Delta I(0.53) \). The solid curve is given by \( R(\lambda) = 0.53 \lambda^{-1} \), with the error bars equal to \( \pm 1 \sigma \), determined from 10 observations.

where \( R(\lambda) = \Delta I(\lambda)/\Delta I(0.53) \) and with \( \lambda \) in micrometers. An unweighted least-squares fit to the five points gives

\[
R(\lambda) = -0.0568 \pm 0.0634 + (0.582 \pm 0.038)\lambda^{-1},
\]

with a correlation coefficient of 0.994, which is significant at the \( 10^{-3} \) level. Equation (1) is not significantly different from equation (2).

A physical dependence of contrast on \( \lambda^{-1} \) can be understood from the derivative of the Planck function in the Wien approximation, namely,

\[
\frac{\Delta I}{I} = \frac{\Delta B}{B} \approx \frac{hc}{kT^2} \lambda^{-1}.
\]

We find that, for the data used in constructing Figure 2, equation (3) requires \( \Delta T = 4.33 \, \text{K} \) if \( T \approx 5600 \, \text{K} \). For an angular basis of one quadrant rather than one radian, \( \Delta T \) would be 2.8 K. We notice from Figure 2 that the blue contrast lies about 1 \( \sigma \) above the \( \lambda^{-1} \) curve. This deviation, if real, may be the result of an increasing opacity in the blue and an increasing facular \( \Delta T/T \) in the upper layers of the photosphere. An increasing opacity in the blue may be due to line haze since the blue filter has a 78 nm width.

III. DISCUSSION

In order to determine the wavelength variation of the apparent solar oblateness caused by faculae, one must know the wavelength variation of the appropriate calibration factors. In this case we have (cf. Dicke and Goldenberg 1974)

\[
\frac{\Delta r}{r} = \frac{\Delta I}{I} = \frac{2}{\pi} \int_{\Phi_2}^{\Phi_1} \int_{r_2}^{r_1} \Delta I/ \langle I \rangle d\phi dr,
\]

where \( \langle I \rangle \) refers to the averaged intensity for the quiet Sun (without faculae) and \( \Delta I \) is the change in \( \langle I \rangle \) due to the facular region. The quantity \( \Delta I/\langle I \rangle \) is wavelength-dependent, where \( I_i \) is the intensity at the inner edge of the aperture and \( R \) is the solar radius.

Table 2 gives the wavelength variation of \( \Delta I/\langle I \rangle \), for \( \delta = R - r = 16^\circ \) determined from the limb-darkening data of Pierce and Waddell (1961). Their data were obtained under conditions probably similar to those for the ELP data, and their data agree reasonably well with preliminary data from the ELP on the wavelength variation of \( \langle I \rangle/\langle I \rangle \). The more recent limb-darkening data of Pierce and Slaughter (1976), where scattered light has been carefully removed, have poorer agreement with the ELP results.

The wavelength variation of a brightness-induced oblateness gives the possibility of clearly distinguishing its effect from that of a geometrical oblateness by observations at two or more widely separated colors. Table 2, second row, shows the wavelength variation to be expected from the facular contribution to oblateness measurements. Between 0.44 \( \mu \text{m} \) and 1.0 \( \mu \text{m} \) a variation of 2 or more is to be expected. For example, the apparent oblateness at 1.0 \( \mu \text{m} \) and 0.70 \( \mu \text{m} \) due to faculae is approximately 0.58 and 0.80, respectively, with respect to that obtained at 0.53 \( \mu \text{m} \). (The value of 0.80 at 0.70 \( \mu \text{m} \) supersedes the value recently used by Dicke 1976.) The two wavelengths used at Princeton in 1966 were ~0.71 \( \mu \text{m} \) and ~0.54 \( \mu \text{m} \).

In order to separate the effects of faculae from those that may be caused by a more uniform excess brightness (such as discussed by Hill and Stebbins 1975a and references therein), one must obtain observations of the excess brightness with high time and spatial resolution. Such observations, with a time and space

<table>
<thead>
<tr>
<th>TABLE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle I \rangle/\langle I \rangle ) VERSUS WAVELENGTH, ( \delta = 16^\circ )</td>
</tr>
<tr>
<td>( \lambda(\text{nm}) )</td>
</tr>
<tr>
<td>( \langle I \rangle/\langle I \rangle )</td>
</tr>
<tr>
<td>( R(\text{eq. [1]}) \times \langle I \rangle/\langle I \rangle )</td>
</tr>
<tr>
<td>Normalized at 0.53 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>
resolution of, respectively, ~ 1 hr and ~ 5° heliocentric or better, should be made throughout the entire observing period. In this way, a clear separation can be achieved between a facular excess brightness and any possibly uniform equatorial excess brightness.

The wavelength variation of the facular excess brightness, and its corresponding apparent oblateness, are not in conflict with the 1966 Princeton data (Dicke 1975; Hill and Stebbins 1975a) because the latter were obtained at \( \lambda \approx 0.71 \mu \text{m} \) except for six days at the end of the season where \( \lambda \approx 0.54 \mu \text{m} \). The wavelength and spatial variation of facular brightness remain as important checks for experiments designed to measure the visual oblateness or to identify the excess brightness of Hill et al. (1974).

This research has been supported by funds from the company-financed research program of The Aerospace Corporation. The authors wish to thank Dr. Pierce for sending us limb-darkening data in advance of publication. One of us (G. A. C.) wishes to thank Dr. J. C. Pecker and the staff of DASOP at the Observatoire de Paris, Meudon, where this paper was completed, for their kind hospitality during his stay.

REFERENCES

———, 1975, private communication.

G. A. CHAPMAN: The Aerospace Corp., A-6, P.O. Box 92957, Los Angeles, CA 90009
T. E. McGUIRE: Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726