ON THE PHYSICAL CONDITIONS IN THE PHOTOSPHERIC NETWORK: AN IMPROVED MODEL OF SOLAR FACULAE

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Abstract. Semi-empirical models of solar faculae, cospatial with strong photospheric magnetic fields, have been constructed from continuum observations. The center-to-limb contrast of the various models was computed taking into account their geometrical shape. The adopted model whose horizontal size was taken to be 750 km, indicates that, in field regions, the temperature begins to rise outwards at $z \approx - 125$ km (above $r_{5000} = 1$) and that the extrapolated temperature at $z \approx - 400$ km is about 1500 K above that of the undisturbed atmosphere; the electron density is higher by a factor of about 30.

1. Introduction

The chromospheric network, visible in the center of the CaII K-line, gives vivid evidence of the non-uniformity of the chromosphere (e.g. Title, 1966). Similarly, the more delicate photospheric network, visible in many Fraunhofer lines, shows that the upper photospheric regions are quite non-uniform. This photospheric network is cospatial with the strong, non-sunspot, magnetic fields (Chapman and Sheeley, 1968; Ramsey, 1969; Harvey and Livingston, 1969), and can be seen in white light near the solar limb where its segments are referred to as faculae. Under conditions of good seeing, this network tends to be resolved into small structures having characteristic dimensions of about one arc-second (Rogerson, 1961; Bray and Loughhead, 1961; Chapman, 1968; Sheeley, 1969). In this paper, the more familiar term, faculae, will be used to describe elements of the photospheric network regardless of their position on the solar disk.

A number of studies have been made to determine the physical conditions prevailing in solar faculae. Spectroscopic techniques have been employed by Mitropol’skaya (1952), Voikhanskaya (1966), Polonskii (1966), and Chapman and Sheeley (1968) to determine, primarily, a mean temperature difference of faculae with respect to the surrounding atmosphere. Photometric measurements of facular limb darkening have been made by Richardson (1933), Wormell (1936), Waldmeier (1949), Rogerson (1961), and Kuz’minykh (1963). The latter (Kuz’minykh, 1965) has published a model giving the depth dependence of various physical quantities in an average facula. Reichel (1953) published a table giving the temperature difference at a number of optical depths. Rogerson (1961), from Stratoscope observations, determined a mean temperature excess for an idealized column of facular material. With the exception of Rogerson, none of these authors has allowed for the relatively small horizontal size of most faculae. It was felt that a depth-dependent facular model was needed that included the effects of small horizontal size.

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This paper, while presenting a preliminary height-dependent model of the physical conditions in an idealized facula (having a characteristic horizontal size of 750 km), is largely intended to explore the effects of geometry on facular contrast.

An improved model will be presented at a future date when better observations become available.

Section 2 describes the observational material used for the model calculations. Section 3 outlines the calculations and presents the models, while Section 4 discusses the results.

2. Observational Material

The observations used in this study come from two sources: near the limb ($\cos \theta < 0.2$) the observations of Rogerson (1961) have been used. Away from the limb, observations obtained at Haleakala, Maui, Hawaii have been used. The Haleakala observations were obtained with a 6-inch photheliograph at 5300 Å and do not have resolution as high as the 5490 Å Stratoscope pictures. To partially compensate for the resolution difference, the Stratoscope contrast measurements have not been corrected for instrumental broadening, whereas the Haleakala observations have been corrected for instrumental smearing. An approximate correction for wavelength difference has been applied to the Stratoscope contrast as

$$\left( \frac{\Delta B}{B} \right)_{5300\AA} = \left( \frac{\Delta B}{B} \right)_{5490\AA} \approx 1.036,$$

where $B$ is the Planck function.

The faculae, which are not visible at 5300 Å near the center of the disk, were found and measured by reference to a photograph made with a 3840 Å violet filter (Chapman, 1969), which shows faculae across the solar disk. Facular contrast from the violet filter has not been used when constructing models of the faculae due to the uncertainty

Fig. 1. The filled circles represent 5300 Å data for 31 May 1969 from Haleakala. The open squares represent 3840 Å contrast for some of the 5300 Å features. The open circles represent Rogerson's spatially-uncorrected Stratoscope observations for 5300 Å.
of physical interpretation. However, limb darkening observed with this violet filter suggests that it 'looks' at $\tau_{5300} \approx 0.2 - 0.3$. Figure 1 shows the 5300 Å-contrast data used from Haleakala in constructing models as well as the 3840 Å-contrast for some of the features not readily visible at 5300 Å. To minimize the effects of large-scale image distortion on pictures at the two wavelengths, positions of faculae on the violet-filter photograph were measured from small, nearby sunspots. Relative distortion prevented measurements from being made more than a small fraction of a solar radius away from small reference sunspots. Simultaneous observations at these two wavelengths would probably remove the distortion. However, some positional uncertainty may be caused by the features appearing relatively coarser through the violet filter, probably an instrumental effect. It is estimated that the positioning accuracy of the microphotometer on a green picture was approximately 1" - 2" when referenced to the violet picture. (The overall sizes of many of the faculae, at 5300 Å, were in the range 2" - 3" in their measured extent.) The scanning aperture of the microphotometer was 1" for the 5300 Å picture, 31 May 1969. The small smearing effect of the microphotometer and telescope have been allowed for assuming gaussian-shaped smearing functions of 1" and 0.8" FWHM, respectively.

Facular contrast, $\Delta I/I$, at 5300 Å has been converted to facular limb darkening, $\Phi_f$, by using photospheric limb darkening, $\Phi_{ph}$, interpolated from the Bilderberg (BCA) atmosphere (Gingerich and de Jager, 1968):

$$\Phi_f = (1 + \Delta I/I) \Phi_{ph},$$

where

$$\frac{\Delta I}{I} = \frac{I_f - I_{ph}}{I_{ph}}.$$

The facular limb darkening is used in the next section to obtain the initial facular model.

3. Analysis of Data

In this section a description will be given of the way in which facular models were produced and then compared with the data of Figure 1. Briefly summarized, an initial model of a facula was obtained from limb darkening data assuming the facula was a semi-infinite, plane parallel atmosphere. This trial model was then horizontally limited, surrounded by a model of the undisturbed photosphere, and its contrast computed as a function of viewing aspect. Comparison of observed and computed contrast then led to corrections to the structure of that model. This cycle of computation and comparison was continued until the observed contrast was reached within acceptable limits. A more detailed description is given next.

To obtain the initial facular model, facular limb darkening is inverted, yielding a $T(\tau_{5300})$ relation. The technique is similar to that of Pierce and Aller (1951),

$$\frac{B_\lambda(\tau_\lambda)}{I(0, 0)} = A_\lambda + B_\lambda \tau_\lambda + C_\lambda E_2(\tau_\lambda),$$
where $B_\lambda(\tau_\lambda)$ is the Planck function, and $I(0, 0)$ is the photospheric intensity at the center of the disk. Assuming, for the moment, the faculae are semi-infinite in the horizontal direction, the limb darkening becomes

$$\Phi_\lambda(\mu) = A_\lambda + B_\lambda \mu + C_\lambda [1 - \mu \ln (1 + 1/\mu)],$$

where $\mu = \cos \theta$. For the data of Figure 1, $A = 0.7655$, $B = 0.3554$, $C = -0.3883$, ($\lambda = 5300$ Å) from least squares.

Having obtained $T(\tau_\lambda)$ from $B_\lambda[T(\tau_\lambda)]$, the dependence of the remaining quantities on depth was determined by modifying the Bilderberg atmosphere. At each depth-level the gas pressure, determined from

$$\frac{dP}{d\tau_\lambda} = \frac{g}{\kappa_\lambda},$$

and the new temperature are used to determine the change in the electron pressure, using tables in Aller (1963) and Unsöld (1955). The change in electron pressure is then used to correct the opacity and physical depth scale. (The whole process is iterative, of course.) The major simplifying assumptions are: (1) the change in $\kappa_\lambda$ is due only to the change in the H$^-$ absorption coefficient (the dominant absorber at the temperatures encountered here), (2) the mean molecular weight is unchanged, and (3) the wavelength dependence of the absorption coefficient between 5300 Å and 5000 Å, is approximated by a linear expression (to put the model on a $\tau_{5000}$ depth scale). The change in hydrogen ionization is calculated from the Saha equation.

The main reason for modifying a model of the photosphere, such as the Bilderberg, was to minimize differences between the facular and photospheric models arising solely from computational differences. Any facular model so derived will be affected by errors or uncertainties in the photospheric model. Next, we will discuss the calculation of facular contrast for a facular model.

The initial facular model was based on a semi-infinite atmosphere, an unreal situation because, for a horizontal size of 750 km, the horizontal optical depth is roughly unity near radial $\tau_{5000} = 0.1$. In other words, one is, to some extent, seeing through a facula near the limb. The contrast of facular models is calculated by numerically

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Fig. 2. The emergent ray geometry in the calculation of facular contrast is shown for $\mu = \cos \theta = 0.5$. The dashed horizontal line represents $z = 0$ for the photosphere. The ray path is translated vertically up and down from the position indicated to maximize the emergent intensity.
Fig. 3. The heavy line is the least squares fit to the 5300 Å data of Figure 1. The filled circles represent the computed contrast of the initial facular model (Figure 5) approximating semi-infinite width. The open circles represent the same model but having a width of 750 km; the contrast for \( \cos \theta \leq 0.2 \) is markedly reduced.

Fig. 4. The computed contrast, \( \Delta I/I \), and limb darkening, \( \Phi \), at 5300 Å for the adopted facular model are shown (open triangles) along with the observations of Figure 1. The line shows the limb darkening for the Bilderberg model for comparison.
integrating the equation of transfer along the line of sight through the undisturbed and facular atmospheres. Figure 2 illustrates the geometry of the calculation. The line of sight is varied from $\cos \theta = 1.0$ to $\cos \theta < 0.1$, where the approximation of plane-parallel stratification is beginning to fail for the photosphere. The facula is assumed to have a square cross-section and be homogeneous in a horizontal plane. The variation of the physical quantities with depth is given by the facular model. The physical depth scale of the facular model is matched to that of the Bilderberg model, but the zero point of the facular depth scale is varied to obtain maximum intensity for a given $\cos \theta$. Figure 3 shows the computed contrast and limb darkening for a semi-infinite and 750 km-wide facular atmosphere derived by inversion of limb darkening from the data of Figure 1. One can clearly see the decreased contrast of the 750 km model, near the limb, due to its finite width. The indication is that a model will be required that has even higher source function values (hence temperature) in the region around $\tau \approx 0.1 - 0.2$. Although the limb contrast could be increased by a higher opacity in the appropriate layers, such a condition would require a higher electron pressure, hence higher temperature, assuming LTE and hydrostatic equilibrium to hold.

To increase the computed contrast near the limb, the $T$ vs $\tau$ relation was modified by trial and error. More systematic techniques, involving inversion of limb darkening, were unsuccessful. For each new model, the center-to-limb contrast was computed and if it was not sufficiently close to the desired contrast the model was modified again. This procedure was carried out until satisfactory agreement was obtained between observed and computed contrast. It should be noted that such a trial and error procedure seems to be self-limiting because the opacity at a given height, does not change

Fig. 5. The variation of temperature with optical depth for the Bilderberg Continuum-Atmosphere (light line), the initial facular model, based on a semi-infinite facular atmosphere (open circles), and the adopted facular model (heavy line). Equal optical depths do not, of course, correspond to the same physical depth. The range of optical depths for the facular models is larger than was used for the contrast calculations.
rapidly with temperature. As the temperature is increased, the H\(^+\) mass absorption coefficient becomes larger (due to \(P_e\) increasing) but the density tends to decrease, hence the product \(\kappa_0\) changes more slowly than does either variable individually.

Figure 4 shows the contrast computed from the adopted facular model along with the observed data of Figure 1. Figure 5 shows the \(T\) vs \(\tau_{5000}\) for the BCA photosphere and the adopted facular model. Figure 6 gives the variation of \(\Delta T\) vs \(z\) where \(\Delta T\) is

\[ \Delta T = T_{\text{facular}} - T_{\text{BCA}} \]

and \(z\) is physical depth. The adopted facular model is given in tabular form in Table I. One should note that the model is not reliable above \(\tau \approx 0.1\) since this represents the range of the observations and the higher levels are extrapolated. Furthermore, there is an additional uncertainty with reference to the photosphere, in the zero-point of the depth scale, \(z\), due to assumptions concerning horizontal equilibrium (see discussion in Section 4B). Therefore, the zero-point has been placed at facular \(\tau_{5000} = 1\).

4. Discussion

The facular model proposed in this paper involves several assumptions which will now be discussed.

A. HYDROSTATIC EQUILIBRIUM

This simplifying assumption has been used to construct facular models even though faculae are the site of photospheric magnetic fields which have reported strengths in
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Table I of the adopted facular model (7B2J) has been interpolated to match the physical depth scale of the BCA. The column headings are: $\tau$, optical depth; $T$, temperature (K); $P$, gas pressure (cgs); $P_e$, electron pressure (cgs); $\kappa$, absorption coefficient (cm$^2$/gm); $\varrho$, density (cgs); $Z$, physical depth (cm); $T' - TP$, temperature difference, facula-photosphere.
the vicinity of $3 \times 10^2$–$5 \times 10^2$ G. The exact influence of these fields is not yet known but may not be of great importance. In sunspot umbrae the field strength is about 5–6 times greater than in faculae (thus resulting in a magnetic pressure about 25–36 times that in faculae). Yet hydrostatic equilibrium may apply in sunspot umbrae (Mattig, 1969). The magnetic pressure, $H^2/8\pi$, in faculae should be about $10^4$ dyne/cm$^2$ (for $H = 5 \times 10^2$ G) which is only $\approx 20\%$ of the gas pressure at $z \approx -100$ km. In any case, the vertical gradient of the field is unknown; the possible influence of the field on the pressure gradient has been assumed negligible. The departure of the facular model from the photosphere is likely to become even larger than here, in this study, if the field significantly affects the pressure distribution and height scale.

Another, perhaps important, challenge to hydrostatic equilibrium is presented by reports of slowly ($\approx 0.1$ km/sec) downflowing material often found at the sites of photospheric magnetic fields (Frazier, 1970). Since he used a magnetograph with a scanning aperture of 2.4 arc-sec square, the true value of the velocity, if cospatial with the magnetic field, may be $\approx 0.6$ km/sec, assuming the field to have a cross-section of $1$(arc-sec)$^2$. However, nothing is known about the velocity gradients, either vertical or horizontal. In view of the lack of knowledge concerning motions, their influence has been neglected for the present.

**B. HORIZONTAL EQUILIBRIUM**

The lifetime of faculae probably exceeds 8 h (Bray and Loughhead, 1961) thus demonstrating that these structures are quite stable. Their stability implies near equality of horizontal pressures inside and outside the facula. For a uniform magnetic field we would expect $P_{\text{facula}} + H^2/8\pi \approx P_{\text{photosphere}}$. To satisfy this condition with the facular

![Fig. 7. Photospheric (heavy solid line) and facular (light solid line) gas pressure versus physical depth. The dashed line shows the shifted facular depth scale, discussed in Section 4, that gives horizontal equilibrium and assumes negligible magnetic pressure at $z \approx -400$ km.](image)
model, we require a vertical shift in the facular height scale relative to the photosphere. The smallest shift for the present facular model is a downward shift of the facula with respect to the photosphere of about 60 km (Figure 7). This shift approximately equalizes the facular and photospheric gas pressures at \( z \approx -400 \) km and thereby implies no significant magnetic field pressure at this level. Neglecting tension forces from field curvature, the pressure difference, \( P_{\text{photosphere}} - P_{\text{facular}} \), from this shift implies a magnetic field that increases roughly linearly inwards from \( H \leq 20 \) G at \( z \approx -400 \) km to \( H \approx 1300 \) G at \( z = 0 \) (\( \tau_{\text{photosphere}} = 1 \)) at which depth the flux tube would have an inferred diameter of about 450 km. Abdusamatov and Krat (1969) have reported magnetic knots, from balloon photographs presumably in the continuum, having measured ‘half-widths’ of 0.3" – 0.4" or \( 2 \times 10^2 - 3 \times 10^2 \) km. The authors suggest that the field strength is likely to exceed 1000 G in such small knots, based on their own subsequent ground-based observations. However, the vertical shift in Figure 7 is not unique since we don’t know what the field gradients are and possible tension forces have been neglected.

To some degree, horizontal equilibrium may be influenced by mass motions. The kinetic energy of supergranular motions is small (\( \approx 4 \times 10^2 \) dyne/cm\(^2\)), but vertical granular velocities of 2.2 km/sec have been reported (Kirk and Livingston, 1968). This velocity corresponds to \( \frac{1}{2} g v^2 \approx 8 \times 10^3 \) dyne/cm\(^2\) at \( z = 0 \), a pressure considerably less than the \( 6.7 \times 10^4 \) dyne/cm\(^2\) to be expected from \( H_z = 0 \approx 1300 \) G implied by Figure 7. The actual influence of mass motions requires that we know something about the velocity gradients.

C. FURTHER CONSIDERATIONS

The facular model presented in this paper should be considered as preliminary and is open to improvement on observational grounds for several reasons: (1) the difficulty in obtaining sufficient resolution to study structures that are perhaps less than an arc-sec in width, (2) the presence of an undetermined amount of scattered photospheric light, and (3) the difficulty in identifying the faculae, in the continuum, near the disk center.

The effect of clustering or grouping, which one often sees in the photospheric network, has been neglected in testing the present facular model. For instance, if two faculae are close together then the emerging intensity, \( I(0, \mu) \), will also be a function of azimuth. There are, however, numerous isolated faculae which can be treated as independent entities, thus making the contrast calculations presented here, a valid test of the model for many faculae. Because of clustering (seen nicely in Sheeley’s (1969) observations) the general applicability of a facular model, based on observations of isolated faculae, may be questioned. However, Harvey and Livingston (1969), while studying the influence of the facular temperature excess on magnetograph calibrations, found no obvious dependence of this excess on flux observed with a 2.4 arc-sec square aperture, implying that the structure of faculae may not depend on their clustering.

The facular model presented here gives a considerably steeper temperature rise than in previous studies. Comparing this model with Rogerson’s, if we average all tempera-
ture differences between $\tau = 0.304$ and $\tau = 0.005$ in the adopted model here, we have $\Delta T \approx 950$ K, compared to Rogerson's $\Delta T = 910$ K.

Even though this paper is concerned directly only with the photospheric regions, if one extrapolates the facular model into the chromosphere, the difference in physical conditions between magnetic-field and non-field regions will become quite large. We see, further, that the temperature inversion in field regions, which make-up the supergranule boundaries, begins deeper than previously assumed (Beebe and Johnson, 1969).

An effort is being made to obtain improved data on the continuum contrast, over the widest possible range in $\cos \theta$ in order to improve the facular model given in this paper. However, to extend significantly the height range of continuum observations one must go to greatly different wavelengths; either the infrared, which presents one with detector and resolution problems, or the ultraviolet, which must be done in space and may not really represent continuum, if strong emission lines lie in the passband. An alternate method of looking at various heights is by using Fraunhofer lines as a height probe, but one is then presented with a considerably more difficult task in obtaining quantitative information since one will be dealing with line formation processes (which may be non-LTE) in a magnetic field. The wings of the Ca $\textsc{ii}$ K-line might prove useful for such a height study. The effective Doppler and Zeeman sensitivity should be low due to the relatively shallow slope of the wings.

Acknowledgements

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